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Policy Analysis

Detecting Illegal Intercountry Trade of Mercury Using Discrepancies in Mirrored Trade Data

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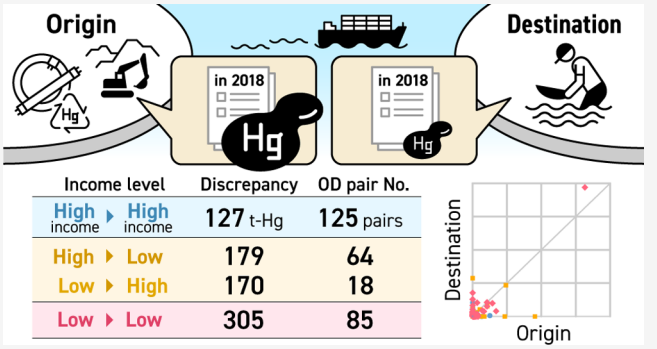
ABSTRACT: The ongoing international movement to phase out mercury, mainly led by the Minamata Convention on Mercury, raises concerns about illegal intercountry trade, including smuggling. This study aims to detect the existence of illegal intercountry mercury trade under the social mercury phase-out movement, focusing on discrepancies in each country's trade statistics. To analyze the trends by year and country for discrepancies in intercountry mercury trade, an intraclass correlation coefficient (ICC) was applied to the mirrored exports and imports from trade statistics of each country provided by the UN Comtrade. The year-based ICC analysis identified a tendency to reduce the detection of discrepancies in the reported mirrored exports and imports for mercury at the intercountry level under the recent mercury phase-out movement. Through an ICC analysis focusing on exporting and importing countries, the validity of the ICC analysis was verified as a way to detect illegal intercountry trade of mercury. Our analyses detecting the illegal trade of related countries contribute to the effectiveness evaluation and custom capacity building required in the Minamata Convention by offering a data-driven method to enable the effective detection of illegal mercury trade.



KEYWORDS: *The Minamata Convention on Mercury, illegal intercountry trade, smuggling, trade statistics, discrepancy, intraclass correlation coefficients (ICCs)*

1. INTRODUCTION

Our society is phasing out mercury through international environmental regulations because of its damaging effects on human health and ecosystems. Regulations targeting mercury-added products include the End-of-Life Vehicles (ELV) directive of 2003, the Restriction of Hazardous Substances (RoHS) directive of 2006 in the European Union (EU), and the Electronic Waste Recycling Act (EWRA) of 2007 in California.[1−4] Additionally, the EU and the United States have directly banned the exports of mercury since 2011 and 2013, respectively.[5,6] To control mercury's anthropogenic life cycle internationally, including mining, international trade, production, use, and waste management, the Minamata Convention on Mercury (hereafter, "Convention") was adopted in 2013.[7,8] The Convention came into force in 2017 and currently includes 137 party countries.[9,10] The Convention's advantage over other environmental conventions is that it includes a tripartite institutional design comprising legally binding regulations, an independent financial mechanism, and a compliance mechanism.[11] As the international movement to phase out mercury gains momentum, concerns about international mercury trade are increasing.[12]

Article 3 of the Convention includes provisions to control international mercury trade and adopts a prior informed consent procedure.[7−9] Mercury's export without prior consent is banned, and the export can be made only for permitted uses or environmentally sound storage. Difficulties in controlling international mercury trade are caused by illegal trade practices not clearly defined in the Convention.[13−15] This study's definition of "illegal" follows that of the United Nations Environment Programme (UNEP), which defines the import and export of mercury without meeting legal requirements as illegal.[15] Previous works have reported illegal imports, mainly the smuggling of mercury that originated from artisanal and small-scale gold mining (ASGM) in Asia,[16,17] Africa,[18,19] and Latin America.[20−22] International mercury trade presents a link between the supply side, such as mercury mining, and the demand side, such as ASGM, which is a major mercury user. Mercury mining is regulated by the parties in the context of Article 3,[7−9] which bans mercury mining by signatory countries but allows it to continue for up to 15 years after

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treaty accession.[7−9] ASGM is a critical regulatory target of the Convention, corresponding to Article 7.[7−9] Thus, illegal international mercury trade may be affected not only by trade regulations but also by regulations on mercury mining and ASGM. Research has addressed the Convention's limitations on combating illegal trade.[13,14] Despite the regulations mentioned above, illegal mining and illegal supply and export of mercury to domestic and foreign ASGM have been reported in Indonesia and Mexico.[23−26]

Analyzing the relationship between illegal international mercury trade and the mercury phase-out movement centered on the Convention is important for evaluating the Convention's effectiveness, especially Article 22. A previous study proposed the "amount of Hg trade (legal and illegal)" as a metric for evaluating the effectiveness of Article 3 of the Convention.[27] However, owing to its illegal nature, it is extremely difficult not only to judge the amount of illegal mercury trade itself but also to detect its existence. For example, mercury trade data from the UN Comtrade, which compiles trade statistics from various countries, is incomplete.[12,15] The UNEP estimated annual net informal mercury imports through the material balance of mercury use in ASGM and reported mercury exports and imports targeting 15 countries.[15] This estimation cannot directly detect illegal intercountry mercury trade or identify the corresponding imports' origin because net informal mercury imports, including illegal overseas and informal domestic imports, are aggregated to the target country. Another study detected possible illegal gold or mercury trade based on the relationship between ASGM gold production and mercury losses in 27 countries.[28] This study also fails to detect the illegal intercountry mercury trade. Furthermore, recent research detected domestic hidden mercury use and flows based on the gap between apparent mercury consumption and ASGM mercury input in 39 countries between 2010 and 2018.[29] However, that research did not detect illegal intercountry trade. Therefore, no study has detected the illegal intercountry mercury trade in the context of the international movement to phase out mercury because of difficulties in monitoring illegal intercountry trade by each country's trade statistics.

A discrepancy in trade statistics is defined as the gap between the exports reported by the exporting country's trade statistics and the mirrored imports reported by the importing country's trade statistics.[30−32] In economics, illegal intercountry trade has been historically detected using such discrepancies. The discrepancy originating from the black market in the importing country was first mentioned by Bhagwati.[33] Discrepancy-based approaches have been applied to detect smuggling,[34−37] tariff evasion and bribes,[38−40] misinvoicing,[41−43] and overall illegal intercountry trade.[44−46]

Although the UNEP analyzed discrepancies in global and national mercury trade,[12] it did not examine the discrepancy at the intercountry level, which could illuminate illegal intercountry trade. The intercountry discrepancy analysis is limited to Mexico's exports and imports.[47] The existing discrepancy assessment index evaluates only discrepancies in mirrored trade data and cannot evaluate the overall coincidence between exports and imports.[33,48−50] As an assessment index of the degree of coincidence, correlation coefficients have been used,[51] but they are insufficient as a quantitative coincidence index of the mirrored trade data. Hence, our first attempt was by using the intraclass correlation coefficient (ICC) as the coincidence index, as it can statistically assess the reliability of the results by different raters based on two-way analysis of variance.[52]

This study aims to detect the existence of illegal intercountry mercury trade in the international movement to phase out mercury. To detect illegal intercountry mercury trade, the discrepancy in mirrored trade data from the UN Comtrade is analyzed using the ICC.

2. METHOD

This study analyzes three types of ICC for detecting the existence of illegal intercountry mercury trade: year, exporting country, and importing country. The study targets mercury, which is subject to international trade restrictions by the parties under Article 3 of the Convention. Mercury-added products, although regulated by the parties, are excluded from this study. The mirrored trade data analyzed herein were obtained from the UN Comtrade, which provides trade statistics by country.[53] The reported import and export mercury values (weight) with HS item code 280540 in the trade statistics of 196 countries were downloaded from the UN Comtrade. Mercury used in ASGM may be legally imported as a dental amalgam or other mercury-added products mainly from the case studies of Brazil and Zimbabwe and interviews of experts.[7,54−57] If the item name is falsely reported as a dental amalgam or other mercury-added product at import customs and correctly reported as mercury at export customs, such illegal intercountry trade can be detected from the discrepancy. Research shows that in the international trade of used cars and engines, the item name as reported by the exporting country, "used cars", and the item name reported by the importing country, "scraps", differ so that tariffs are lowered on the import side.[51,58] However, if the item name is falsely reported as a dental amalgam or other mercury-added product at both export and import customs, illegal intercountry trade cannot be detected from the discrepancy. The analysis period of the trade data was from 1999 to 2018. Although the trade data for 2019−2021 are also available from the UN Comtrade, a limited number of countries have reported data for these years because of the time lag in countries opening their trade statistics. The combination of exporting and importing countries, that is, the "origin−destination (OD) pair", included in this ICC analysis for mercury trade has 140 exporting countries of origin and 180 importing countries of destination. The information about both party countries or nonparty countries among the 196 reporting countries in the Convention is summarized in Table S1.

In this study, an ICC of case 2 recommended by Shrout and Fleiss[52] was employed. The ICC used in this study targets the export data and import data. The ICC of case 2 and one time for repeat tests can be estimated as follows:

$$\mathrm{ICC} = \frac{\mathrm{BMS} - \mathrm{EMS}}{\mathrm{BMS} + (k-1)\mathrm{EMS} + k(\mathrm{JMS} - \mathrm{EMS})/n}$$

where BMS is the between-targets mean square for the OD pairs corresponding to the combination of exporting country i and importing country j, JMS is the between-judges mean square for the raters, and EMS is the residual mean square for the error term. The details of BMS, JMS, and EMS are addressed in the Supporting Information. k is the number of raters, and when $k = 2$, there are two reporting countries, one each for the export and import data. n is the number of OD pairs.

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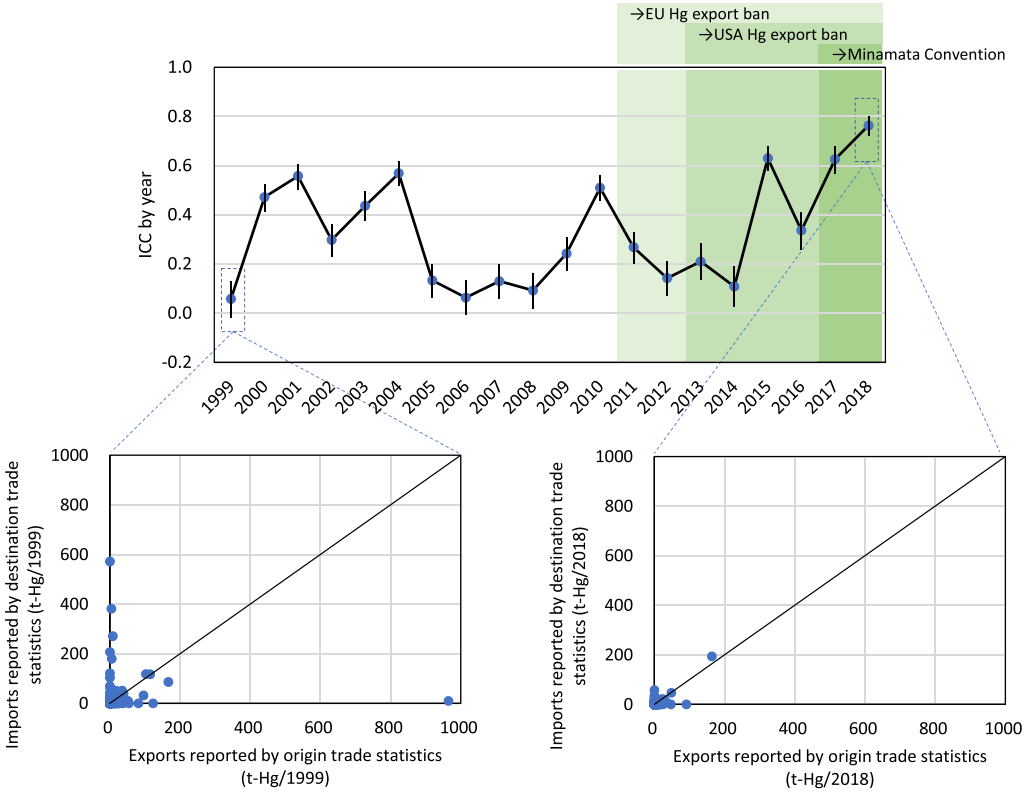
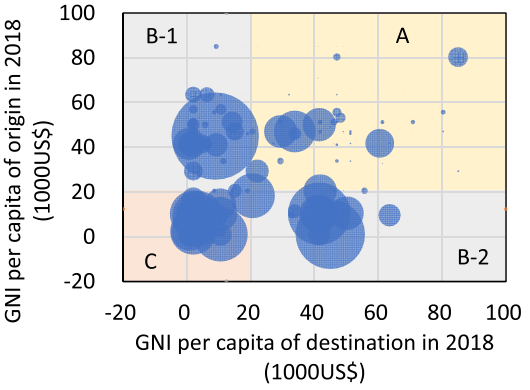


Figure 1. Estimation results of the intraclass correlation coefficient (ICC) for intercountry mercury trade from 1999 to 2018 and scatter plot of the exports as reported by the origin trade statistics and that of imports as reported by destination trade statistics in 1999 and 2018 with the lowest and highest ICC, respectively.



OD pattern		Discrepancy	OD pair No.
A	**High-income** To **High-income**	127 t-Hg	125 pairs
B-1	**High-income** To **Low-income**	179 t-Hg	64 pairs
B-2	**Low-income** To **High-income**	170 t-Hg	18 pairs
C	**Low-income** To **Low-income**	305 t-Hg	85 pairs

Figure 2. Relationship between discrepancy in intercountry mercury trade and the gross national income (GNI) per capita in 2018 and the origin−destination (OD) patterns. The size of the bubble represents the discrepancy amount.

ICC takes values between −1 and 1, and an ICC value close to 1 has a high degree of coincidence between the countries. Landis and Koch[59] proposed five levels of evaluation criteria for ICC (slight, 0.00−0.20; fair, 0.21−0.40; moderate, 0.41−0.60; substantial, 0.61−0.80; and almost perfect, 0.81−1.00). This study determines that ICC values of 0.00−0.20 indicate a high likelihood of illegal trade and ICC values of 0.81−1.00 indicate a low likelihood of illegal trade. An ICC based on the least-squares method with a normal assumption of the error term has statistical properties of overevaluating the effect of outliers. This statistical property of ICC is appropriate for analyzing illegal intercountry trade with an extremely large gap in the mirrored trade data.

3. RESULTS AND DISCUSSION

3.1. ICC Analysis Focusing on the Year. Figure 1 shows the estimation results of the ICC based on the year of intercountry mercury trade in 1999 and 2018. The bar of the ICC results in Figure 1 represents the 95% confidence interval for the ICC estimation results.

As depicted in Figure 1, the ICC estimation results show a trend of fluctuating ICC values between 0.06 and 0.57 for the period from 1999 to 2012, before international mercury regulation began. In contrast, after 2013, when the Convention was adopted and mercury export from the United States was banned, the ICC increased from 0.11 in 2014 to 0.76 in 2018. ICC values of <0.2, indicating a high discrepancy, were obtained for 1999, 2005−2008, 2012, and 2014. In recent

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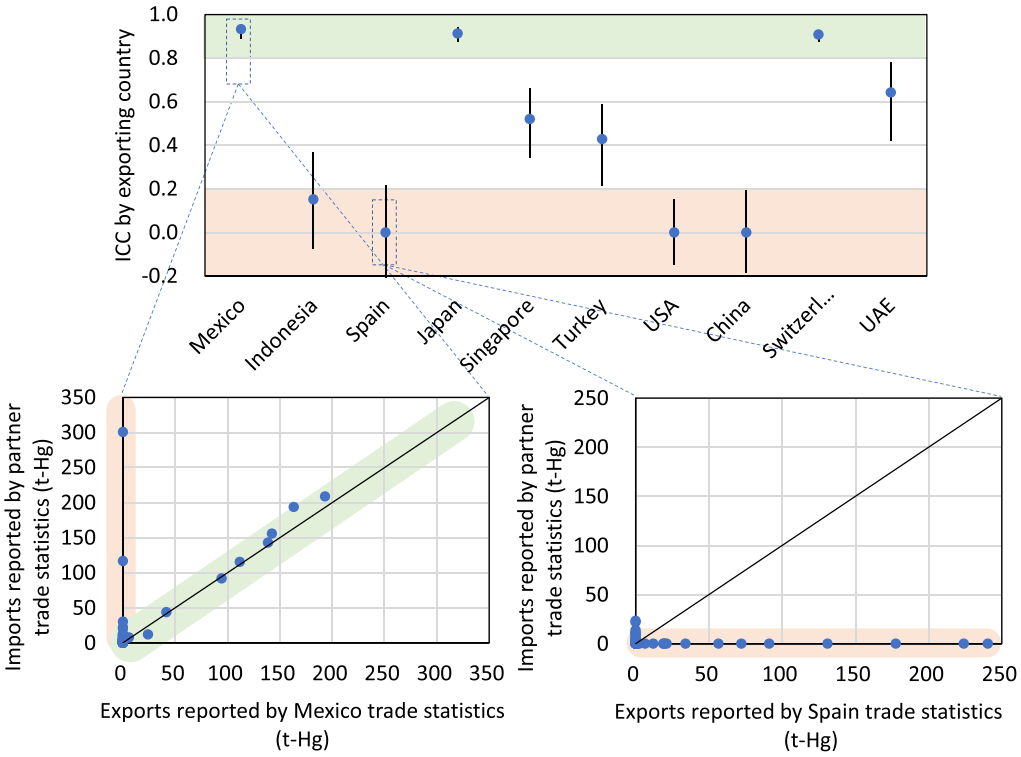

Figure 3. Estimation results of the intraclass correlation coefficient (ICC) by the top 10 exporting countries in intercountry mercury trade from 2014 to 2018, scatter plot of exports reported in the trade statistics of Spain and Mexico, and imports of mercury reported by the partner countries with the lowest and highest ICC.

years, illegal intercountry mercury trade may have been rampant as the mercury phase-out has progressed. The ICC value tends to increase from 2014 to 2018 with a decrease in discrepancy around 2017, when the Convention came into force.

Figure 1 also provides a scatter plot of exports and imports 1999 with the lowest ICC value (0.06), where large discrepancies of >100 tons of mercury were identified for the OD pairs reporting only exports or imports. In the scatter plot of 2018 with the highest ICC value (0.76), large discrepancies that originated from one-sided reporting of exports or imports were not observed.

In summary, our ICC analysis roughly detects decreasing discrepancies in the reported mirrored exports and imports for mercury under the recent phase-out movement. It should be noted, however, that this result detects only the discrepancy in each country's trade statistics. A comparison of the scatter plots between 1999 and 2018 shows that the discrepancies decreased in 2018. One possible reason for this is that developing countries that used to report their mercury imports have stopped doing so and are illegally importing mercury after the Convention. Veiga and Marshall referred to the case of Cuba not reporting mercury imported into its country.[60]

We focus here on the OD patterns of discrepancy in the reported intercountry mercury trade data to detect illegal mercury trade. Figure 2 displays the relationship between the discrepancy in intercountry mercury trade in 2018 and its OD patterns. The vertical and horizontal axes represent the gross national income (GNI) per capita in the exporting country corresponding to the origin in the OD pair.[61] The horizontal axis also represents GNI per capita in the importing country corresponding to the destination in the OD pair.[61] The size of the circle represents the absolute value of the discrepancy by each OD pair. To identify OD patterns, the origin and destination countries are divided into two types: high-income and low-income countries. A high-income country in this study is the same as a "high-income economy", with GNI per capita greater than 12 375 US$, as defined by the World Bank.[62] The low-income countries in this study include low-income countries, lower-middle-income countries, and upper-middle-income countries, with GNI per capita below 12 375 US$, as defined by the World Bank.[62]

As shown in Figure 2, there are four OD patterns of discrepancies in intercountry mercury trade: trade between high-income countries (A), trade from high-income countries to low-income countries (B-1), trade from low-income countries to high-income countries (B-2), and trade between low-income countries (C). The detailed data in Figure 2 are summarized in Table S2. The 305 total tons of mercury observed as the OD pair-level aggregated discrepancy in pattern C may reflect the illegal intercountry trade connecting ASGM activities in low-income countries in Asia, Africa, and Latin America.[16−22] Pattern C shows direct intercountry mercury trade from mercury-supplier countries to mercury-demand countries with ASGM, while patterns A, B-1, and B-2 show transit intercountry trade of mercury through transit countries with hub ports such as Hong Kong and Singapore. The discrepancy volume of mercury per OD pair for each pattern was 1.0 (127/125) for pattern A, 2.8 (179/64) for pattern B-1, 9.4 (170/18) for pattern B-2, and 3.6 (305/85) for pattern C. These discrepancy volumes suggest that in transit trade, illegal intercountry trade between high-income countries is unlikely, as in pattern A, while that of illegal intercountry trade between low- and high-income countries is likely, as in pattern B-2.

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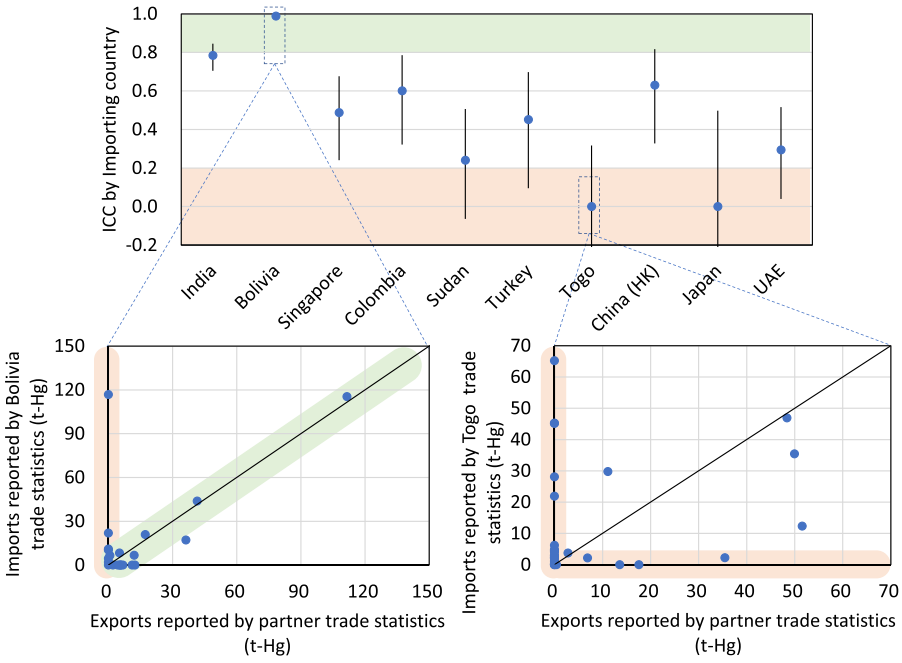

Figure 4. Estimation results of the intraclass correlation coefficient (ICC) of the top 10 importing countries in intercountry mercury trade from 2014 to 2018, scatter plot of the imports reported in the trade statistics of Togo and Bolivia, and exports of mercury reported in the partner trade statistics with the lowest and highest ICC.

3.2. ICC Analysis Focusing on Exporting Countries. The estimation results of the ICC by the top 10 exporting countries in intercountry mercury trade from 2014 to 2018 are shown in Figure 3. The ICC bar in Figure 3 represents the 95% confidence interval for the ICC estimation results.

As shown in Figure 3, the top 10 exporting countries from 2014 to 2018, accounting for 75% of the world's mercury trade, are Mexico, Indonesia, Spain, Japan, Singapore, Turkey, the United States, China, Switzerland, and the United Arab Emirates (UAE). Exporting countries with ICCs of >0.8 include Mexico, Japan, and Switzerland, while countries with ICCs of <0.2 include Indonesia, Spain, the United States, and China. The 95% confidence intervals for ICCs for countries other than Mexico, Japan, and Switzerland, which have high ICCs, were close to 0.3−0.4. Thus, the results of these estimates of ICCs should be interpreted with caution. The scatter plot of the exports and imports for Spain with the lowest ICC (0.00) shows that there are many cases in which the exports are reported but the mirrored imports are not reported. In the scatter plot of Mexico with the highest ICC (0.93), the major discrepancy in the mirrored trade data is limited to a few OD pairs, and most of the mirrored trade data are plotted around the 45° line with a high coincidence between exports and imports.

Mercury exports have been banned since 2011 and 2013 in Spain and the United States, respectively;[5,6] low ICCs can be seen in Figure 3. In Spain, mercury exports were reported in 2014 trade statistics, but its partner did not report trade statistics. This discrepancy has not been observed since 2015 when mercury exports from Spanish trade statistics reached zero. Thus, it can be inferred that the EU's export ban policy has not fully functioned in Spain since 2014 and that there may be illegal trade such as smuggling on the side of the importing country. In the United States, which also bans mercury exports, trade statistics did not report mercury exports, but partner country trade statistics reported exports from the United States. Such discrepancies indicate the possibility of false declarations of items other than mercury at the time of export to circumvent the mercury export ban policy.[15,16] ICC analysis also detected illegal exports in Indonesia, where mercury is illegally mined,[24] and in China, where mercury waste from vinyl chloride monomer production is generated.[15] In China, the influence of the false declaration of origin or destination by traders is considered to be significant owing to trade through Hong Kong.[15,41,48] This analysis also confirmed the existence of illegal exports from Indonesia.[15,24] Furthermore, the scatter plot of Mexico, which has a high ICC in Figure 1, shows that no discrepancy occurred in Bolivia but one did occur in Colombia, both major trading partners. In another case, reported exports from Mexico were zero, while reported imports from its partner country, Colombia, were recorded. This may be due to illegal exports resulting from illegal mercury mining in Mexico.[23] This ICC analysis focusing on exporting countries could detect illegal international trade under the U.S. mercury export ban policy that could not be determined by the world-level ICC analysis in Figure 1.

3.3. ICC Analysis Focusing on the Importing Countries. Figure 4 provides the ICC estimation results of the top 10 importing countries in intercountry mercury trade from 2014 to 2018. The ICC bar in Figure 4 represents the 95% confidence interval for the ICC estimation results.

In Figure 4, the top 10 importing countries, accounting for 57% of the world's mercury trade, are India, Bolivia, Singapore, Colombia, Sudan, Turkey, Togo, China (Hong Kong), Japan, and the UAE. The importing countries with ICCs of ≳0.8 include Bolivia and India, while the countries with ICCs of <0.2 include Togo and Japan. The 95% confidence intervals for the ICCs of countries other than Bolivia and India, which have high ICCs, were close to 0.4−0.6. Thus, the results of ICC estimates for importing countries should be interpreted with

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caution compared to those for exporting countries. The scatter plot of the mirrored trade data for Togo with the lowest ICC (0.00) shows that there are many unreported cases on the import and export sides, and in some cases, import data are more underreported than export data. In the scatter plot of Bolivia with the highest ICC (0.99), the major discrepancy is limited to a few OD pairs, and most of the export and import data are plotted around the 45° line with a high coincidence between exports and imports.

In Sudan and Colombia, which were identified by UNEP as having illegal international trade,[15] this analysis detected a trend toward illegal international trade. Furthermore, these results were confirmed in this analysis of Bolivia, where UNEP does not point to the existence of illegal international trade.[15] The analysis also detected illegal international trade in Togo, where the issue of re-export was discussed only qualitatively in UNEP.[15] While the ICC analysis focusing on exporting countries in Figure 3 did not confirm illegal international trade in Japan, this analysis focusing on imports confirmed illegal trade in the country. This is due to Indonesia, which reports a large value of its exports in the trade statistics while Japan reports a small value of its imports. Figure 3 confirmed the existence of illegal exports in Indonesia. As smuggling is difficult in an island country like Japan, which has a more advanced customs system, the possibility of false reporting by the partner country on the Indonesian side is considered.

4. ENVIRONMENTAL IMPLICATIONS

This study is the first to highlight the detection of illegal intercountry mercury trade in the mercury phase-out movement using discrepancy in mirrored trade data from UN Comtrade. The methodological advantage of this study over previous discrepancy studies is that the ICC was first used in the attempt to assess the discrepancy.

This study conducted an ICC analysis focusing on year, exporting country, and importing country. The year-based ICC analysis revealed a time-series decreasing trend in discrepancies in the reported exports and imports for mercury under recent efforts, such as by the Convention, to phase out mercury. The analysis that focused on exporting countries detected illegal mercury trade in the United States, Spain, and Indonesia, which have banned the export and mining of mercury. The analysis focusing on importing countries verified the validity of the ICC analysis through comparison with the UNEP reports.[15] In conclusion, this study successfully detected illegal intercountry mercury trade through ICC analysis.

The ICC analysis is useful as a detection method of illegal mercury trade in the effectiveness assessment of Article 3 of the Convention proposed by Evers et al.[27] The detection of the origin and destination in the illegal intercountry trade in this study also contributes to the enhancement of Article 14 (through capacity building, technical assistance, and technology transfer) of the Convention. Our ICC analysis enables the identification of countries in need of increased customs capacity and intercountry cooperation among the Convention parties. The contribution of mercury science to the Convention is expected through communication between scientists and policymakers.[25,26,63] This study, which offers a data-driven method for effectively detecting illegal mercury trade, is positioned as an indispensable part of mercury science and contributes to its development.

While the ICC analysis used in this study is useful from a mercury science perspective, it also has limitations because of incomplete trade statistics. For example, the goods to be declared at customs depend on each country's customs regulations. If a shipment is treated as portable goods according to its quantity, value, or purpose (personal use), the shipment is not recorded in trade statistics. A case of used car exports from Japan[64] confirms that the amount of portable goods is not negligible. In addition, this study focuses on smuggling as a typical case of illegal intercountry trade. In the ICC analysis used in this study, it is assumed that smuggling is reported in either of the trade statistics of the two countries forming the OD pair. There may be unreported cases of smuggling in the trade statistics of both countries. In this case, smuggling cannot be detected through ICC analysis. Thus, the ICC analysis has limitations in accurately detecting all illegal intercountry trade. However, to detect major trends in illegal intercountry trade, we consider this limitation to be acceptable on the basis of the results of past discrepancy studies in economics[30−46] and the present ICC analysis focusing on importing countries.

Given that the ICC analysis presented here was conducted for only mercury, it may have overlooked the existence of illegal intercountry trade through dental amalgams or other mercury-added products for specific countries such as Brazil and Zimbabwe, as pointed out in previous studies.[7,54−57] Therefore, a challenge for the ICC analysis is to include mercury-added products. Furthermore, this study is limited to detecting illegal intercountry mercury trade. The next step is to judge the volume of such trade. To do so, it is important to conduct a field survey of the illegal mercury trade targeting the exporting or importing countries detected in this study. Additionally, another approach based on the discrepancy in trade statistics for estimating illegal mercury trade volume is possible. For example, previous studies proposed methods for statistically correcting the discrepancy in trade statistics, targeting international trade in used cars and used home appliances.[58,65,66] The field survey and discrepancy approaches lead to an accurate understanding of the global mercury supply chain recognized as a challenge in mercury science.[25] Furthermore, judging the illegal intercountry trade contributes to more accurate estimates of mercury material flows and their emissions, which is well-known to be uncertain.[67−74]

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.est.2c04327.

Supplementary description for the intraclass correlation coefficient (ICC) for case 2, information about the parties to the Minamata Convention, and supplementary results of discrepancies in intercountry mercury trade in 2018 (PDF)

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Notes

The authors declare no competing financial interest.

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