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Evaluating the effectiveness of the Minamata Convention on Mercury: Principles and recommendations for next steps

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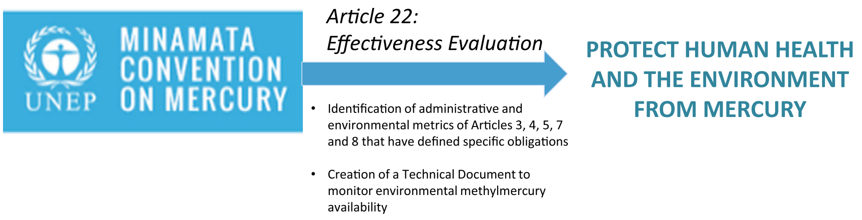
GRAPHICAL ABSTRACT



- Identification of administrative and environmental metrics of Articles 3, 4, 5, 7 and 8 that have defined specific obligations
- Creation of a Technical Document to monitor environmental methylmercury availability

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ABSTRACT

The Minamata Convention on Mercury is a multilateral environmental agreement that obligates Parties to reduce or control sources of mercury pollution in order to protect human health and the environment. The Convention includes provisions on providing technical assistance and capacity building, particularly for developing countries and countries with economies in transition, to promote its effective implementation. Evaluating the effectiveness of the Convention (as required by Article 22) is a crucial component to ensure that it meets this objective. We describe an approach to measure effectiveness, which includes a suite of short-, medium-, and long-term metrics related to five major mercury control Articles in the Convention, as well as metrics derived from monitoring of mercury in the environment using select bioindicators, including people. The use of existing biotic Hg data will define spatial gradients (e.g., biological mercury hotspots), baselines to develop relevant temporal trends, and an ability to assess risk to taxa and human communities of greatest concern. We also recommend the development of a technical document that describes monitoring options for the Conference of Parties, to provide science-based standardized guidelines for collecting relevant monitoring information, as guided by Article 19.

1. Background

Mercury (Hg) is a contaminant of global concern due to its potent toxicity. While Hg pollution may occur from natural sources, Hg also enters the environment from multiple anthropogenic sources including atmospheric emissions and direct releases to land and water (UNEP, 2013a). Once Hg enters the environment, its transport and fate is complex, influenced by chemical, physical, and biological factors (Mason et al., 2005; Harris et al., 2007a; Selin, 2009; Driscoll et al., 2013). Under certain conditions, Hg can be transformed into the more toxic and bioavailable methylmercury (MeHg), which is easily absorbed by organisms and can biomagnify within a food web and bioaccumulate within an individual over time. The adverse effects of MeHg exposure on the health of wildlife and people are well documented (Scheuhammer

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et al., 2011; Karagas et al., 2012; Ackerman et al., 2016), and the significant societal benefits associated with regulating mercury are now being realized (Sunderland et al., 2016). Monitoring efforts and models have demonstrated that declines in anthropogenic releases of Hg can result in the near-term reduction of environmental Hg loads (Soerensen et al., 2012; Sunderland and Selin, 2013; Amos et al., 2014, 2015), while failure to reduce releases may result in significant increases in seafood Hg concentrations (Sunderland et al., 2009).

Mercury is easily transported across national boundaries (Driscoll et al., 2013), thus requiring international cooperation for its control (UNEP, 2013a). The Minamata Convention on Mercury (the Convention), adopted on 10 October 2013 and signed by 128 countries, is a legally binding international agreement that is designed specifically to address global Hg pollution (UNEP, 2013b). The objective of the Convention is "to protect the human health and the environment from anthropogenic emissions and releases of mercury and mercury compounds" (Article 1). The Convention will enter into force 90 days after 50 countries have ratified it.

The Convention includes a mix of provisions to control, reduce, or eliminate major sources of Hg. These include: Hg supply sources and trade (Article 3); Hg use in products (Article 4); manufacturing processes that use Hg (Article 5); Hg use in artisanal and small-scale gold mining (ASGM; Article 7); air Hg emissions from coal-fired power facilities and other sectors (Article 8); releases of Hg to land and water (Article 9); interim storage of commodity Hg (Article 10); management of Hg-containing wastes (Article 11); and management of contaminated sites with Hg (Article 12).

Several Articles define control measures with a high level of specificity. For example, the Articles on Hg products and processes contain specific requirements for phase out within well-defined timeframes (though limited time extensions may be granted under certain circumstances). Other Articles allow flexibility in implementation that takes into account the circumstances of particular countries. For example, new sources of air emissions governed by the Convention must be controlled using best available technology and best environmental practices (BAT/BEP), but the specific selection of BAT may vary depending on the level of technical and economic development of a given Party to the Convention. As a result, the sources may be controlled at different times and in different ways, among the different Parties. However, while the Convention does afford some flexibility, Parties must ultimately use the available control measures to achieve significant Hg reductions, in order for the Convention to be effective.

The assessment of changes in emissions and releases resulting from Convention measures will be challenging. Attributing changes in human and environmental exposures to these measures will be even more complicated, because: (1) Hg cycling in the environment is complex; (2) Hg pollution can result from both local and distant sources; (3) there are ongoing emissions as well as re-emission of legacy pollution; and (4) there are natural sources of Hg releases (Soerensen et al., 2012; Driscoll et al., 2013). And, although all major categories of new emissions and releases are addressed by the Convention, global Hg models continue to have a relatively high level of uncertainty (Gustin et al., 2016) and therefore, monitoring and evaluation efforts are recommended (Selin, 2014).

As a result of these complexities, as well as inherent variability in the way Parties will implement the Convention requirements, any evaluation of the Convention's effectiveness cannot rely solely on a single set of metrics, but instead must be constructed from a collection of metrics that complement each other and capture different dimensions of effectiveness around the world and over different time scales.

For this reason, Article 22 of the Convention specifies a variety of information that must be included when conducting the effectiveness evaluation. The evaluation must be based on a combination of mercury monitoring data on "the presence and movement of mercury and mercury compounds in the environment as well as trends in levels of mercury and mercury compounds observed in biotic media and vulnerable populations," information reported by the Parties on implementation measures (per Article 21), compliance information and recommendations (per Article 15), as well as "reports and other relevant information derived from financial assistance, technology transfer and capacity-building activities" under the Convention. The Conference of Parties (CoP) will need to develop and implement a sound and transparent methodology for compiling, integrating, relating and evaluating this wide variety of administrative, technical and scientific information in a holistic evaluation framework.

To promote understanding among Parties and other stakeholders of all the required dimensions of the effectiveness evaluation, this paper proposes metrics for evaluating effectiveness of the specific measures designed to control Hg uses, emissions and releases, as well as metrics (or bioindicators) for assessing environmental responses to these changes.

2. Approach

We have organized the results, discussion, and recommendations in this paper into three separate sections. In Section 3.1, we describe a suite of metrics that can be used as indicators of effectiveness of implementation of Convention measures. Effectiveness evaluation will take place at intervals defined in Article 22 and agreed upon by the CoP. The first evaluation is to occur no later than six years after the Convention enters into force, and subsequent evaluations will be conducted periodically. To match these intervals, we identify potential implementation metrics that can be used in short-term (<6 years), medium-term (6–12 years), as well as longer-term (>12 years) timescales, to measure the effectiveness relative to specific Articles of the Convention.

In Section 3.2, we discuss biomonitoring strategies, which can be used to evaluate the effectiveness of the Convention at reducing Hg exposure across global ecosystems using key bioindicators and human communities. Such monitoring can be directed at ecosystems and populations in proximity to sources, as well as areas remote from sources where cumulative effects are potentially problematic.

In Section 3.3, we present recommendations for creating a science-based system of data collection, interpretation and monitoring, which will produce coordinated and consistent monitoring to develop baselines and track effectiveness evaluation over time.

2.1. Metrics for tracking effectiveness of specific convention measures

To illustrate an approach to evaluate the effectiveness of implementation of specific control measures in the Convention, Section 3.1 describes metrics to evaluate five key Hg control Articles that include well-defined specific obligations (Articles 3, 4, 5, 7, and 8). However, we do not develop metrics for other control Articles that have less-defined obligations (Articles 9, 10, 11, and 12) (Table 1). This latter group of Articles contains measures that will be defined in greater detail by the CoP (or by a Party itself) at a later date; therefore, it is not possible to suggest consistent global metrics for measuring their effectiveness at this time.

2.2. Biomonitoring for effectiveness evaluation

Section 3.2 of this paper describes the use of bioindicators to assess and monitor environmental Hg concentrations and associated changes resulting from controls on point sources. We also discuss recommendations for establishing long-term, globally coordinated monitoring to collect standardized measurements from the abiotic and biotic environment as well as from humans (in response to Articles 16 and 19) in order to track and evaluate progress on overall reduction in global Hg pollution. Such monitoring would not be directly tied to implementation of specific Articles of the Convention, but would instead reflect long-term integrated changes in biotic Hg concentrations that will

Table 1
Consideration of control articles of the Minamata Convention in this analysis.

Minamata Convention article (number and name)	Analysis included in this paper?	Description
Art. 3. Mercury supply sources and trade	Yes	Contains specific obligations to control Hg supply sources and trade of Hg
Art. 4. Mercury-added products	Yes	Contains specific obligations to phase out (or phase down, as specified) certain Hg-added products
Art. 5. Manufacturing processes in which mercury or mercury compounds are used	Yes	Contains specific obligations to phase out (or phase down as specified) certain industrial processes that use Hg
Art. 7. Artisanal and small-scale gold mining	Yes	Contains specific obligation to reduce and where feasible eliminate Hg use in ASGM
Art. 8. Emissions	Yes	Contains specific obligations to control and where feasible reduce specified sources of Hg air emissions
Art. 9. Releases	No	Contains obligations to control and where feasible reduce major sources of Hg releases to land and water that are not covered in other Articles of the Convention, but allows countries significant flexibility in identifying which sources they choose to control, as well as the specific control measures they wish to employ
Art. 10. Environmentally sound interim storage of mercury, other than waste mercury	No	Contains obligations for Hg storage, but guidance on control measures will be determined by the Conference of Parties at a later time
Art. 11. Mercury wastes	No	Contains obligations for Hg waste management, but guidance on control measures will be determined by the Conference of Parties at a later time
Art. 12. Contaminated sites	No	Contains obligations for developing strategies to identify and assess sites but does not include obligations for remediation

result from the cumulative effect of the full range of measures taken under the Convention.

2.3. Recommended next steps for monitoring

Finally, to ensure coherence and consistency among the varying monitoring systems upon which a key part of the effectiveness of the Convention will be based, Section 3.3 outlines an approach, for consideration by the CoP, to create a technical document that will provide science-based guidance on how to collect and use existing and new data to track and evaluate in a standardized, transparent, and scientific manner. Such a document would foster consistency and comparability of data, and would help build local and regional capacities.

3. Results and discussion

Using the approach outlined above a series of metrics for well-defined specific obligations (Table 1) and bioindicators (fish, wildlife, and humans) are presented, concluding with strategies for next steps.

3.1. Metrics for tracking effectiveness of the implementation of key convention articles

In this section, we provide recommended metrics for tracking effectiveness of implementation of Articles 3, 4, 5, 7, and 8. For each Article considered, we briefly summarize the Convention requirements, and then provide a table of the recommended short-, medium-, and long-term metrics for evaluating effectiveness. A detailed description of the metrics follows each table.

3.1.1. Article 3: Mercury Supply Sources and Trade

Commodity mercury supply is produced from: mercury mining; recovery of mercury as a by-product when processing certain other metal ores; mercury remaining from decommissioned industrial plants (such as some chlor-alkali facilities that used mercury in their processes; and recovery of mercury from recycling, as well as recovery from petroleum and natural gas processing. The Convention recognizes that available mercury supply must be reduced in order to create an incentive for users to switch to Hg-free alternatives. Reducing supply is particularly critical for tackling Hg use in ASGM (see Article 7), a largely informal and dispersed sector where direct interventions to reduce demand will be challenging.

As a critical measure to control supply, Article 3 focuses in particular on two mercury sources: (1) primary mining and (2) mercury from decommissioned mercury-cell chlor-alkali (MCCA) facilities. Article 3 bans new primary mining of Hg, and phases out existing primary mining within 15 years of “entry into force.” Further, the uses of such primary-mined Hg are limited to certain products and industrial processes covered under Articles 4 and 5; the result is that primary-mined Hg cannot be used in ASGM. Similarly, Article 3 also requires that Hg remaining after the decommissioning of MCCA facilities, which is deemed “excess” mercury, must be managed in an environmentally sound manner.

Finally, the Article contains specific control measures on the trade of Hg, including the requirement specifying that a Party may only export Hg if it has received informed consent or a general notification from the importing country, and only for a use allowed under the Convention.

To measure the effectiveness of the supply and trade requirements under Article 3, the evaluation should consider both the overall reduction in total global supply and trade, as well as the effective control of supply reaching the ASGM sector. Table 2 identifies seven metrics that can be used for evaluation of steps taken to implement Article 3 of the Convention.

3.1.1.1. Short-term metrics. The ban on new primary Hg mines will go into effect immediately on entry into force for the Party, as will the use of restrictions and provisions that require exporting Parties receive consent or a general notification from importing Parties before engaging in mercury trade (“prior informed consent” or PIC procedures). Therefore, short-term metrics should evaluate how effectively Parties are moving toward creating supply and trade control regimes (e.g., how many Parties have adopted PIC procedures), and assess if any new mines are illegally opened after entry into force. The evaluation may also want to track any mines opened by non-Parties who are not subject to the requirements of the Convention. An inventory of existing primary Hg mines will have to be developed as a baseline, prior to entry into force.

An obvious metric for Article 3 is the change in the overall global supply of Hg (from all sources) compared to a baseline prior to entry into force. In practice, the level of supply may not significantly decrease during the first evaluation period because: (1) existing mines are not required to close during that time; and (2) the phase out of most Hg products and processes will have just gone into effect shortly before the first evaluation, and reductions in supply may lag the reduction in demand. However, there may be reductions in the supply from primary mining due to domestic policies in China, promotion of measures to reduce reliance on Hg from primary mining for use in vinyl chloride monomer (VCM) production (as required in Annex B, Part II), and the immediate Convention restrictions against the use of primary-mined Hg for ASGM. These changes can be tracked as a short-term metric of effectiveness.

Table 2
Convention requirements for Article 3 (supply sources and trade) and potential metrics over three time periods.

Convention requirements	Metrics	Relevant time period		
		Short term (<6 years)	Medium term (6–12 years)	Long term (>12 years)
I. Phase out of primary Hg mining; II. Restrictions on reuse of chlor-alkali Hg; III. Controls on and tracking of Hg trade	1. Number of Parties establishing Hg trade tracking systems	✓		
	2. Number of new Hg mines (if any) opened after entry into force[a]	✓	✓	✓
	3. Overall global Hg production from all sources	✓	✓	✓
	4. Reduction in Hg production from primary mining in advance of the Convention deadline	✓	✓	
	5. Amount of Hg trade (legal and illegal)	✓	✓	
	6. Amount of excess Hg from MCCA facilities that is soundly managed		✓	✓
	7. Number of existing primary Hg mines that remain in operation and tonnes of mercury production remaining, if any			✓

[a] Here, and elsewhere in the document, the term “entry into force” refers to entry into force for each Party. The Convention itself goes into force on the 90th day after the 50th country deposits its ratification instrument with the Secretariat, and for those first 50 countries, the requirements of the convention are anchored to that date. Countries that ratify after the Convention goes into force are subject to its requirements based on the 90th day after they submit their ratification documents. For these “late-joining” countries, some requirements noted in the table's short-, medium, or long-term timeframes may, in fact, fall outside. These differences in the effective dates for requirements among Parties will have to be taken into account in the effectiveness evaluation.

Change in global Hg supply sources, compared to a baseline prior to entry into force, may also be considered a relevant metric in the short-term. The supply and trade report (UNEP, 2006) and its update (anticipated in 2017), may serve as the pre-Convention baseline. Upon entry into force, the Hg tracking and reporting regimes of some Parties may still be under development or just recently enacted. In this case, estimates of changes in supply during the early years of the Convention will be based on existing national and international data (such as COMTRADE); however, these data are incomplete and difficult to compile. For this reason, reporting under Article 21 will be key to effectiveness evaluation. Article 21 requires Parties to periodically report on compliance with all Articles of the Convention including Article 3. Although the CoP has not yet specified what data will be reported under this Article, it will be critical for Article 21 reporting to include global Hg production and supply data, as well as trade statistics, in order to be able to adequately evaluate the effectiveness of the Convention's supply and trade provisions.

3.1.1.2. Medium-term metrics. By the 6-to-12-year time period, many Parties will have phased out products and processes that use Hg covered by the Convention, and some Hg mines may be closed, even before the 15-year deadline, in response to reduced demand or political pressure. Further, most ASGM countries will have begun to implement their ASGM National Action Plans, which outline steps to reduce Hg use in the sector. The combination of reduced supply (i.e., closing of primary Hg mines) and the beginning of new restrictions on demand within the ASGM sector may begin to reduce the amount of Hg on the global market. Therefore, medium-term evaluation metrics should include the change in Hg production resulting from Hg mines closed in advance of the Convention deadline, as well as an ongoing assessment of trends in global Hg supply sources. Again, while the CoP must specify the information that must be included in Article 21, the reporting should be designed to provide needed information to evaluate the amount of global Hg legally produced by Parties via primary mining, as well as from sources other than primary mining (such as Hg produced as a byproduct of nonferrous metal smelting), as accurate data are difficult to obtain through other means.

Trends in Hg trade are also a relevant metric for effectiveness of Article 3, both as it reflects overall supply, and as a means to evaluate compliance with supply restrictions to the ASGM sector. Information on legal Hg trade could be captured from the PIC forms that must be filled out as a condition of trade (UNEP, 2014) and/or Article 21 reporting. However, to be effective, the Convention must result in a decline of illegal trade of Hg. This metric will be more challenging to evaluate, and may require independent data collection rather than reliance on official information. For example, estimates of illegal trade may be derived from: (1) hotspot investigations of suspected illegal trade, especially to informal sectors such as ASGM; and/or (2) subtracting ASGM legal sources from total estimated ASGM demand (based on National Action Plan submissions, which contain baseline ASGM Hg use estimates).

Finally, in the medium term, the requirements to phase out MCCA facilities will go into effect (see Article 5 discussion below), leaving a pool of “legacy” excess Hg at these facilities that must be managed, since by this point mercury will no longer be allowed to be deployed elsewhere in the chlor-alkali industrial sector. Therefore, an additional medium-term metric is the amount of excess Hg that is sequestered or otherwise managed in an environmentally sound manner. This excess Hg can be determined from the trade reporting forms, from Article 21 reporting, and from independent data gathered on the fate of Hg at each of the facilities listed in baseline inventories through the Global Mercury Partnership (UNEP, 2013c).

3.1.1.3. Long-term metrics. In later evaluation periods, all primary Hg mines should be closed, therefore a relevant metric will be the number (if any) of remaining operating primary mines, and, where available, the amount of Hg still produced by primary mining. The metrics on global trends in supply and trade will also continue to inform the effectiveness evaluation, using the same data collection approaches used in the medium-term.

3.1.2. Article 4: mercury-added products

Under Article 4, Parties “shall not allow the manufacture, import, or export” of specific Hg-added products listed in Annex A, Part I, by 2020. Parties must also phase down the use of Hg in dental amalgam (Annex A, Part II). This discussion focuses only on metrics for Part I. The Part I list includes certain batteries, switches and relays, and measuring devices, among other products. In some cases, the list specifies a maximum Hg content allowed for certain products, such as compact fluorescent lamps. Under Article 6, Parties can register for an exemption to the 2020 phase-out date, although the exemptions will be limited to 5 years, in most cases. Extensions beyond 5 years will require a case-by-case decision of the CoP.

The prohibition on the manufacturing of these products will reduce occupational exposures to Hg. In the longer-term, the end of manufacturing and trade will eventually mean the cessation of sales and use of these products as existing stocks are depleted, leading to a reduction in exposures from the use and disposal of these products. However, because some countries will likely apply for an exemption for at least some products, there will still be continued manufacture, use, and trade in selected countries up to 2025 (or longer in special circumstances). We suggest five metrics that can be used to evaluate the effectiveness of Article 4 of the Convention (Table 3).

3.1.2.1. Short-term metrics. The overall effectiveness of Article 4 will be reflected in the speed and extent to which Hg-added products

Table 3
Convention requirements for Article 4 (Hg-containing products) and potential metrics over three time periods.

Convention requirements	Metrics	Relevant time period		
		Short term (<6 years)	Medium term (6–12 years)	Long term (>12 years)
Phase out by 2020 (Annex A, Part 1), unless exemption	1. Amount of Hg used in manufacturing of Annex A products (relative to baseline numbers):			
	• in countries with 2020 deadline	✓	✓	✓
	• in countries with time exemptions		✓	✓
	• for any new products added to Annex A, due to CoP review		✓	✓
	2. Reduction in amount of Hg trade reported for manufacturing of Annex A products, per Article 3	✓	✓	✓
	3. Occupational monitoring data at product manufacturing sites	✓	✓	✓
	4. Amount of remaining product inventory of Annex A products			✓
	5. Emissions from product waste incineration (per Article 8)			✓

disappear from store shelves, homes, businesses, hospitals and other medical facilities, and waste streams. The Convention aims to achieve this result by prohibiting the manufacture, export, and import of the specified Hg-added products. However, due to the difficulty of tracking exports and imports of these varied products in many countries around the world, we recommend focusing on metrics that track the manufacturing of these products, which is concentrated in fewer countries. As manufacturing is phased out, we assume that decline of exports and imports will naturally follow.

Because the initial effectiveness evaluation period is likely to occur only shortly after the 2020 phase-out date for most products, the initial evaluation should focus on manufacturing in those countries that have not applied for an exemption and that must comply with the 2020 deadline.

Ideally, manufacturing data could be gleaned from domestic industrial data sources, but the availability of such data is currently very uneven and difficult to obtain in many countries. Therefore, reporting on the manufacture of these products (or, on the amount of Hg used for the manufacturing of these products) under Article 21 will again be critical to meaningful effectiveness evaluation.

To augment product manufacturing data, Hg trade reporting under Article 3 will provide information about the level of the trade in Hg for allowable uses. The reduction in Hg trade reported over time for manufacture of products, as these products are phased out, will also be an indicator of effectiveness for Article 3.

Elimination of Hg in manufactured products that contain Hg should lead to a decline in occupational exposures to Hg at manufacturing sites, as new Hg no longer enters the manufacturing site (although Hg contamination may linger at manufacturing sites even after operations are shut down, and so exposures may continue if the legacy contamination is not addressed). Routine monitoring and compliance data from occupational regulatory agencies could be used to evaluate reductions in worker exposures at these locations.

3.1.2.2. Medium-term metrics. In the medium term, tracking of these metrics should continue, but later evaluations should include countries that were granted exemptions to the 2020 phase-out date. All parties with timing exemptions will be listed in a register, per Article 6, paragraph 3, so these countries can be distinguished easily. Further, under Article 4, paragraph 8, no later than 5 years after entry into force, the CoP will review Annex A and may consider additional products for listing. If this occurs, these newly listed products will also have to be included in these metrics.

3.1.2.3. Long-term metrics. Tracking of manufacture, trade, and sales of Annex A, Part I products should continue in the long-term to document their phase out. As manufacturing and trade of these products come to an end, the existing stocks of products will gradually be depleted. The rate at which this occurs is an indicator of the ultimate effectiveness of Article 4 measures. While the Convention does not require collection of such information, some Parties may wish to collect market data and/or conduct surveys to monitor trends in sales of products, which can be conducted and reported under Article 21, to document the disappearance of these Hg-added products from store shelves.

Furthermore, as these products reach the end of their useful life and are disposed (or placed in long-term storage), and are replaced with non-Hg alternatives, the number of items entering the waste stream should decline over time, thus reducing exposures from waste disposal, especially from waste incineration. Monitoring of emissions from waste incinerators can provide a picture of this decline; trends of such emissions may also be collected as part of measures to comply with BAT/BEP for waste incinerators, under Article 8.

3.1.3. Article 5: manufacturing processes in which Hg or Hg compounds are used

Article 5 of the Convention limits the intentional use of Hg in industrial processes. Its related annex (Annex B, Part I) requires that MCCA manufacturing be phased out by 2025, while manufacturing of acetylaldehyde with a Hg catalyst must cease by 2018. As with Hg-added products, Parties can register for an exemption to the process phase-out dates, although the exemptions will be limited to 5 years in most cases, and any subsequent extension will require a case-by-case decision of the CoP.

In Annex B, Part II, other processes are named where certain phase-down requirements are elaborated. Particularly important is the phase down of Hg use in vinyl chloride monomer (VCM) manufacturing, as this is the largest use of Hg in any formal industrial process. By 2020, the Convention requires a 50% reduction in Hg use (compared to a 2010 baseline), as well as ongoing work to find a Hg-free catalyst for this process.

The prohibition of these processes will reduce occupational exposures to Hg, and reduce emissions and releases to the environment. The prevalence of some of these processes has already been declining in many countries. Therefore, many countries will likely achieve a straightforward phase out of the MCCA process by 2025. However, other countries may apply for an exemption, as some countries will still have these facilities in operation for years to come. We have identified eight metrics to help evaluate the effectiveness of Article 5 of the Convention (Table 4).

3.1.3.1. Short-term metrics. The overall effectiveness of Article 5 will be reflected in the speed with which the target processes are phased out for Annex B, Part I processes, or Hg use is phased down for Part II processes. Under Part I, the Convention requires that acetylaldehyde plants using Hg as a catalyst should be closed by 2018 and MCCA facilities by 2025. However, there are no known acetylaldehyde plants using Hg currently in operation, therefore, it is likely unnecessary to include a metric specifically on this element. For MCCA facilities, since the initial effectiveness evaluation is likely to occur before the 2025 phase-out date, short-term metrics could consider both the number of facilities that have closed prior to the required deadline, as well as the number of plants committing to close by the required date. Because these are large industrial operations, which presumably need operating permits, regulatory authorities of the governments should already know their

Table 4
Convention requirements for Article 5 (intentional use of Hg in industrial processes) and potential metrics over three time periods.

Convention requirements	Metrics	Relevant time period		
		Short term (<6 years)	Medium term (6–12 years)	Long term (>12 years)
I. Closure of MCCA facilities by 2025 (Annex B, Part I) II. Phase down of VCM production by 50% by 2020; adoption of Hg-free catalyst for VCM when available; and other specific phase-down requirements for other Annex B processes including 10-year phase-out objective	1. Number of MCCA facilities:			
	• committing to close by deadline	✓		
	• already closed prior to deadline	✓		
	• closed or converted in countries with 2025 deadline		✓	
	• closed or converted in countries with time exemptions			✓
	2. Amount of excess Hg from MCCA facilities managed in an environmentally sound manner	✓	✓	✓
	3. Quantity of Hg used in VCM compared to 2010 baseline, as well as quantity of Hg used from primary mining	✓	✓	✓
	4. Annual amount of Hg used in Annex B facilities	✓	✓	✓
	5. Reduction in Hg trade over time for Annex B manufacturing processes, as reported under Article 3	✓	✓	✓
	6. Occupational monitoring data at Annex B sites		✓	✓
	7. Once Hg-free VCM processes are deemed available by CoP: number of Hg-catalyst VCM plants closed/ number illegally in operation		✓	✓

identities. Moreover, the Global Mercury Partnership (UNEP, 2013c) maintains a global inventory of such facilities and the estimated amount of mercury on site.

For Annex B, Part II processes, the effectiveness evaluation should consider progress on the required measures described in the Annex. By 2020, for example, Hg use per unit production of VCM should be reduced by 50% compared to 2010, and measures must be taken to reduce reliance on primary-mined Hg in VCM manufacture. Article 21 reporting should include information about progress made toward these goals. Further, Article 5, paragraph 5(c) says that Parties shall “endeavor to” submit information to the Secretariat on the estimated annual amount of Hg used in Annex B facilities, and the reduction in these reported amounts over time can also provide a short-term metric of the effectiveness for both Part I and Part II processes.

Finally, to supplement direct information on manufacturing, Hg trade reporting under Article 3 will provide information about the amount of the trade in Hg for allowable uses; the reduction in Hg trade reported over time for these industrial processes will be an additional indicator of Convention effectiveness for this Article.

3.1.3.2. Medium-term and long-term metrics. By 2025, the bulk of MCCA facilities should no longer exist. Post-2025, the number should rapidly reach zero. Thus, in the medium and long terms, the number of facilities that have converted or closed can serve as the key metric. The medium-term evaluations can focus on plant closures in countries that did not request a time exemption, while subsequent evaluations can include Parties that were permitted exemptions. All Parties with timing exemptions will be listed in a register, per Article 6, paragraph 3, so these countries can be distinguished easily.

Excess mercury from decommissioned MCCA facilities must be disposed in an environmentally sound manner, as required by Article 3, rather than resold to the global commodity market. Thus, management of this Hg should also be tracked as these MCCA facilities are closed or converted. Some countries, such as the United States and those within the European Union, already have regulations in place banning the export of Hg or Hg related to MCCA facilities (Fig. 1; see Article 3 discussion).

For Annex B, Part II processes, metrics used in the short term can continue to be tracked to determine progress on the measures required. For VCM manufacturing, once a Hg-free catalyst has been identified and deemed “available” by the CoP, Parties have 5 years to prohibit the use of Hg in this process. Thus, depending on when the catalyst becomes available, medium- and long-term evaluations should also consider the number of facilities adopting this catalyst, and the number of facilities still using the Hg-based method in contravention of the obligation of the Convention.

3.1.4. Article 7: artisanal small-scale gold mining

ASGM is estimated to be the largest source of Hg pollution in the world (UNEP, 2013a; Steenhuisen and Wilson, 2015). ASGM operations are estimated to release about 1600 tonnes of Hg to the environment every year (approximately 727 tonnes of which is emitted to air and 881 tonnes released to land and water; AMAP/UNEP, 2013). Great uncertainties and gaps exist in the available data, and the actual figure may be higher because access to many ASGM sites is lacking. This Hg can cause significant local effects on miners, their families and communities, and the local environment, but it also contributes to the overall pool of global Hg pollution.

Article 7 requires that parties “reduce and where feasible eliminate the use of Hg in ASGM.” Those countries with “more than insignificant” use of ASGM must develop and implement a National Action Plan (NAP). The mandatory contents of the NAP are detailed in Annex C, and require not only technical measures to reduce Hg use, but also the creation of an enabling policy framework (e.g., the formalization/legalization of the sector) to support the transition away from Hg, as well as the creation of a public health strategy to deal with the health consequences of the direct and significant exposures to Hg in mining communities, particularly among vulnerable groups (i.e., children and women of child-bearing age).

Although all parties subject to Article 7 must reduce Hg use in the sector, the reductions achieved will be highly variable country to country, because each country-specific NAP will contain country-tailored Hg use reduction goals. This variability is a challenging factor in the effectiveness evaluation of this sector. However, Annex C of the Convention describes the common elements that are required to be included of each Party's NAP, and these elements can form the basis of metrics for evaluating effectiveness (Table 5).

3.1.4.1. Short-term metrics. Because NAPs must be completed 3 years after entry into force for each Party, and progress reports are due 3 years after that, the first progress reports for many Parties will be submitted 6 years after entry into force. This timing coincides with the first effectiveness evaluation, so the data collected for the first NAP progress report will be a key source of information to feed into the first evaluation. In fact, the timely submission of NAPs is itself a short-term metric of effectiveness.

The NAPs are required to establish a baseline of Hg use and practices and then create Hg reduction targets relative to the baseline. One short-term effectiveness measure could be the percent Hg reduction targets identified in the NAP; more ambitious targets may signal strong commitment of countries to the reduction of Hg in the sector. Reports on progress under the NAP, required every 3 years, should report on the

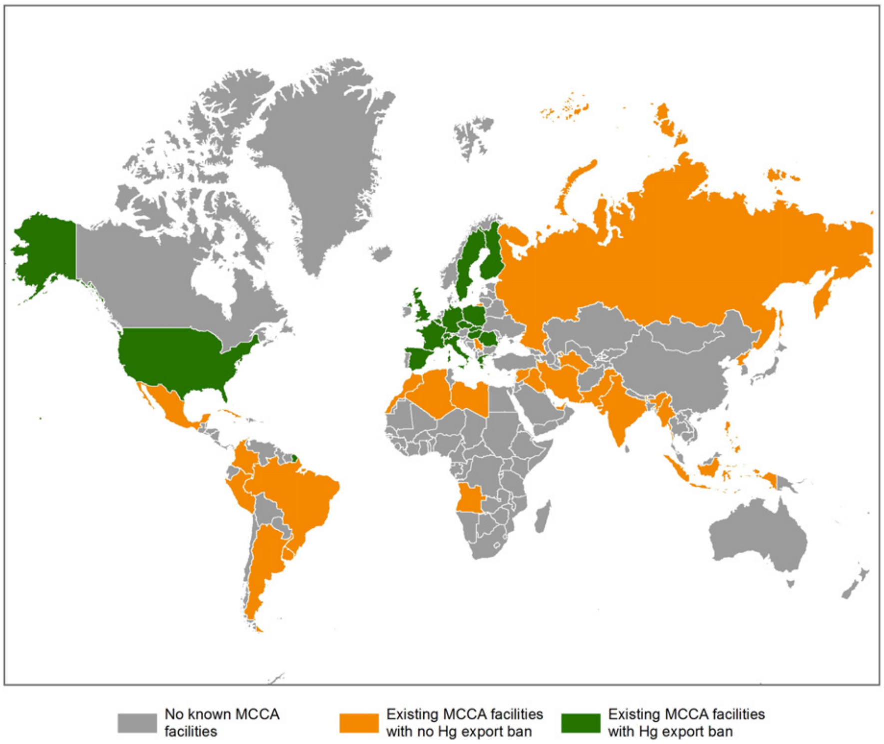

Fig. 1. Countries with existing mercury-cell chlor-alkali (MCCA) facilities in 2013, with Hg export ban status (AMAP/UNEP, 2013; UNEP, 2013c).

reduction in Hg use relative to this baseline, and whether or not the reduction is on track for achieving the targets. Reports on efforts to eliminate the worst practices identified in Annex C could also be included. The quantity of Hg traded for use in ASGM, and compliance with the Hg trade restrictions to ASGM (no primary-mined Hg, no excess Hg from decommissioned MCCA facilities), as reported under Article 3, can be used to supplement these country progress reports.

The NAP must contain a number of enabling policy measures to support Hg reduction, including plans for formalization or regulation of the sector, preventing diversion of Hg supply sources to the ASGM sector, as well as direct measures to reduce Hg use. According to UNEP draft guidance (UNEP, 2015), NAPs themselves should contain country-specific evaluation metrics to measure progress. Short-term metrics may include indicators from intervention programs with targeted mining communities (such as number of new miners formalized/registered, number of miners trained in alternative methods, number of miners purchasing alternative mining equipment, or other short-term indicators).

The NAPs must also include a public health strategy on exposure of artisanal and small-scale miners and their communities to Hg. These public health measures should result in reduced exposures to miners and their communities. Direct measures of Hg exposures in miners may be used to characterize this exposure (Gibb and O'Leary, 2014). While human monitoring is not a required dimension of the public health strategy, it offers an objective and measurable approach. It can be done in representative populations to evaluate the effectiveness of exposure reduction interventions. Mercury in urine reflects exposures to ASGM-related Hg amalgamation; urine can be easily and noninvasively obtained from participants and there are no specialized storage or handling requirements, factors that are particularly useful in resource-limited settings (Basu et al., 2015). While there are costs associated with such programs, when designed carefully (including collection of pre-intervention baselines), the resulting information is powerful in terms of documenting whether the interventions have indeed lowered Hg exposures, which directly meets the Convention's main objective.

Progress in individual countries can contribute to an evaluation of how overall Hg use in the global ASGM sector is changing. To track this progress, information across ASGM countries can be compiled, and global changes tracked and mapped (see Fig. 2).

Table 5
Convention requirements for Article 7 (artisanal small-scale gold mining) and potential metrics over three time periods.

Convention requirements	Metrics	Relevant time period		
		Short term (<6 years)	Medium term (6–12 years)	Long term (>12 years)
Reduction and where feasible elimination of Hg use in ASGM	1. Number of submissions of NAPs (both before and after the deadline set out in Article 7)	✓		
	2. Mercury reduction targets identified in NAPs	✓		
	3. Short-term metrics specific to interventions (such as number of miners trained), as identified in the NAPs	✓		
	4. Progress made against NAP requirements, including amount of Hg reduced, compared to NAP baseline, and elimination of worst practices, per Annex C	✓	✓	✓
	5. Quantity of Hg trade reported for ASGM, per Article 3, and compliance with supply restrictions	✓	✓	✓
	6. Mercury exposures of miners and community members, as measured in urine	✓	✓	✓
	7. Establishment and maintenance of mapping database to track global progress	✓	✓	✓

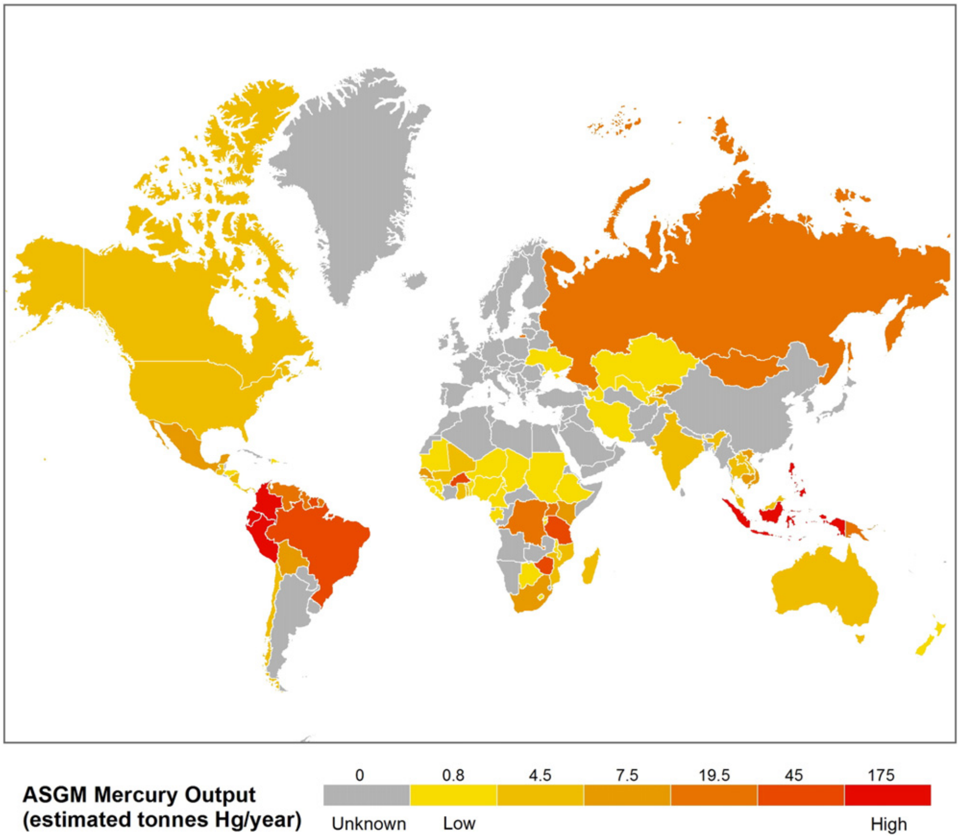

Fig. 2. Estimated annual Hg output (released to air or water) from ASGM activities by country (tonnes Hg/year; AMAP/UNEP, 2013; UNEP, 2013c; Artisanal Gold Council Mercury Watch pers. com.).

3.1.4.2. Medium- and long-term metrics. Subsequent progress reports on NAP implementation will provide input to effectiveness evaluations in later years, using the same metrics as were employed in the short-term evaluation. While new comprehensive Hg-use inventories may not be conducted for subsequent effectiveness evaluations, there could be focused new inventories in locations where Hg-reduction interventions are taking place, in order to evaluate changes in Hg use and whether progress is being made toward reduction targets. These data could be supplemented with targeted surveys in other locations, and with Article 3 reporting on Hg trade for ASGM.

3.1.5. Article 8: emissions

The control and, where feasible, reduction of Hg released through stack emissions of coal-fired utilities and industrial boilers, cement plants, nonferrous metal smelters, and waste incinerators is a critical part of the Convention. For new facilities in these source categories, the Convention requires application of Best Available Technologies and Best Environmental Practices (BAT/BEP) to each facility no later than 5 years after entry into force (Table 6). Existing facilities must be addressed within 10 years of entry into force. For these existing facilities, a range of control options are available; these control measures must cover at least 75% of emissions from each source category.

It is important to note that Parties are not required to limit total emissions in each sector under the Convention, but rather to control emissions from new sources, and, "where feasible," reduce emissions. Thus, the introduction of a significant number of new facilities could partially offset progress gained from implementing the required control measures over existing sources (Fig. 3). In this case, total emissions may remain steady for a long period of time, or may decline slowly for one or more countries. Nonetheless, the ultimate reduction of global mercury emissions is an important factor to consider when evaluating Convention effectiveness.

Table 6
Convention requirements for Article 8 (Coal-fired utilities and industrial boilers, cement plants, nonferrous metal smelters, and waste incinerators) and potential metrics over three time periods.

Convention Requirements	Metrics	Relevant time period		
		Short term (<6 years)	Medium term (6–12 years)	Long term (> 12 years)
I. BAT/BEP for new sources[2] within 5 years of entry into force; II. A range of options for control of existing sources, within 10 years of entry into force	1. Number of Parties with BAT/BEP standards established for *new* sources	✓		
	2. Percentage of new global sources with BAT/BEP applied	✓	✓	✓
	3. Number of Parties and percentage of global sources with controls in effect for *existing* sources		✓	✓
	4. Number of source and emission inventories developed and maintained	✓	✓	✓
	5. Emissions reductions based on inventories	✓	✓	✓

[2] A new facility is defined as a facility built or substantially modified within 1 year of entry into force.

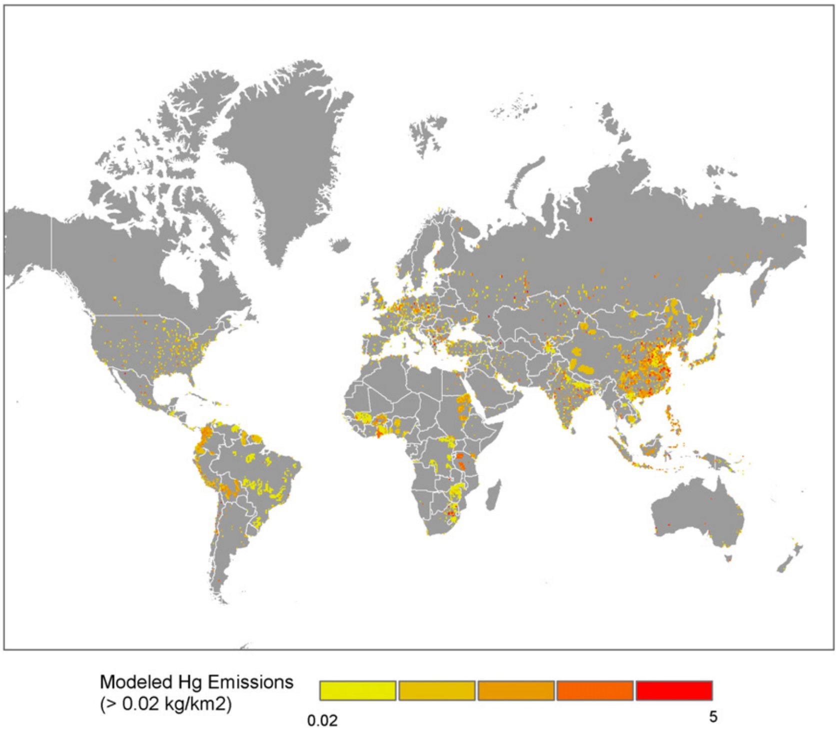

Fig. 3. Modeled global anthropogenic mercury air emissions (kg Hg/km^2; AMAP/UNEP, 2013).

Paragraph 7 of Article 8 requires Parties to develop and maintain an emissions inventory within 5 years from entry into force. Paragraph 9(b) of Article 8 directs the CoP to adopt guidance on preparing inventories for the purposes of the Convention. Such guidance should help ensure that inventories are comparable, verifiable, and high quality.

The guidance may include a discussion of how new tools and techniques (e.g., remote sensing, satellite, and ground-based ambient Hg measurements) could be used to better understand and ultimately reduce uncertainties in emissions inventories (e.g., Gustin et al., 2013) for Parties where such technologies are available. Quality control for gaseous oxidized mercury (GOM) and particle-bound mercury (PBM) measurements are particularly important (Jaffe et al., 2014). Further, ongoing research and monitoring under the global climate mitigation regime (Rafaj et al., 2013) could provide models for assessing Hg emissions inventories. In the U.S., the National Acid Precipitation Assessment Program (NAPAP) emissions inventory, a high quality-assured national inventory for multiple uses (policy development, modeling, human health, and ecological research), could be used as an example for these inventories.

3.1.5.1. Short-term metrics. In the first evaluation period, the requirements for applying BAT/BEP to new sources will come into play for many Parties. Because BAT/BEP is established at the national level, one short-term measure of progress is the number of Parties that will have adopted BAT/BEP standards, at least for new sources, during this period. Once these standards are in place, the percentage of sources globally to which these standards apply can also serve as a metric of effectiveness. Under Article 21, Parties must report on progress on implementing Article 8, and these reports should also contain relevant information for the evaluation of these metrics.

Further, as noted above, the Convention requires Parties to establish an inventory of emissions. While Parties are not required to achieve specific overall emission reductions, the effectiveness evaluation should still consider whether emissions reductions are occurring over time, and thus achieving the Convention objective of protecting human health and the environment from such emissions, and the overall Article 8 objective of reducing emissions “where feasible.” The inventory information will help the CoP understand whether requirements in the future should be strengthened, and/or implementation of the existing requirements more rigorously enforced, if the Convention is not demonstrating the intended environmental results. In the short-term, to evaluate if reductions have taken place, these emissions estimates may be compared to baseline estimates available in the Global Mercury Assessment (UNEP, 2013a) or produced through country-specific inventory efforts, such as the Minamata Initial Assessments (MIAs).

Under paragraph 3 of Article 8, some countries may also choose to develop a National Plan, “setting out the measures to be taken to control emissions and its expected targets, goals, and outcomes.” Although creating a National Plan is not a mandatory requirement, if a Party chooses to create such a plan, it must be submitted to the CoP within 4 years of entry into force. Where created, such plans may also provide relevant information on baseline levels of controls and emissions, and progress reports on these Plans (for example under Article 21 or through the inventories) may also provide relevant data for effectiveness evaluation.

Data from emissions can provide input into modeling efforts to evaluate regional and/or global impacts of changes in emissions. Observations from regional or global mercury monitoring networks can also be evaluated in light of these emissions data. Existing networks such as North America's Mercury Deposition Network (Prestbo and Gay, 2009) or the Global Mercury Observation System (Pirrone et al., 2013) can serve as important templates for how emissions information can be used in conjunction with such monitoring efforts and understanding global patterns (Fig. 3). Monitoring could be conducted independently by Parties, as part of existing regional or global networks, or as part of new regional networks (e.g., the Asia Pacific Mercury Monitoring Network).

3.1.5.2. Medium- and long-term metrics. For existing sources, Parties must apply one or more control measures, no later than 10 years after entry into force. Options for control measures include: (1) a quantified goal for controlling and, where feasible, reducing Hg emissions; (2) emission limit values for controlling and, where feasible, reducing Hg emissions; (3) the use of BAT/BEP to control emissions; (4) a multipollutant control strategy that would provide co-benefits for control of Hg emissions; and (5) alternative measures to reduce emissions from relevant sources. Whatever measures are chosen, paragraph 6 of Article 8 requires that the overall objective of the measures must be to reduce emissions over time.

For the medium- and long-term evaluation periods, the requirement to control existing sources will come into play for virtually all Parties. Metrics similar to those for new sources, which is the number of Parties with controls in place and the percentage of global sources subject to these controls, will be critical measures of the Convention's effectiveness at controlling air emissions. Article 21 reporting and the required inventories should provide the needed data for this evaluation. Emissions inventories will be critical in evaluating whether Parties are achieving “reasonable progress” required under paragraph 6.

3.2. Biomonitors for evaluating the effectiveness of the convention to reduce Hg exposures

In this section we present potential bioindicators and relevant case studies for evaluating the effectiveness of the Convention at reducing environmental Hg loads and associated ecological impacts, as well as human exposures. The use of bioindicators is critical because they best reflect the bioavailability of MeHg generated and made available to the food web within an ecosystem (Mason et al., 2005). The choice of bioindicators depends on many criteria such as the ability to capture and sample individuals (e.g., cost-effectiveness, abundance, sampling ease) and the objectives (e.g., understanding spatial gradients, tracking temporal changes in environmental Hg loads, and determining significant health effects in the most sensitive species) (Wolfe et al., 2007; Ackerman et al., 2016). Unlike the specific metrics and more defined timelines provided in Section 3.1, evaluating the effectiveness of the Convention through biomonitoring and subsequent modeling requires further discussion about its design (as recommended in Section 3.3).

Monitoring may be directed at tracking changes in Hg concentrations of select bioindicators associated with controls on specific point sources, and/or it may be used to track changes that result from the cumulative effects of multiple Convention measures. Monitoring changing environmental Hg loads and ecological impacts may occur in the short-term (<6 years) as pilot efforts by Parties under existing Hg monitoring networks, or may continue in the medium and long term under more systematic global efforts developed specifically by the CoP.

3.2.1. Using bioindicators for evaluating effectiveness of point source controls

Bioindicators are commonly used for assessing environmental Hg loads and associated ecological impacts resulting from controls on point sources. For such assessments, changes in environmental Hg loads from mandatory Convention requirements are of greatest importance globally (i.e., those related to Articles 5, 7, and 8). However, for some Parties, monitoring environmental Hg loads may also be relevant for important sources that they choose to control voluntarily; Article 12 states that “Each Party shall endeavor to develop appropriate strategies for identifying and assessing sites contaminated by mercury or mercury compounds.” Although remediation of such sites is not mandatory, it is encouraged, and the CoP may call to adopt guidance standards for managing such sites that would include “human health and environmental risk assessments” (UNEP, 2013b).

The measurement and monitoring of Hg in biota is a well-established approach for assessing the success of reducing or eliminating the release of Hg into the air and water or on land from point sources. For the purposes of the Convention, monitoring of biota at and near contaminated sites may be necessary for determining when areas are safe from an ecological and human health standpoint.

In North America, there are relevant case studies that detail the amount of Hg released and time taken for ecological recovery for various Hg source types. For example, in two U.S. states, New Hampshire and Massachusetts, the release of approximately 3.1 tonnes of Hg emitted in the air through waste and hospital incineration was rapidly reduced over 3 years from 1998 to 2000; then, from 2000 to 2010, average Hg concentrations of fish and birds from lakes in the immediate area significantly declined—by 50% in the first 5 years (Evers et al., 2007). The English-Wabigoon River system in western Ontario, Canada, has been monitored for >30 years to determine the recovery of Hg in biota (e.g., crayfish and fish) after the closure of a MCCA facility in 1970 (where approximately 10 tonnes of Hg were released into the river). After the release of Hg ended, Hg concentrations in sport fish declined four-fold from 1973 to 1985 (Rudd et al., 1983; Kinghorn et al., 2007). In the U.S., a textile dye production facility on the Sudbury River in Massachusetts was closed in 1978. The contaminated site was capped in 1991 and biotic Hg concentrations were monitored thereafter, and declined nearly two-fold in fish endpoints after 10 years (Haines et al., 2003). These three case studies, and others, support models that show relatively rapid initial declines of biotic Hg concentrations in some freshwater ecosystems once the source of Hg is eliminated (Harris et al., 2007b; Knightes et al., 2009).

In recognition of resource constraints, assessments are most important at sites contaminated by Hg that are associated with aquatic ecosystems, especially those with extensive wetland habitat. The selection of sites for assessing human and ecological health should emphasize areas considered to be of greatest risk due to MeHg availability and those that relate to elevated human health concerns (e.g., because of high consumption of local food items) or conservation of fish and wildlife populations of concern (e.g., species on the International Union for Conservation of Nature's Red List; Rodrigues et al., 2006). Some ecosystems, such as wetlands, are more sensitive to Hg input than others (Driscoll et al., 2007). These and other habitats are places where biological Hg hotspots can be created (Evers et al., 2007; Fig. 4); therefore, risk assessments and future spatially customized biomonitoring programs need to account for significant differences across the landscape. Sampling strategies that can encompass multiple fish species and sizes often are most cost-efficient for modeling ecological health and assessing potential dietary exposures through fish that affect human health (Wiener et al., 2012; Lepak et al., 2016).

Ultimately, the distance at which biota should be measured from a significant Hg point source will depend on the source type, transfer mechanism (i.e., air, land, or water), and proximity of sensitive ecosystems. The downstream adverse effects of point sources of Hg releases to water are known to have large footprints of impact. Jackson et al. (2011) found biotic Hg concentrations at levels of concern (e.g., impacting avian reproductive success) 150 km from a single and large Hg source on the South River in Virginia, U.S.A. Along the Peru and Ecuador border, the impacts of Hg from ASGM activities have been measured at levels of concern for fish and humans >160 km downstream (Bastos et al., 2015). Airborne point sources can have significant impacts on local downwind ecosystems and communities (Evers et al., 2007; Hutcheson et al., 2008), but also at regional or even global levels (Sunderland et al., 2009). The mixing of airborne and waterborne sources on the landscape and waterscape, often hundreds or thousands of kilometers away, creates greater challenges for monitoring and understanding ecological health and human health concerns and may require different bioindicators that relate to remote sources that may have cumulative effects.

3.2.2. Using bioindicators for cumulative effectiveness evaluation

In the long term, the effectiveness evaluation must include metrics that reflect progress on measuring the overall goal of the Convention—the long-term reduction in the amount of Hg pollution circulating globally that will lower impacts on human health and the environment. Long-term evaluation will require thoughtfully designed and coordinated local, regional, continental, and global monitoring systems that can be customized to meet the needs of individual Parties, regional interests, and global policymakers. The best approach will include a

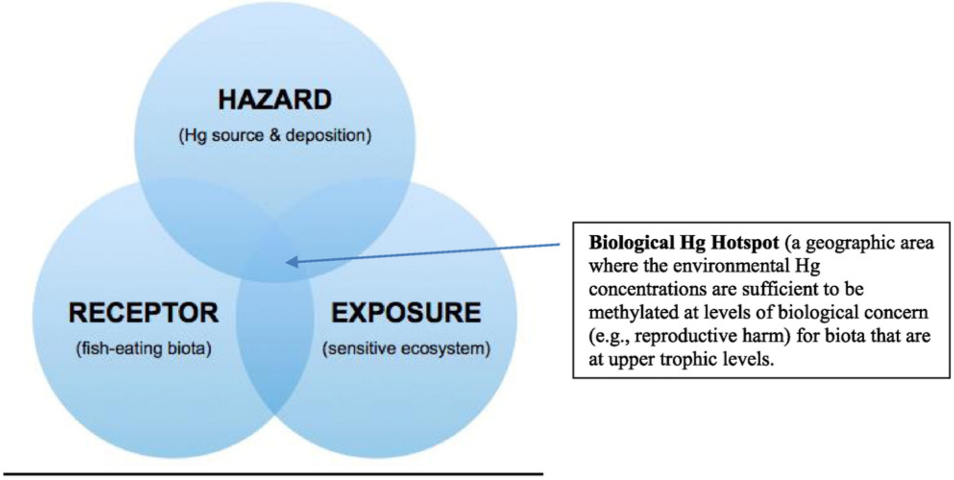

Fig. 4. A Venn diagram illustrating the critical relationships among three components of the Hg issue: (1) Hazard (magnitude of Hg source and its transport and fate); (2) Exposure (sensitivity of ecosystem to methylating Hg); and (3) Receptor (trophic level of bioindicator).

global system of monitoring air deposition in key ecosystems, coupled with monitoring of selected bioindicators.

Traditionally, pollutants are monitored through measurements of abiotic media such as air, water, and sediments. For air, several long-term annual monitoring networks are currently measuring rates of air Hg deposition; in the United States (National Atmospheric Deposition Program's Mercury Monitoring Network; Schmeltz et al., 2011); in the Canadian Arctic (Northern Contaminants Program; Steffen et al., 2005); in Asia (Asia Pacific Mercury Monitoring Network); and around the world (Global Mercury Observation System; Pirrone et al., 2013). These systems can be used and further enhanced to observe global changes in Hg deposition over time. However, because of the ephemeral traits of total Hg and MeHg in water, monitoring Hg in the water column is not useful for evaluating spatiotemporal trends in air or biota (Brigham et al., 2009). Surface sediment and soil concentrations are rarely correlated with biota concentrations as well (Drevnick et al., 2012). Therefore monitoring Hg in water and sediment is not particularly useful for evaluating the effectiveness of the Convention.

The deposition of Hg on the landscape and its movement through an ecosystem and potential methylation are strongly dependent on many biogeochemical factors that vary across terrestrial habitats (Driscoll et al., 2007; Harris et al., 2007b) and marine habitats (Mason et al., 2012). Because these factors can either dampen or enhance Hg entering an ecosystem's food web over years or even decades, fully predictive models of the relationship of Hg entering an ecosystem and its methylation and biomagnification in the food web remain elusive (Gustin et al., 2016). The often nonlinear relationship between the magnitude of Hg entering an ecosystem and biotic MeHg concentrations requires biotic monitoring components (rather than only measuring Hg in air).

Recognizing the need to use biotic endpoints, Article 22 requires the CoP to arrange for "comparable monitoring data on…levels of mercury and mercury compounds observed in biotic media and vulnerable populations." In addition, Article 19 encourages Parties to develop and improve "modeling and geographically representative monitoring of levels of mercury and mercury compounds in vulnerable populations and in environmental media, including biotic media such as fish, marine mammals, sea turtles, and birds, as well as collaboration in the collection and exchange of relevant and appropriate samples."

Initial (i.e., short-term) environmental monitoring will likely be relegated to specific locations in countries and regions that have dedicated funding sources that are not necessarily related to the Convention process, or are country-specific pilot projects to help establish baseline information and approaches that can be eventually incorporated for medium- and long-term evaluations. Pilot study information and ongoing studies will be useful to model geographic areas and landscapes to best emphasize locations for eventual long-term monitoring. More formal and standardized efforts (i.e., medium- and long-term time periods) will require guidance from the CoP.

For any of the time periods used, monitoring of Hg will require the selection of key bioindicators that can answer the necessary objectives for the ecosystems or biomes sampled. Tissue types used can reflect short-term (e.g., blood), medium-term (e.g., muscle, eggs), and long-term (e.g., feathers, fur) exposure (Evers et al., 2005; Wolfe et al., 2007). An approach for a comprehensive biomonitoring program is well-defined in North America (Mason et al., 2005; Harris et al., 2007a), with specific descriptions about wildlife indicators (Wolfe et al., 2007) and for marine ecosystems (Evers et al., 2008). An exemplary long-term biotic monitoring effort that focuses on Hg in fish, birds, marine mammals, and people is being conducted by the Arctic Council's Arctic Monitoring and Assessment Programme (AMAP, 2011).

Based on these programs as well as a large number of field studies, relevant fish and wildlife indicators of elevated Hg exposure can be confidently identified across aquatic and terrestrial ecosystems to monitor both ecological and human health concerns (see Table 7 for potential bioindicators—note, this is not a comprehensive list). Because of differing methylating abilities in ecosystems and varying home ranges of key taxa, the world's landscapes need to be divided into defined biomes to identify the best bioindicators. There are many ways to group major biomes. We recommend that long-term monitoring emphasize four terrestrial biomes that are most likely to rapidly and effectively methylate Hg: (1) tundra; (2) boreal forest and taiga; (3) temperate broadleaf and mixed forest; and (4) tropical rainforest. The methylation of Hg is greatest and most effective in aquatic-based ecosystems (Driscoll et al., 2007); therefore, associated oceans, estuaries, lakes, rivers, and wetlands (including emergent, scrub-shrub, and forested) within the four major biomes are the locations of greatest concern. Using targeted bioindicators within each of these four major biomes, long-term monitoring efforts can be built on existing monitoring systems and networks.

Other biomes, such as deserts, grasslands, and savannahs, are not included here as a priority for biomonitoring because these generally dry, soil-based ecosystems inherently lack an ability to methylate Hg and therefore the magnitude of Hg introduced into an ecosystem may be of less concern. In upland landscapes with predominately xeric soils, biotic Hg concentrations are low, irrespective of Hg source types and magnitude. For example, in Africa, fish Hg concentrations are generally well below World Health Organization and U.S. Environmental Protection Agency human health criteria (Black et al., 2011, Hannah et al., 2015). However, within these arid and semi-arid areas, pockets of wetlands and other sensitive habitats that can methylate Hg at high rates exist (Eagles-Smith et al., 2016), especially in areas with locally contaminated

Table 7
A provisional slate of some potential bioindicators for evaluating and monitoring environmental Hg loads for ecological and human health purpose in four target biomes—general taxa include those identified in Article 19 of the Minamata Convention (i.e., fish, sea turtles, birds, and marine mammals).

Target terrestrial biomes	Associated aquatic ecosystems	Ecological health bioindicators				Human and ecological health bioindicators		
		Freshwater and marine fish	Freshwater birds	Marine birds	Marine mammals & sea turtles	Freshwater fish	Marine fish	Marine mammals
Arctic tundra	Arctic Ocean and associated estuaries, lakes, rivers	Sticklebacks[1] (freshwater); Arctic Cod[2] Sculpin[3] (marine)	Loons[4,5]	Fulmars[6] Murres[6]	Polar Bears[7] Seals[8]	Arctic Char[9] Arctic Grayling[10]	Halibut[11] Cod[11]	Beluga[2, 12] Narwhal[2, 12]
Boreal forest and taiga	North Pacific and Atlantic Oceans and associated estuaries, lakes, rivers	Perch[13] (freshwater); Mummichogs[14] (marine)	Loons[15] Eagles[16] Osprey[17] Songbirds[18] (Warblers, Flycatchers, Blackbirds)	Osprey[19] Petrels[20]	Mink[21,22] Otter[21,22] Seals[23]	Catfish[11] Pike[10] Sauger[10] Walleye[10]	Flounder[11] Snapper[11] Tuna[11]	Pilot Whale[24]
Temperate broadleaf and mixed forest	North Pacific and Atlantic Oceans, Mediterranean and Caribbean Seas, and associated estuaries, lakes rivers	Perch[13] (freshwater); Mummichogs[14] Rockfish[11] Sticklebacks[25] (marine)	Loons[4] Grebes[5,26] Egrets[27] Herons[27] Osprey[17] Terns[26] Songbirds[18] (Warblers, Flycatchers, Wrens, Blackbirds, Sparrows)	Cormorants[28] Osprey[5,19] Terns[26,28]	Otter[21,22] Sea Turtles[29] Seals[23]	Bass[10,30,31] Bream[11] Mullet[11] Walleye[31]	Barracuda[11] Mackerel[11] Mullet[11] Scabbard-fish[11] Sharks[11,32] Tuna[11,32]	
Tropical rainforest	South Pacific and South Atlantic and Indian Oceans and associated estuaries, lakes, rivers	Catfish[23] Piranha[34] Snook[11] (freshwater); Bay Snook[11,34] (marine)	Egrets[27] Herons[27] Kingfishers[35] Songbirds[36] (Wrens, Thrushes, Flycatchers)	Albatrosses[37,38] Noddy[39] Shearwaters[39] Terns[39] Tropicbirds[39]	Otter[40] Sea Turtles[29] Seals[41]	Catfish[11] Snakehead[11]	Barracuda[11] Grouper[42] Sharks[43,44] Snapper[11] Swordfish[11,45] Tuna[11,45]	

[1]Kenney et al. (2014), [2]AMAP (2011), [3]Rigét et al. (2007), [4]Evers et al. (2014), [5]Jackson et al. (2016), [6]Braune (2007), [7]Rush et al. (2008), [8]Dietz et al. (2013), [9]Gantner et al. (2010), [10]Eagles-Smith et al. (2016), [11]Evers et al. (2016), [12]Wagemann and Kozlowska (2005), [13]Wiener et al. (2012), [14]Weis and Kahn (1990), [15]Evers et al. (2011), [16]Bowerman et al. (1994), [17]Odsjö et al. (2004), [18]Jackson et al. (2015), [19]Wiemeyer et al. (1988), [20]Goodale et al. (2008), [21]Yates et al. (2005), [22]Klenavic et al. (2008), [23]Brookens et al. (2008), [24]Dam and Bloch (2000), [25]Eagles-Smith and Ackerman (2009), [26]Ackerman et al. (2016), [27]Frederick et al. (2002), [28]Braune, (1987), [29]Day et al. (2005), [30]Kamman et al. (2015), [31]Monson et al. (2008), [32]Cai et al. (2007), [33]Bastos et al. (2015), [34]Mol et al. (2001), [35]Lane et al. (2013), [36]Townsend et al. (2013), [37]Finkelstein et al. (2006), [38]Burger and Gochfeld (2000), [39]Kojadinovic et al. (2007), [40]Fonseca et al. (2005), [41]Marcovecchio et al. (1994), [42]Evers et al. (2009), [43]Kiszka et al. (2015), [44]Maz-Courrau et al. (2012), [45]Storelli and Marcotrigiano (2001).

sites (e.g., Walker Lake, Nevada, USA; Seiler et al., 2004). Antarctic ecosystems generally appear not to have Hg concentrations in upper trophic level taxa (e.g., penguins and seals) that are of significant biological concern (Carravieri et al., 2013) and may not be experiencing the increasing environmental Hg loads observed in the northern hemisphere (Braune, 2007), based on penguin Hg concentrations over time (Scheifler et al., 2005).

3.2.3. *Using human Hg exposure metrics to evaluate convention effectiveness*

For most of the general human population, dietary exposure is the primary source of Hg exposure. Food items of concern for human health include shellfish (Nakagawa et al., 1997), freshwater fish (Wiener et al., 2012), marine fish (Sunderland, 2007), marine mammals (AMAP, 2011), and, to a far lesser extent, rice (Zhang et al., 2010; Rothenberg et al., 2014; Fig. 5). Pregnant women and neonates are considered most sensitive to the neurological effects of Hg (Oken et al., 2005); and, there is evidence that effects are lasting into adult ages (Debes et al., 2016). Additionally, a growing body of evidence has revealed that all individuals are potentially at risk, with newer studies showing associations between low-level exposure and subclinical changes in cardiovascular and immunological health (Karagas et al., 2012).

To evaluate changes for general human population-level exposure, we recommend coupling two monitoring approaches. First, develop a comprehensive system for monitoring changes in seafood concentrations in species that are consumed by humans. Seafood Hg data can then inform dietary surveys to estimate individual and population-level MeHg exposures. The approaches can extend beyond seafood to evaluate exposures via other sources (e.g., rice, river turtles, marine mammals) that are of local nutritional and cultural relevance. Dietary surveys on the type, amount, and frequency of target foods consumed over a defined time period will be required to compare trends over geographic and temporal scales.

Second, human biomonitoring in high risk and/or representative populations can be used to track changes in exposure, and thus represents a powerful and potentially cost-effective tool to track the effectiveness of the Convention in terms of gauging changes over time and space. Human biomonitoring is an exposure assessment method in which chemicals of interest are characterized in human specimens. Accepted biomarkers of Hg exposure include hair (for MeHg), urine (for inorganic Hg), and blood (mostly MeHg but can contain inorganic Hg). Hair and urine samples are particularly suitable as they provide information on the two main forms of Hg, and their collection is relatively noninvasive, requires no specialized training, and is relatively inexpensive (e.g., sampling and analyses can likely be done for $50 USD or less per item). Furthermore, hair grows at approximately 1 cm per month and thus Hg measurements can be tracked over time. National biomonitoring programs (for many chemicals including Hg) are established in many countries including the U.S. (via National Health and Nutrition Examination Survey; NHANES), Canada (via Canadian Health Measures Survey), Germany (via Human Biomonitoring Commission), and Korea (via Korea National Health and Nutrition Examination Survey). The results from these programs have enabled countries to establish baselines and reference ranges (at the national and regional level), help set priorities, take action, and track changes over time as part of surveillance efforts.

For example, in the U.S., NHANES program findings demonstrate a decrease in blood Hg concentrations between 1999 and 2010 (Birch et al., 2014). Besides national monitoring programs, there have been several studies worldwide documenting human exposures to Hg. The review by Sheehan et al. (2014) is noteworthy in its systematic coverage of literature to identify 3042 articles, from which 164 were prioritized for deeper investigation, to understand Hg exposures among women and infants across the world. The development of biomonitoring programs in low- and middle-income countries may be challenging, though there exist large-scale demographic surveillance programs (e.g., U.S. Agency for International Development's Demographic and Health Survey) that are now beginning to collect biospecimens that could potentially be used to document exposure to Hg.

In addition to gauging general population exposures, efforts may also focus on tracking occupational exposure (Fig. 5) given that several of the Convention Articles target specific industries (as discussed earlier in Section 3.1). Industrial activities generally involve the use of inorganic forms of Hg (Hg^0, Hg^{2+}, Hg^{1+}), and exposures can be gauged through atmospheric workplace monitoring and urinary measurements. The effectiveness of the Convention may also be tracked by documenting reductions in workplace exposures. Two relevant examples of workplace exposure include: (1) the reduced Hg exposure among American dental professionals, where members of the American Dental Association has shown a nearly 10-fold decrease of mean urinary Hg concentrations between 1975 and 2012 (Goodrich et al., 2015) and (2) the exposure and health of individuals working within ASGM communities (Gibb and O'Leary, 2014). In ASGM communities, exposure could be both occupational and environmental (Ashe, 2012).

3.3. Recommended next steps for monitoring

The Minamata Convention recognizes the need for international cooperation to confront the substantial global problem of Hg pollution. The evaluation of the effectiveness of the Convention will require worldwide cooperation and coordination in collecting and analyzing a wide range of information to assess impacts of Convention measures in the short, medium, and long term. To facilitate such cooperation, we recommend that the CoP create consistent and comprehensive data collection systems to best structure information needed to support effectiveness evaluation. Data reported by Parties under Article 21 will provide information to track effectiveness in the short term, but the Convention does not provide specific guidance on content and format. Thus, the CoP should formulate clear guidance for these data and any other information routinely collected and related to implementation of the Convention measures to support the effectiveness evaluation.

Similarly, to guide Parties and other stakeholders to support a comprehensive system of coordinated global monitoring of environmental and biological receptors (including humans), we recommend the development of a technical document that explains measuring and monitoring Hg (i.e., how, where, what, and why) that can be used as a platform for decision making. The development of a scientifically sound strategy, based on transparent processes, harmonized methodologies, and reliable and comparable existing data (both abiotic and biotic) is critical. Country-specific Hg inventories generated through MIAs, NAPs, and other means will be increasingly important to facilitate the effectiveness evaluation and assure data quality and comparability.

Ultimately, the creation of such a science-based guidance document could describe how Parties design, implement and/or participate in new or existing monitoring networks, best report on findings, and meet compliance requirements set by the CoP. A technical document that describes monitoring and measuring Hg could be supported with: (1) a standardized and comprehensive database made available to Parties (e.g., through UNEP Live); (2) a group of scientists and policymakers who can serve as advisors to the CoP; (3) a peer-reviewed scientific platform of information that can be translated for policy purposes; and (4) a demonstrated model for training local field biologists and lab technicians that will ultimately build regional capacity and independence. Iterative efforts to link realistic and applied biomonitoring efforts at local levels with science groups dedicated toward assisting the CoP will help keep pace with the many emerging scientific findings that may fill existing information gaps that are important for global policymaking (Selin, 2014; Gustin et al., 2016). While there are many countries across the Western Hemisphere, Europe, Africa, and Asia that generate and publish empirical findings about Hg biomonitoring, more needs to be accomplished to build local and regional confidence in decision making.

Based on an existing global Hg dataset called the Global Biotic Mercury Synthesis (GBMS), generated under the Global Mercury Partnership (UNEP, 2013c), patterns of biotic Hg are being realized (Evers et al., 2016). Areas that we predict will be key for biomonitoring and building larger data sets (e.g., where there is the nexus of high methylation abilities and dependence by people for local food) encompass coastal marine ecosystems, such as estuaries and river deltas, from the tropics (Costa et al., 2012) to the Arctic (Chételat et al., 2015; Schartup et al., 2015). There is a critical knowledge gap in our understanding of

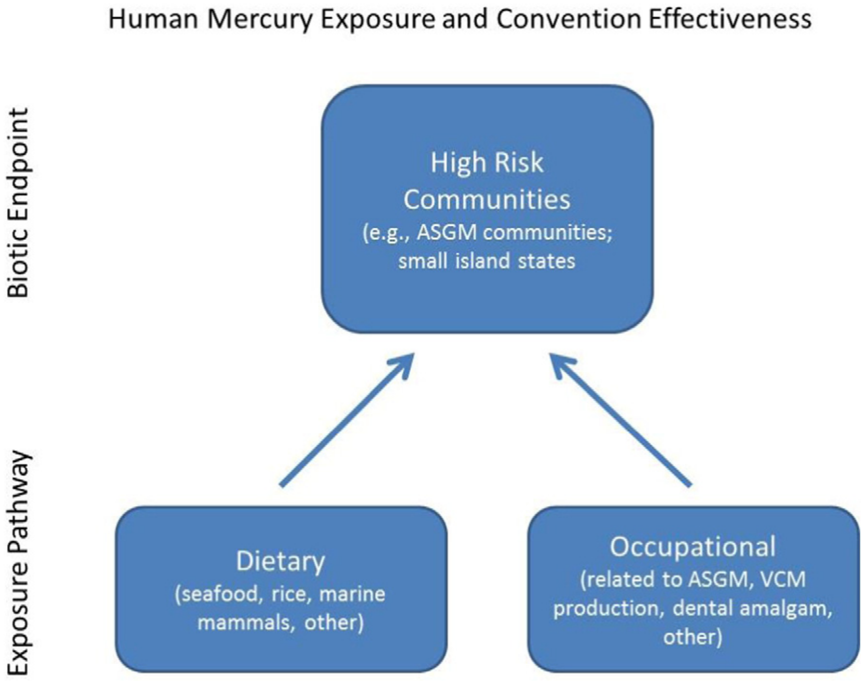

Fig. 5. Interaction of high-risk communities of people with either dietary or occupational exposure.

how the release of Hg from ASGM activities will influence Hg exposure in fish, wildlife, and humans in sensitive tropical ecosystems of Central and South America.

To supplement this approach at the global level, regional science/policy/management groups can be created to customize implementation at finer or regional geographical scales that are more relevant from a scientific and policy standpoint. Temporal trends and spatial gradients (including the identification of biological Hg hotspots) could be generated through modeling efforts at regional levels and ultimately could help with prioritizing the use of limited resources toward biomonitoring at biological Hg hotspots and therefore evaluating the effectiveness of the Minamata Convention in the most confident and long term manner.

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