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Examining the inconsistency of mercury flow in post-Minamata Convention global trade concerning artisanal and small-scale gold mining activity

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ABSTRACT

In 2017, the Minamata Convention (MC) on mercury (Hg) control entered into force. However, whether the MC is effective and how it reshapes the global Hg flow remain unclear. In this study, we established a method to detect inconsistencies in data on global Hg trade, and calculated the gap between the demand and supply of Hg to the artisanal and small-scale gold mining (ASGM) sector (i.e., the largest source of Hg emissions globally) in 39 countries across four regions. According to our results, inconsistencies in statistical data concerning Hg for ASGM activities exist in both Africa and Central and South America. Asia showed a considerably lower amount of Hg applied to ASGM than apparent Hg consumption; nevertheless, the largest consumer of Hg was Asia, predominantly China and India. Many countries in which ASGM is conducted are already MC parties; however, only few submitted their national action plans (NAPs) or have established/enforced specific laws to curb Hg use in ASGM. Analysis of Hg-related trade information suggests that in 2017, the trade of metallic Hg disappeared in some African and Central and South American countries, but new trade flows of goods with higher Hg content emerged. The method established in this study can support the search for countries implementing ASGM with hidden Hg use and flows, thereby contributing to the planning of further Hg control regulations. To enforce sound Hg management, the submission of NAPs should also be promoted in addition to the expansion of MC parties.

1. Introduction

Mercury (Hg) is a toxic pollutant. Owing to its high vaporization, it travels a long distance and affects areas that are located long distances from the emission sources (Moreno-Brush et al., 2016). Elemental Hg in the gas phase can be inhaled, thereby inducing toxic effects at elevated concentrations (Swain et al., 2007). After deposition into soil or water, metallic Hg can be oxidized and transformed into an organic form, such as methylmercury (MeHg), and bioaccumulated in the food web (Bravo et al., 2017; Göthberg and Greger, 2006; Wang et al., 2018). Humans are often exposed to MeHg predominantly via seafood and rice consumption (Swain et al., 2007; Zhang et al., 2010). MeHg, which is also known as the cause of Minamata disease half a century ago in Japan, has health impacts associated with neurocognitive deficits in human fetuses and cardiovascular effects in adults (Axelrad et al., 2007; Roman et al., 2011).

While the total emissions of Hg to the atmosphere represent 6,500 to 8,200 tonnes/a, natural sources account for 56% to 82% of this amount (Driscoll et al., 2013). The main anthropogenic sources of Hg emissions include artisanal and small-scale mining (ASGM) (Telmer and Veiga, 2009), coal combustion (Streets et al., 2018), cement production (Kogut et al., 2021), and nonferrous metal production (Pacyna et al., 2006). Among these sources, ASGM is the largest source of anthropogenic Hg emissions, accounting for 38% of total Hg emissions or 838 tonnes of Hg going into the atmosphere in 2015 (UNEP, 2019a). Anthropogenic releases of Hg to water and land account for 1,800 tonnes/a in which ASGM represents 67% or 1,200 tonnes/a (UNEP, 2019a). Mercury emissions, as well as the direct release, are of primary concern because of the extensive use of Hg to amalgamate gold by artisanal miners (Basu et al., 2015; Cordy et al., 2013). Approximately 15 million individuals,

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including approximately 4–5 million women and children, participate in the ASGM industry in 70 countries (Planet Gold, 2021).

The Global Mercury Assessment (GMA) (UNEP, 2019a) estimates that 2,060 tonnes/a of Hg is used and lost in the ASGM sector worldwide. Given its broad and deep impact on human health and wellbeing, accurate numbers related to Hg releases are an issue with political relevance once the Minamata Convention (MC) party countries are bound to apply policies to reduce Hg use and trades (UNEP, 2019b). Under the MC, new primary Hg mining should not be commissioned, and existing Hg mines should only operate for a period of up to 15 years after the MC came into force. Each party is required to develop and implement a national action plan (NAP), and the development of strategies to prevent the diversion of Hg or Hg compounds for use in ASGM is required by the MC. In addition, the manufacture, import, or export of Hg-added products, such as batteries, switches, compact fluorescent lamps, and non-electronic measuring devices that contain Hg, were scheduled to be phased out in 2020.

However, in many cases, ASGM is poverty-driven and is a deeply rooted activity in the developing world (Haundi et al., 2021; Hilson, 2009). After the MC came into force, the demand for Hg in the ASGM sector may not have decreased, thus driving the increase in the Hg trade through informal or illegal routes such as mislabeling, smuggling, or black markets (Yoshimura et al., 2021). Substance material flow analysis (SFA) has been conducted on a national scale in countries including the United States (Jasinski, 1995), China (Habuer et al., 2021; Hui et al., 2017), India (Burger Chakraborty et al., 2013), and Poland (Panasiuk and Głodek, 2013), for which domestic Hg flows, the final fate of Hg, and Hg consumption drivers were thoroughly investigated. However, these research studies mostly focused on the final fate of Hg in the environment. In reality, not all countries, especially those that experience significant rates of poverty, are able to provide detailed SFA at a national level. Moreover, Hg flows to the ASGM sector are often informal or illegal, meaning that they are often not reflected in statistics and escape the MC and other Hg emission control measures, thus making Hg management difficult. In addition, Hg is commonly contained as impurities in natural resources, such as coal and copper ores, which are primary sources of Hg emissions (Ghosh, 1972; Hylander and Herbert, 2008; Savva et al., 2014; Tian et al., 2010). It can either be emitted to the atmosphere during its production and transportation or be recycled to produce Hg in ASGM countries after the Hg trade was ceased by the MC, which made Hg more difficult to obtain in some countries. The inconsistencies in Hg data and the lack of monitoring of Hg in trade flows are, therefore, of great concern. Nevertheless, such gaps in Hg management are seldom studied, which results in a large part of the Hg flow being excluded from monitoring and hinders effective Hg control.

Therefore, in this study, we conducted a material flow analysis of global trade flow related to Hg. We focused mostly on the import and export of Hg to each country, rather than the final fate of Hg, and we included the flow of Hg to countries that are unable to conduct a domestic SFA. The objectives of this study are as follows: First, to establish a method that can detect the inconsistency in Hg trade in countries in which ASGM activities are conducted, so as to understand the possible informal Hg flow in countries that may be relatively vulnerable to Hg mismanagement; second, to determine the inconsistencies detected using the method on different levels, including an overview of the Hg problem for each continent and a further investigation of each country; third, to report the trade flow of commodities that are significantly reshaped after the MC entered into force.

2. Methods

To examine the inconsistencies in data on global Hg trade, we first investigated countries in which ASGM activities are conducted and estimated their ASGM Hg input, and then compared the amount of Hg input to ASGM with the total Hg available domestically, considering their NAPs on Hg control. We then screened out the trade flow that showed a significant change in the studied countries after the MC came into force.

2.1. Gap between Hg demand and supply

2.1.1. ASGM Hg input

According to the GMA (UNEP, 2019a), we selected countries in Africa, Asia, Central and South America, and Oceania, in which ASGM activities are carried out. The mean value of ASGM production provided by the GMA was used in our calculations. We calculated the gold production from ASGM in 2010–2018 based on the estimate made by Metals Focus (2020), and the amount of Hg applied in ASGM (Hg input) by multiplying the ASGM production by the Hg (input): Au (produced) ratio. The term "Hg input" is the Hg that entered the amalgamation process and was lost with tailings and amalgam burning (when retorts are not used). The Hg:Au ratios are reported to range between 3:1 and 5:1 for whole-ore amalgamation (WOA) and between 1:1 and 3:1 for concentrate amalgamation (CA) (Kopanos and Puigjaner, 2019; Persaud and Telmer, 2015). The Hg:Au ratio was calculated as (Hg[entering] − Hg [excess])/Au (sponge), for which the excess Hg is the amount that does not form amalgam (gold sponge) and was thus removed (and reused) during the amalgam filtration (Persaud and Telmer, 2015). In this study, we applied the specific Hg:Au ratios reported by Yoshimura et al. (2021) for Africa, Asia, and Central and South America, i.e., 1.96, 1.23, and 4.63, respectively. The calculation for Oceania adopted the same Hg:Au ratio as that used for Asia (1.23). For countries with specific Hg:Au ratios provided, the calculations were conducted with the specific ratio for each country. The Hg:Au ratios are summarized in **Table S1** in the Supporting Information (**SI**).

2.1.2. Apparent Hg consumption

Apparent Hg consumption is defined as domestic production plus imports minus exports for Hg-related commodities, according to the Organization for Economic Cooperation and Development (OECD) Guide for Life Cycle Assessment (OECD, 2008):

$$ApparentHgconsumption(A) = Hgproduction + import[Hg] - export[Hg] \tag{1}$$

Each Hg flow was calculated by multiplying the Hg content of the product by its amount (Nakajima et al., 2018), as described in the **SI**. The Hg content in each product is summarized in **Table S2**.

The apparent Hg consumption is the total amount of Hg available in the studied countries. The Base pour l'Analyse du Commerce International (BACI) database (CEPII 2017) was used to extract trade data for 231 countries/regions, and 5,000 commodities and domestic Hg production were surveyed. The BACI database is an improvement compared to the UN Comtrade database (CEPII 2017). Of the 5,000 commodities, a total of 112 were Hg-related, and were selected for this study. These Hg-related commodities include ores and fossil fuels (e.g. zinc ores, lead ores, copper ores, and coals that contain Hg as impurities), raw materials (e.g. Hg and precious metal compounds), and components or final products (e.g. watches, lamps, batteries, ships, machinery, and pills). The Hg flows and apparent Hg consumption in global trade were then calculated for 2010–2018.

2.1.3. Detection of inconsistency: Gap between ASGM Hg input and apparent Hg consumption

Using the data obtained from the above calculations, the difference between Hg input in the ASGM sector and the apparent Hg consumption was calculated for the studied counties in 2010–2018.

$$G_j = I_j - A_j \tag{2}$$

Here, G_j denotes the gap between ASGM Hg input and the apparent Hg consumption in country j, and I_j and A_j represent the ASGM Hg input and apparent Hg consumption in country j, respectively. When $I \leq A$, this indicates that the ASGM Hg input is within the total amount of Hg available in the studied country. When $I > A$, it indicates a larger amount of Hg input in ASGM than the total amount of Hg that can be obtained in the country, which can be attributed to inconsistencies in the formal statistics.

2.1.4. Vulnerability in Hg management: normalized gap

As the volume of Hg-related trade varies from country to country, the gap (G) results alone cannot determine whether and to what extent a particular country is vulnerable to managing Hg. To assess the vulnerability of countries in terms of Hg management, we also calculated the normalized gap (normG), using the mean value from 2010 to 2018 as follows:

$$normG = G/A \tag{3}$$

The threshold for the detection of vulnerability was set as 1.2. When normG < 1.2, inconsistencies in statistics or vulnerabilities in Hg management are considered minor. An extremely high normG is considered a sign of poor Hg management in the country.

2.2. Changes in global trade concerning Hg after the MC entered into force

To evaluate the changes in Hg trade after 2017 (i.e., when the MC came into force), we analyzed the trade flow related to Hg in both imports and exports based on the BACI database (CEPII 2017). The 112 Hg-related commodities selected in this study were categorized into one of three types: ores and fossil fuels, raw materials, or components/final products. The average amount of Hg traded in each category during 2010–2016 and in 2017 was calculated to determine if the MC reshaped the overall Hg trade flow.

To evaluate the effectiveness of the MC in controlling Hg trade, we also calculated the rate of change in each commodity in the year 2017. Typically, we paid more attention to the Hg embedded in traded commodities that showed the highest flow fluctuations (top 1 percentile) in the 2010–2016 period and in 2017. Changes in global trade concerning Hg were sorted into four categories: disappeared, newly emerged, significantly increased, and significantly decreased, as described in the **SI**.

3. Results

3.1. Gap between ASGM Hg input and apparent Hg consumption in Africa, Asia, Central and South America, and Oceania

At the regional level, from 2010 to 2018, comparable amounts of ASGM Hg input and apparent Hg consumption were detected in Central and South America (Fig. 1). Each year, around 1,000 tonnes of Hg were consumed in this region, a large amount of which may have been related to ASGM activities. A similar trend was found in Oceania, although only Papua New Guinea was included in this study, for which almost the same amount of ASGM Hg input and apparent Hg consumption were found. Africa also showed comparable amounts of ASGM Hg input and apparent Hg consumption until 2016 when ASGM Hg input increased and apparent Hg consumption started to decrease. Asia, however, showed a different trend from Africa, Central and South America, and Oceania. In Asia, apparent Hg consumption were much higher than ASGM Hg input. The amount of ASGM Hg input was relatively stable from 2010 to 2018 at 375–530 tonnes over this time period. Peak ASGM Hg input occurred in 2011, after which the value started to decrease gradually. Apparent Hg consumption suddenly decreased in 2011 but subsequently increased gradually. More than 6,000 tonnes of Hg were consumed in Asia in 2018.

3.2. Gaps at the country level and actions concerning Hg control

The gaps between ASGM Hg input and apparent Hg consumption at the country level for each region are shown in Fig. 2. Inconsistencies in Hg-related trade statistic data were generally found for African countries (Fig. 2a) and some countries in Asia (Fig. 2b1) and Central and South America (Fig. 2c), which showed higher ASGM Hg input than apparent Hg consumption. The gaps are affected by the Hg:Au ratios applied in the calculations. Using the Hg:Au ratio (WOA: 5:1; CA: 1.3:1) and the fraction of WOA and CA provided by the AMAP/UNEP (2019), we found similar tendencies in the detected gaps (Fig. S1) to the results from specific Hg:Au ratios (Fig. 2).

Only South Africa and the Democratic Republic of the Congo (DR Congo) showed a lower level of ASGM Hg input than apparent Hg consumption, whereas other African countries generally showed higher amounts of Hg applied in ASGM in 2010–2018. Except for DR Congo and South Africa, this inconsistency was found for all studied African

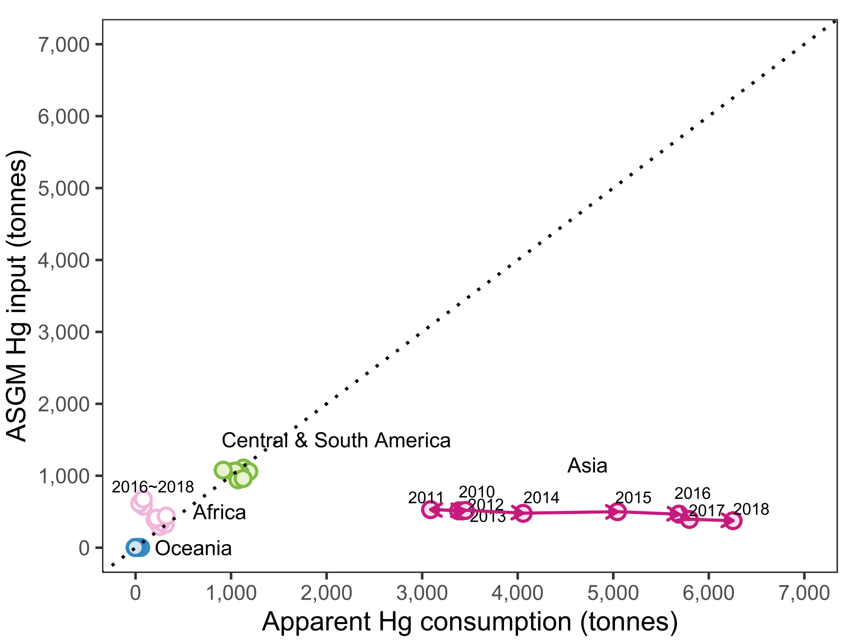


Fig. 1. Apparent Hg consumption and artisanal and small-scale gold mining (ASGM) Hg input in Africa, Asia, Central and South America, and Oceania. ASGM Hg input was calculated according to data gathered from Global Mercury Assessment (UNEP, 2019a), Gold Focus (Metals Focus, 2020), and Yoshimura et al. (2021). Apparent Hg consumption was calculated based on data from domestic Hg production and BACI (CEPII 2017) global trade database. The total amount in each year is shown in circles. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

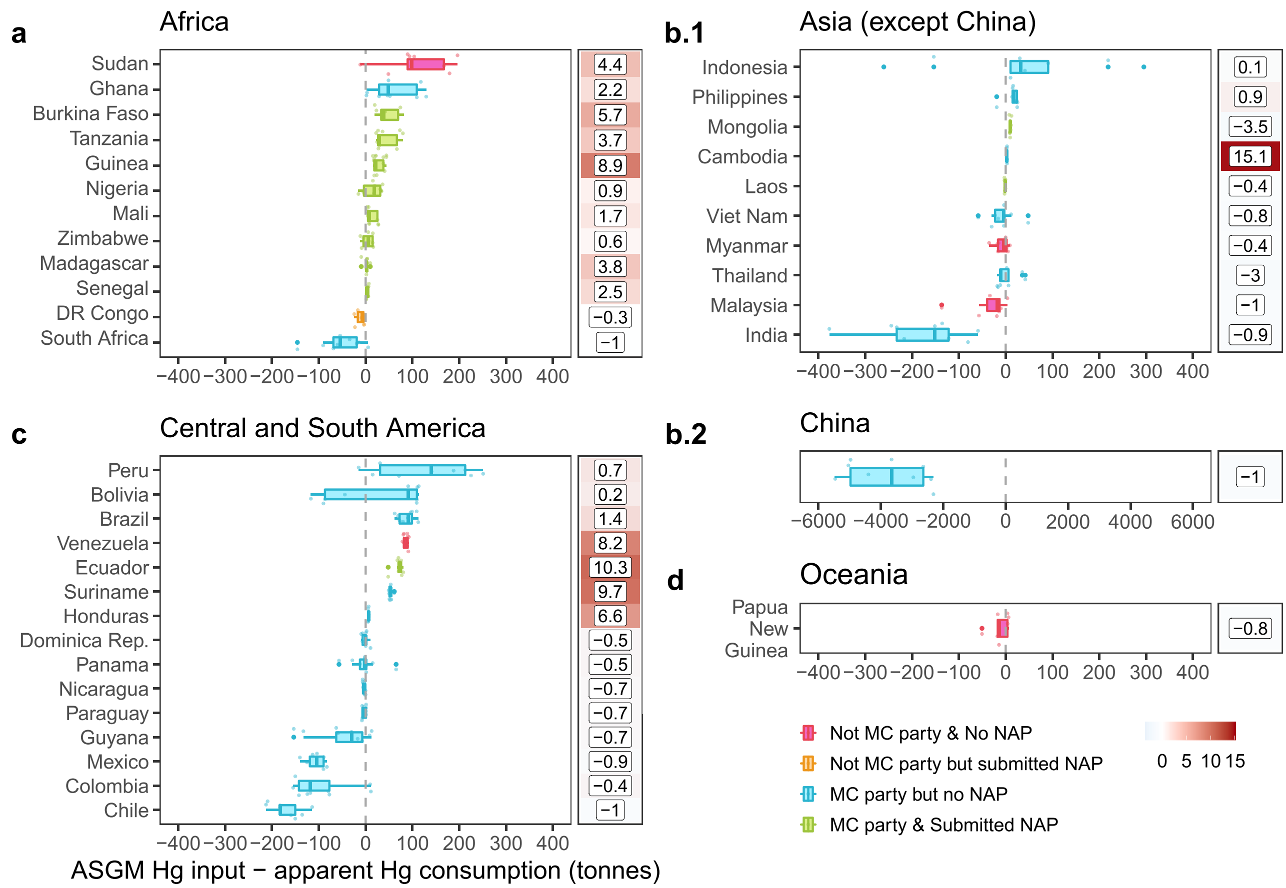


Fig. 2. Gap between ASGM Hg input and apparent Hg consumption for each country from 2010 to 2018 (in tonnes), according to the country's participation in the MC (i.e., whether it is a party or not) and the National Action Plan (NAP) on Hg control. Countries are ranked in descending order in terms of the median gap value for each region. In addition to the median value, dots around the box plot for each country show the difference between ASGM Hg input and apparent Hg consumption in each year. Color bars on the right side of each graph show the mean normalized gap (normG), and thick colors indicate countries with relatively greater vulnerability in terms of Hg management.

countries, which indicates that unreported Hg may have flowed there. Meanwhile, African countries are actively taking actions to control the use of Hg, most of them are already MC parties, and many countries have submitted an NAP. However, as the country that showed the most significant inconsistency in Hg trade statistics, Sudan is not an MC party and did not submit its NAP. DR Congo also did not sign the MC. Although inconsistencies in trade statistics were not found for DR Congo, the Hg problem caused by ASGM may also exist there, and hence actions on Hg control are necessary in this country as they are elsewhere.

For Asia, only Indonesia and the Philippines showed higher ASGM Hg input than apparent Hg consumption. In contrast, China and India showed significantly lower ASGM Hg input than apparent Hg consumption. Almost all the Asian countries studied are MC parties, and Mongolia and Laos submitted their NAPs. Malaysia and Myanmar are still not MC parties; however, they did not show higher ASGM Hg input than consumption. With regard to Central and South America, half of the studied countries were found to have higher ASGM input than apparent Hg consumption, indicating the possibility of underreporting with regard to Hg trade. Generally, most Central and South American countries actively take action on Hg control. All countries, except Venezuela, are MC parties. In Oceania, Papua New Guinea is reported to have ASGM activities and did not sign the MC; however, significantly higher ASGM Hg input than apparent Hg consumption was not found for this country.

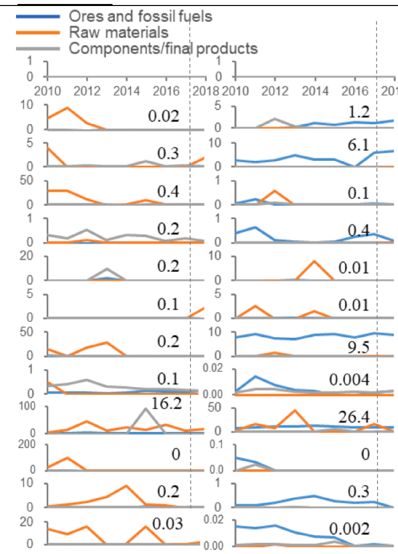
In terms of the normG, several countries showed notably high ratios of ASGM Hg input to apparent Hg consumption, indicating vulnerabilities in domestic Hg management. In particular, countries with narrower gaps, such as Guinea, Cambodia, Ecuador and Suriname showed significantly high normG values (8.9–15.1), which implies that despite the smaller absolute gaps detected in those countries, more serious problems in Hg management might exist, compared to other countries in this study. In contrast, Indonesia, despite having the largest gap among Asian countries, displayed a normG value that was rather low compared to other countries with a positive gap value. Countries such as Mongolia and Thailand showed a normG value lower than −1. This was found to be related to their negative domestic apparent Hg consumption.

3.3. Changes in Hg flow in post-MC global trade

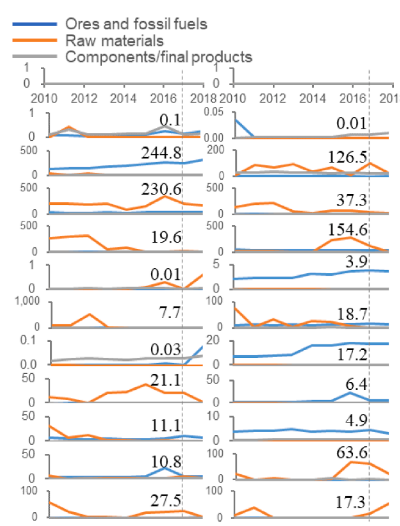
Gaps are closely related to Hg flow in terms of imports and exports, especially for ASGM countries with less domestic Hg production. After the MC came into force in 2017, trade of metallic Hg is expected to disappear in countries that are MC parties, and the total amount of Hg in the classification as raw materials may consequently decrease. The trade flow of Hg in final products is expected to phase out by 2020 for countries that are MC parties. Ores and fossil fuels, despite the Hg content contained (**Table S2**), are not included by the MC. The trend of trade flow for Hg bought/sold as ores and fossil fuels, raw materials, and components/final products from 2010 to 2018, as well as specific data for the year 2017, is summarized in Table 1.

Hg generally enters African countries via raw materials and final products, whereas ores and fossil fuels are the dominant forms in terms of Hg exports. In 2017, slight decreases in imports were found in most of

Table 1
Gap between ASGM Hg input and apparent Hg consumption, status of the Minamata Convention and National Action Plan on Hg control, and Hg flow in global trade. Global Hg flow is made up of ores and fossil fuels, raw materials, and Hg-containing components or final products. "Ores and fossil fuels" refers to Hg contained as impurities in ores and fossil fuels; "raw materials" refers to the trade of metallic Hg and Hg in compounds or amalgams; "components/final products" refers to Hg contained in final products or in components.



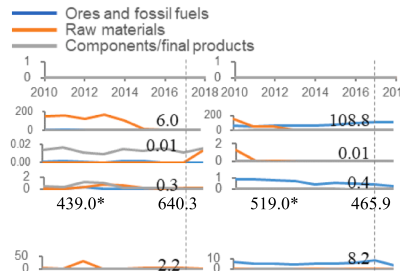
Region/Country	G Gap in 2017	I ASGM Hg input in 2017 (tonnes)			A Apparent Hg consumption in 2017 (tonnes)	Hg production in 2017 (tonnes)	Import from 2010~2018 (Hg in tonnes)	Export from 2010~2018 (Hg in tonnes)	Status of Minamata Convention	Submission year of National Action Plan
		min	mean	max						
Africa										
Burkina Faso	74.1	37.2	74.3	1137.9	0.1	1.3	0.02	1.2	Ratification	2020
DR Congo	-3.7	8.0	31.7	55.6	35.5	41.3	0.3	6.1		2020
Ghana	117.9	29.7	118.8	267.2	0.9	0.5	0.4	0.1	Ratification	
Guinea	40.6	28.4	40.4	52.5	-0.2	0	0.2	0.4	Ratification	2021
Madagascar	3.0	0.8	3.2	5.5	0.2	0	0.2	0.01	Ratification	2018
Mali	26.9	6.8	27.0	60.9	0.0	0	0.1	0.01	Ratification	2020
Nigeria	33.9	21.2	42.3	63.5	8.4	17.7	0.2	9.5	Ratification	2021
Senegal	6.2	4.4	6.3	8.3	0.1	0.01	0.1	0.004	Ratification	2019
South Africa	5.4	0.8	3.1	5.3	-2.3	7.9	16.2	26.4	Ratification	
Sudan	179.2	22.5	179.2	470.6	0	0.02	0	0	Signature	
Tanzania	73.1	18.6	74.1	129.7	1.0	1.0	0.2	0.3	Ratification	2020
Zimbabwe	16.4	4.1	16.5	37.1	0.1	0.03	0.03	0.002	Ratification	2019
Subtotal	573.1	182.6	616.8	2294.0	43.7	69.8	96.6* 17.8	36.3* 43.9		



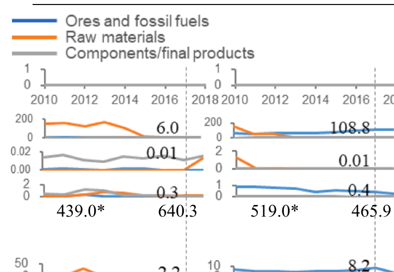
Region/Country	G Gap in 2017	I ASGM Hg input in 2017 (tonnes)			A Apparent Hg consumption in 2017 (tonnes)	Hg production in 2017 (tonnes)	Import from 2010~2018 (Hg in tonnes)	Export from 2010~2018 (Hg in tonnes)	Status of Minamata Convention	Submission year of National Action Plan
		min	mean	max						
Asia										
Cambodia	2.2	1.2	2.3	3.5	0.1	0	0.1	0.01	Ratification	
China	-5028.5	2.4	19.2	33.7	5047.8	4929.4	244.8	126.5	Ratification	
India	-244.3	5.4	14.5	27.1	258.8	65.6	230.6	37.3	Ratification	
Indonesia	-153.5	114.6	305.6	573.0	459.1	594.1	19.6	154.6	Ratification	
Laos	-0.5	1.1	2.2	3.3	2.8	6.7	0.01	3.9	Accession	2021
Malaysia	-14.0	0.3	1.1	1.9	15.0	26.0	7.7	18.7	Signature	
Mongolia	8.9	1.4	5.7	12.9	-3.2	14.0	0.03	17.2	Ratification	2020
Myanmar	-16.4	2.8	11.1	19.5	27.5	12.9	21.1	6.4		
Philippines	15.9	6.7	26.9	60.6	11.0	4.8	11.1	4.9	Ratification	
Thailand	41.8	0.3	1.1	1.9	-40.7	12.1	10.8	63.6	Accession	
Viet Nam	-16.1	0.6	2.3	4.0	18.4	8.2	27.5	17.3	Approval	
Subtotal	-5404.6	136.9	392.1	741.5	5796.7	5673.8	747.8* 573.3	404.9* 450.5		

(*continued on next page*)

Table 1 (*continued*)



Region/Country	G Gap in 2017	I ASGM Hg input in 2017 (tonnes) min	mean	max	A Apparent Hg consumption in 2017 (tonnes)	Hg production in 2017 (tonnes)	Import from 2010~2018 (Hg in tonnes)	Export from 2010~2018 (Hg in tonnes)	Status of Minamata Convention	Submission year of National Action Plan
***Central and South America* (continue)**										
Peru	212.7	106.6	284.3	533.1	71.6	174.4	6.0	108.8	Ratification	
Suriname	53.6	37.6	53.7	69.8	0.01	0.004	0.01	0.01	Accession	
Venezuela	78.6	33.3	88.7	166.3	10.1	10.2	0.3	0.4	Signature	
Subtotal	-128.9	423.6	943.3	1619.9	1072.2	897.7	439.0* 640.3	519.0* 465.9		
Oceania										
Papua New Guinea	6.1	0.6	2.1	3.8	-4.0	2.0	2.2	8.2		
Subtotal	6.1	0.6	2.1	3.8	-4.0	2.0	6.2* 2.2	5.3* 8.2		
Total	- 4954.3	743.6	1954.3	4659.1	6908.6	6643.3	1289.5* 1233.7	965.5* 968.4		



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Total	- 4954.3	743.6	1954.3	4659.1	6908.6	6643.3	1289.5* 1233.7	965.5* 968.4		

*Indicates the mean value of the Hg amount traded in imports and exports from 2010 to 2016. The numbers displayed on top of the graphs embedded in the table show the total Hg amount in terms of imports and exports in each country in the year 2017.

the African countries studied, although imports increased again in 2018 in some countries. In terms of exports, a decrease was identified in some countries such as Madagascar, Tanzania, and Zimbabwe in ores and fossil fuels in 2017; however, this may be not related to the MC. The total amount of Hg that entered Africa in 2017 significantly decreased compared with the mean amount of Hg imported to Africa from 2010 to 2016, from 96.6 tonnes in 2010–2016 to 17.8 tonnes in 2017. Hg exports increased slightly from 36.3 tonnes in 2010–2016 to 43.9 tonnes in 2017.

Asia imports many raw materials that include Hg, China mostly imports ores and fossil fuels and exports ores and fossil fuels and raw materials. In 2016, an increase in the import of raw materials took place in several countries including Cambodia and India, while an increase in the export of raw materials occurred in Indonesia and Thailand. The overall amount of imported Hg decreased from 747.8 tonnes in 2010–2016 to 573.3 tonnes in 2017, but it increased slightly in 2017. The total amount of Hg imported into Central and South America increased in 2017, but the amount exported decreased from 519 tonnes in 2010–2016 to 465.9 tonnes in 2017. This decrease can mainly be contributed to decreases in export from Chile and Mexico.

The total import of Hg decreased significantly but the total export increased slightly in Africa, Asia, and Oceania in 2017. In contrast, imports increased in Central and South America in 2017. The overall import and export levels in 2017 in the studied countries are comparable to the mean values for 2010–2016. Thus, whether the MC was effective in Hg management is not clear from general trade flow data and further investigation of specific commodities is needed.

Investigation of the trade flow of commodities with a Hg content of > 1 ppm (Table S2) provides evidence for the effectiveness of the MC in controlling the trade of Hg (Figs. 3 and 4). After the MC came into force, global trade for Hg in terms of both imports and exports changed significantly. In particular, the import of metallic Hg disappeared from six African countries, namely Burkina Faso, DR Congo, Ghana, Nigeria, Tanzania, and Zimbabwe, as well as from Ecuador and Papua New

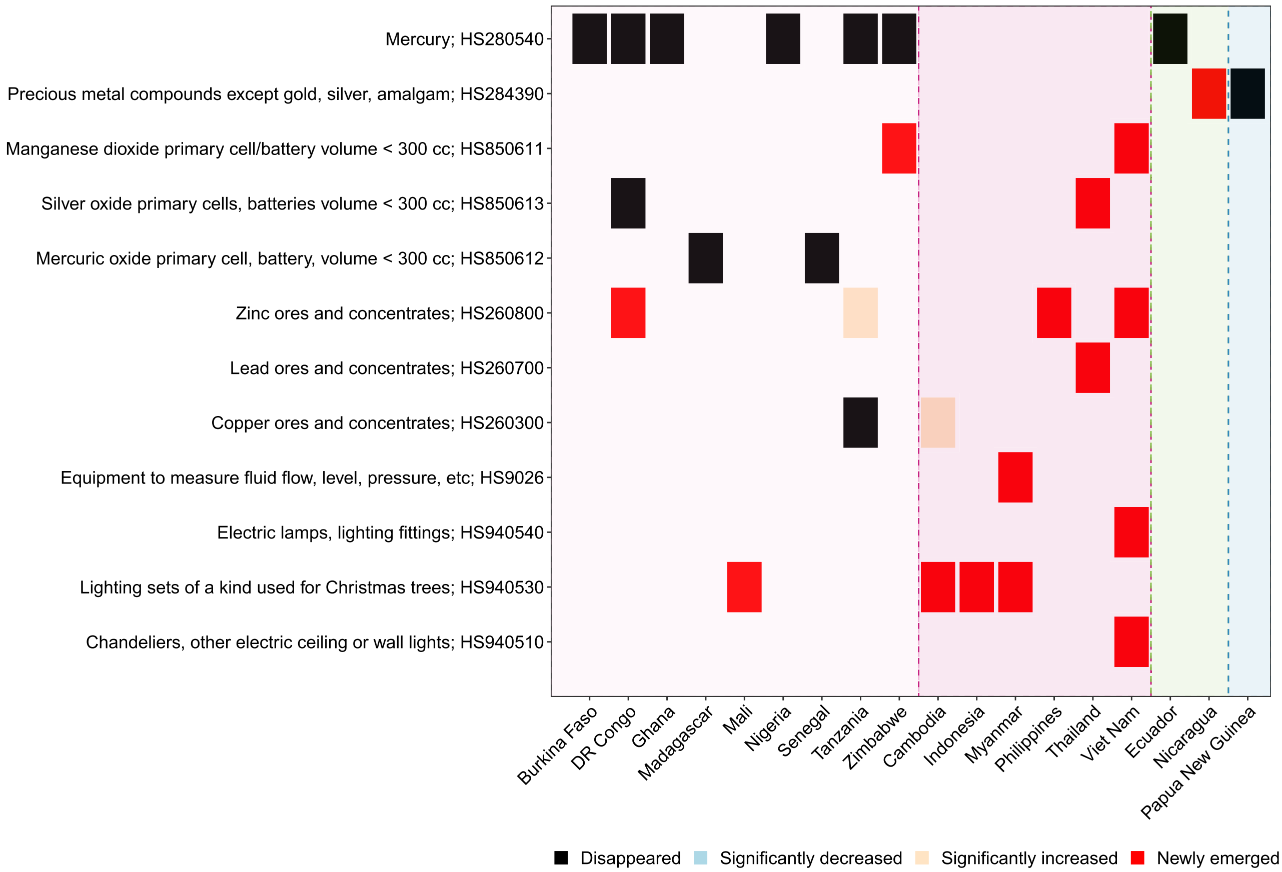

Fig. 3. Changes in the import of commodities with a Hg content > 1 ppm based on 2010–2017 data. Commodities are displayed in the descending order of Hg content from top to bottom. "Disappeared" denotes commodities that had mean Hg amounts > 0 in 2010–2016 and that decreased to 0 in 2017. To screen out less significant trade flows, the threshold for the mean amount of Hg contained in the commodity was set as > 0.1 tonnes. The thresholds for "significantly decreased" and "increased" were set as the 1st and 99th percentiles, as described in the SI. "Newly emerged" represents commodities that averaged 0 in 2010–2016 but emerged in 2017, or for which the Hg amount in 2017 was at least five times greater than the mean Hg amount in 2010–2016. Harmonized System (HS) codes are indicated according to the World Customs Organization (http://www.wcoomd.org/). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Guinea; however, new trade flows emerged in Asia (Fig. 3). The export of metallic Hg also disappeared from some African and Central and South American countries. Significant decreases in exports in commodities with high Hg content were detected in Asia and Central and South America, but significant increases in exports and newly emerged export flows were also detected (Fig. 4).

4. Discussion

4.1. Inconsistencies at the region level

There were varying degrees of the inconsistency of Hg trade data across continents, as evidenced by the gap between apparent Hg consumption and ASGM Hg input by year. The inconsistency was more pronounced in Central and South America, where the actual ASGM Hg input was significantly higher than the reported amounts of apparent Hg consumption. This issue also became more pronounced in Africa after 2016, which is related to the Hg trade ban imposed by the MC.

Sources of the inconsistencies include underreporting at customs, mislabeling of commodities (UNEP and GRID-Arendal, 2020), unfaithful declarations, and illegal routes such as smuggling (Yoshimura et al., 2021). The shortage of Hg in the ASGM sector may cause improper Hg trade, which hinders global Hg management. Such improper Hg trade flows have been reported in Asia, Central and South America, and Europe. For example, Mexico did not report any exports to Peru when Peru reported an import of 1.9 tonnes of Hg from Mexico in 2019 (Marshall et al., 2021). In Germany, pure Hg was mislabeled as "mercury-containing hazardous waste" and exported to Switzerland, from where it was sold abroad (UN Environment, 2017). The customs agent in the Philippines is reported to have intercepted Indonesian Hg and cinnabar (Hg ore) smuggled in shipping containers (UNEP and GRID--Arendal, 2020).

Informal trade flow is not included in trade statistics, and this type of inconsistency may widely exist in ASGM countries. Clearly, however, our results suggest that although the MC intends to control Hg use and emissions, contrary to expectations, if a significant reduction in Hg use occurs in the short term, it may be related to underreporting, concealment, and misreporting of Hg-related data. Therefore, it is necessary to urge countries to take action to control Hg use and emissions, such as signing the MC and producing an NAP, and to monitor the material flow data of Hg in each country to examine the actual Hg control, i.e., implementation of Hg control measures. Our method can be used as a simple screening condition to identify regions with inconsistency problems.

Notably, there were also differences between regions. For example, although the ASGM Hg input in Asia was well below its apparent Hg consumption, this finding may be misleading. China and India, as two mega developing countries with huge industrial Hg use, may have contributed to the large bias in the data. Therefore, we also needed to divide the regions further and amplify the resolution of the study to the national level.

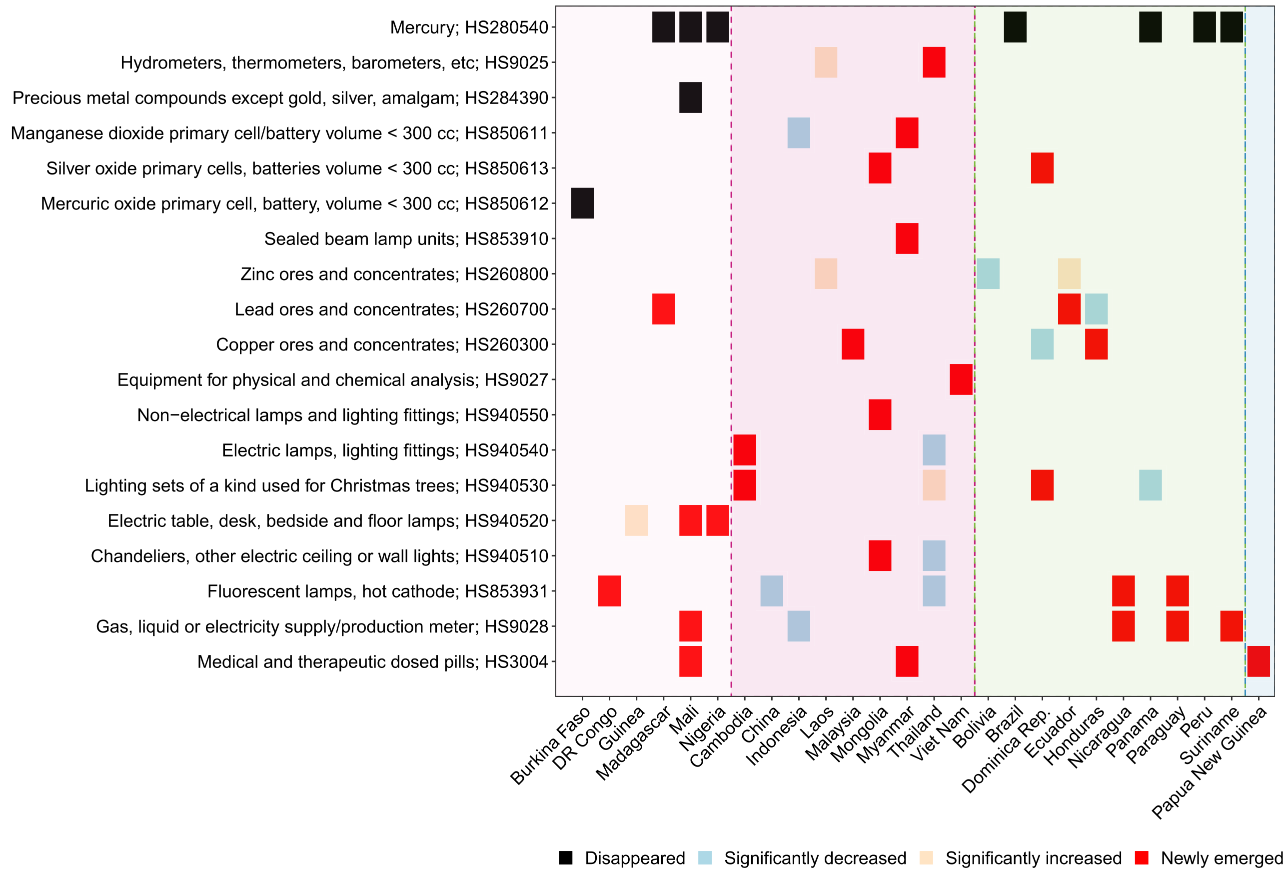

Fig. 4. Changes in the export of commodities with a Hg content> 1 ppm based on 2010–2017 data. Commodities are displayed in the descending order of Hg content from top to bottom. "Disappeared" denotes commodities that had mean Hg amounts > 0 in 2010–2016 and that decreased to 0 in 2017. To screen out less significant trade flows, the threshold for the mean amount of Hg contained in the commodity was set as > 0.1 tonnes. The thresholds for "significantly decreased" and "increased" were set as the 1st and 99th percentiles, as described in the SI. "Newly emerged" represents commodities that averaged 0 in 2010–2017 but emerged in 2017, or for which the Hg amount in 2017 was at least five times greater than the mean Hg amount in 2010–2016. HS codes are indicated according to the World Customs Organization (http://www.wcoomd.org/). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

4.2. Inconsistencies at the country level and vulnerability in Hg management

The size of the gap for each country depends on the domestic Hg production, demand for Hg in ASGM activities, and Hg flow in global trade as well as its actions toward Hg control and management, e.g., if the country is an MC party and whether they have submitted an NAP. To date, 137 countries (UNEP, 2022) out of 195 countries (Worldometer, 2022) have ratified, accepted, approved, or accessed the MC, and 18 countries have submitted an NAP. Among the 80 countries with ASGM activities (UNEP, 2019a), 39 were investigated in this study, of which 33 are MC parties and 12 have submitted an NAP. Notably, nine of the 12 African countries investigated in this study have submitted an NAP, demonstrating an active attitude toward and action on Hg management. The MC requires a halt to trade in metallic Hg, that no new primary Hg mines are opened, a halt to domestic primary Hg production by 2032, and a phasing-out of Hg-added products by 2020 (UNEP, 2019b). Therefore, the gap we identified for 2017 may widen further if demand for Hg from ASGM activities does not decrease, as less Hg is likely to formally flow to artisanal mining countries that are MC parties.

African countries depend greatly on the import of Hg for ASGM activities. According to the latest report, 80% of the ASGM in African countries is illegal or informal (Intergovernmental Forum on Mining, Minerals, 2018), which may lead to informal Hg flow not being recorded in trade statistics. Since the amalgamation of concentrates is predominantly adopted in Africa, the demand for Hg for ASGM activities is much lower in African countries than in other regions that use WOA (Seccatore et al., 2014). Despite the relatively low ratio of Hg applied in ASGM, widespread ASGM activity induces social and economic consequences such as gender and health issues and child labor; and hence, ASGM is of great concern. In response to the MC, the formalisation and consolidation of small mines, involving a process of mergers and acquisitions, appears to be an effective path. However, in many African countries, a lack of centralized and powerful governments capable of imposing such a policy approach and the frequent lack of alternative employment to ASGM as well as corruption make this formalisation much harder to achieve (Grynberg and Singogo, 2021).

China is one of the largest producers of Hg, but its production significantly decreased from ~3,000 tonnes to 1949 tonnes in 2017 (Statista, 2021). More than 1,000 tonnes of the Hg produced in China is used in the vinyl chloride monomer industry and for the production of blood pressure measuring devices, thermometers, and lamps (Lin et al., 2016; UN Environment, 2017). However, most of Kenya's Hg originates in China, and Hg from China has appeared illegally in sub-Saharan Africa and Myanmar (World Bank, 2016).

The least transparent sources of Hg are now the quantities of mined Hg informally leaving Indonesia and Mexico (UNEP and GRID, 2020). In Indonesia, ASGM provides livelihoods to more than one million families, spanning 27 provinces (Balifokus, 2015). Indonesia is the third largest Hg emitter after China and India. In 2017, the Government of Indonesia announced its plan to completely phase out Hg use in ASGM by ratifying the MC into Law (Rahmawati and Adiansyah, 2020). Global restrictions in Hg trade were expected to increase Hg prices and, thus, decrease the amount of Hg applied in ASGM. However, despite global Hg trade restrictions, the recent increase in domestic Hg supply due to new cinnabar mine development has made Hg cheaper and more readily available, undermining efforts to reduce Hg use in Indonesia (Spiegel et al., 2018). While its ambitious pollution phase-out target has been welcomed by some, government announcements regarding Indonesia's Hg plans have elicited a range of skeptical responses (Spiegel et al., 2018).

Mexico is a Hg supplier, and 77% of its total Hg trade is exported to Colombia, Peru, and Bolivia. Most of Mexico's Hg trade to these countries is for ASGM (Marshall et al., 2021). As a result of the ongoing demand for Hg in the face of a gradual reduction in supply, the market price has risen and new Hg mining is taking place, especially in Mexico and Indonesia (UN Environment, 2017; UNEP and GRID, 2020). Peru showed the most significant inconsistency in Hg trade flow, and a large amount of Hg was considered to have entered the country informally. Researchers have estimated that nearly 20% of gold in Peru comes from informal mines and is exported to the United States, Canada, and Switzerland (Kleinhenz, 2017). While the official trade of Hg through imports and exports has declined from historically high levels in 2015 to negligible levels in 2019, there is ample evidence of increasing illegal and informal transfers, which is of growing international concern (Marshall et al., 2021).

As gold prices remain high and the ASGM using Hg amalgamation proliferates around the world, the demand for Hg from countries such as Mexico and Indonesia will continue unabated, even with the implementation of international agreements such as the MC (Marshall et al., 2021). Although countries have signed and ratified the MC, implemented NAPs to reduce the use of Hg in products and manufacturing processes, and identified ways to mitigate Hg-contaminated waste legacy sites, the demand for Hg in the production of vinyl chloride monomers (primarily in China) and the artisanal gold mining sector (in over 70 countries worldwide) is an ongoing problem (Marshall et al., 2021).

4.3. *Effectiveness of the MC in controlling Hg-related trade flow*

The MC reshaped the global Hg trade flow significantly with regard to the commodity of metallic Hg, and this provides evidence of the effectiveness of the MC in Hg management. From our results, the countries that submitted NAPs are the ones that demonstrated early enforcement of the MC and whose trade in metallic Hg disappeared. African countries are actively controlling the trade of Hg and countries that submitted NAPs are also those in which Hg disappeared in 2017. No evidence of the disappearance of Hg in Asia was found, particularly because China and Indonesia are major Hg producers and some informal routes for Hg trade may exist. The increase in commodities containing high Hg content in Asia requires greater attention and further monitoring of final treatment or disposal is needed.

Ores and fossil fuels are not regulated by the MC. However, they may cause severe Hg emissions if not properly treated due to the Hg impurity they contain. Coal burning, for instance, has been estimated to cause 859.12 tonnes of Hg emissions, and approximately 30% of this is embedded in products that are shipped to consumers in other economies through global trade (Chen et al., 2016). More than a quarter (359.7 tonnes) of China's direct Hg emissions from fuel combustion are attributed to the consumption of Chinese goods in foreign countries through external trade. Since China plays a prominent role in processing trade, the Hg emissions embedded in re-exports are responsible for a considerable amount of total Hg emissions in China (Chen et al., 2017). Emerging economies, such as mainland China and India, tend to have larger amounts of embedded Hg emissions in products due to their exports, while developed countries, such as Japan, Germany, and the United States, avoid considerable amounts of direct Hg emissions by transferring the emission-intensive processing to developing economies (Chen et al., 2016). Thus, in addition to the MC, proper monitoring and tracing of Hg-related trade flows and responsibility sharing are also important for global Hg control.

Hg-added products were scheduled to be phased out by 2020 as a result of the MC. Therefore, the newly emerged trade flows of these commodities, especially in some Asian countries, can be attributed to importing countries stockpiling Hg-added products. Meanwhile, exporting countries dumped their products by 2020. This could be seen as demonstrating the effectiveness of the MC in regulating the Hg trade flow in those products; however, whether these Hg-added products will be properly disposed of after they reach the end of their useful life requires continuous monitoring.

In general, the MC could be effective in phasing out the manufacturing of Hg-added products and stopping the trade flow of such products; however, Hg control cannot be achieved simply by stopping such trade flows. Instead, an efficient Hg emission control should be considered, and feasible NAPs should be proposed and implemented. Rather than only regulating Hg-related trade flow, improved technology for the treatment of these products should be thoroughly discussed. For example, the collection of used batteries, lamps, and watches that use Hg, and the treatment and recycling of these Hg-containing wastes should be the final step of Hg control. That is to say, the MC is not simply imposing an end to Hg use; rather, it is a starting point for sound Hg control globally. In addition, to curb the Hg problem, the substantial Hg flow in ores and fossil fuels should also be taken into consideration. The co-benefit of the carbon neutrality goal, particularly in terms of reducing the use of fossil fuels, on global Hg control, should also be assessed.

4.4. *Significance of data inconsistency detection*

Inconsistencies often exist in global trade data and pose difficulties in Hg control. For example, the World Bank (Lassen et al., 2016) reported a discrepancy between the total registered net import of Hg to all countries and the total estimated Hg consumption in ASGM in the sub-region of Western Africa. The volume of discrepancies was estimated to be as large as 1,800 tonnes from 2003 to 2014 in Indonesia, according to the Indonesian Ministry of Trade (Drwiega et al., 2018). This challenge (Federico and Tena, 1991; Hamanaka, 2012), especially concerning the ASGM sector, remains to be addressed. By detecting data inconsistencies, we can target high-risk countries or regions with management vulnerabilities. However, information on data inconsistencies alone is not sufficient to improve Hg management, and it is also necessary to understand the specific high-risk commodity flows. For example, certain extreme variations in trade may be associated with untruthful customs declarations and inadequate regulation, informal trade, or even smuggling (Yoshimura et al., 2021). This makes it particularly important to analyze changes in trade flows.

The method we established in this study, therefore, concentrated on the detection of the inconsistency of Hg data within a country on a demand and supply base in the ASGM sector. Since we used the maximum amount of available Hg as the baseline for comparison, Hg from all routes was involved, including improper, illegal, and illicit trade flows, in addition to the mislabeled trade flow. With this method, countries with a higher risk of gaps in Hg management can be detected, and further monitoring and specific measures can be applied. Yoshimura et al. (2021) also detected gold or Hg smuggling by comparing the Hg lost per unit of gold production and the WOA. Their method is based on the fact that more Hg is lost in WOA than in the amalgamation of concentrates. Our approach, on the other hand, emphasizes the analysis of data over a long time series to determine the inconsistency of Hg trade data across countries or regions and the identification of gaps and risks in Hg management through overall trends. This method of inconsistency detection can also be applied in other fields that involve improper trade flows that need to be monitored.

By monitoring data inconsistencies, we can narrow the scope of countries that need better regulation. Although the existence of informal and illegal trade is often difficult to determine, we can still analyze the significant changes in trade data over time and the rationale for the changes to identify potentially problematic trade flows. Through this step-by-step examination, we can refine the Hg control problem for specific regions, countries, and commodities.

5. Conclusion

In this study, we established a method to detect inconsistencies in data concerning Hg by comparing the amount of ASGM Hg input with the apparent Hg consumption. This method can support the search for countries implementing ASGM with hidden Hg use and flows, which can contribute to the planning of further Hg control regulations. Using this method, inconsistencies in Hg trade statistics were more often identified in African countries and some Central and South American countries; nevertheless, Cambodia showed the greatest vulnerability in terms of Hg management, followed by Ecuador, Suriname, and Guinea, despite the narrower gap between ASGM Hg input and apparent Hg consumption for these countries compared to others.

Among the 39 countries studied, Sudan and Venezuela are still not MC parties despite the large inconsistency detected in the data for these countries for 2010–2018. Myanmar, Malaysia, and Papua New Guinea are not MC parties, but large gaps in Hg flow were also not found for these countries with regard to ASGM activities. The results of this study demonstrate the effectiveness of the MC in controlling the global trade of Hg-related commodities, especially in stopping the import and export of metallic Hg. Trade in metallic Hg largely disappeared from some African countries, as well as from Central and South America. However, Asia was found to lag behind other regions concerning the ceasing of Hg trade. On the contrary, new import flows of commodities with high Hg content emerged in Asia in 2017, although some significant decreases in export were also observed.

Countries that submitted an NAP may have executed early enforcement of Hg management under the MC, as in those countries trade flows of commodities with high Hg content disappeared soon after the MC came into force in 2017. Therefore, for better Hg control, the expansion of MC parties may be insufficient – the NAP should also be encouraged for countries that are already MC parties. Future research will be conducted on evaluating the effectiveness of the MC in phasing out Hg-added products and in ceasing Hg mines.

CRediT authorship contribution statement

Yingchao Cheng: Writing – original draft, Visualization, Investigation, Funding acquisition. **Kenichi Nakajima:** Conceptualization, Methodology, Software, Data curation, Funding acquisition. **Keisuke Nansai:** Writing – review & editing. **Jacopo Seccatore:** Writing – review & editing. **Marcello M. Veiga:** Writing – review & editing. **Masaki Takaoka:** Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.resconrec.2022.106461.

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