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Research article

Economic implications of mercury exposure in the context of the global mercury treaty: Hair mercury levels and estimated lost economic productivity in selected developing countries

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ABSTRACT

Several developing countries have limited or no information about exposures near anthropogenic mercury sources and no studies have quantified costs of mercury pollution or economic benefits to mercury pollution prevention in these countries. In this study, we present data on mercury concentrations in human hair from subpopulations in developing countries most likely to benefit from the implementation of the Minamata Convention on Mercury. These data are then used to estimate economic costs of mercury exposure in these communities. Hair samples were collected from sites located in 15 countries. We used a linear dose-response relationship that previously identified a 0.18 IQ point decrement per part per million (ppm) increase in hair mercury, and modeled a base case scenario assuming a reference level of 1 ppm, and a second scenario assuming no reference level. We then estimated the corresponding increases in intellectual disability and lost Disability-Adjusted Life Years (DALY). A total of 236 participants provided hair samples for analysis, with an estimated population at risk of mercury exposure near the 15 sites of 11,302,582. Average mercury levels were in the range of 0.48 ppm–4.60 ppm, and 61% of all participants had hair mercury concentrations greater than 1 ppm, the level that approximately corresponds to the USA EPA reference dose. An additional 1310 cases of intellectual disability attributable to mercury exposure were identified annually (4110 assuming no reference level), resulting in 16,501 lost DALYs (51,809 assuming no reference level). A total of \$77.4 million in lost economic productivity was estimated assuming a 1 ppm reference level and \$130 million if no reference level was used. We conclude that significant mercury exposures occur in developing and transition country communities near sources named in the Minamata Convention, and our estimates suggest that a large economic burden could be avoided by timely implementation of measures to prevent mercury exposures.

1. Introduction

Industrialization and increases in energy demand have produced rapid increases in anthropogenic mercury (Hg) emissions. Coal-fired power plants and artisanal and small scale gold mining (ASGM) are leading sources of Hg emissions, accounting for more than 50% of all global emissions to the atmosphere (Global Mercury Assessment, 2013). In addition to emissions into the atmosphere,

Abbreviations: ASGM, Artisanal small-scale gold mining; DALY, Disability-Adjusted Life Years; EPA, Environmental Protection Agency; GDP, Gross Domestic Product; IQ, intellectual quotient; LMICs, Low- and middle-income countries; Hg, Mercury; PPP, Purchasing power parity; UNEP, United Nations Environment Programme.

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significant releases of Hg directly into the environment occur from a variety of sources including ASGM, chlor-alkali facilities and other industrial sites. Elemental Hg is converted to inorganic forms in the atmosphere and eventually deposited onto land and in water. Once Hg enters aquatic ecosystems, it can be transformed to an organic form, methylmercury (MeHg) (Guimaraes et al., 2000), a potent neurotoxicant (National Research Council, 2000), especially to the developing brain. It biomagnifies in the aquatic food chains, especially in marine predatory fish at the top of the food chain such as swordfish, tuna, and king mackerel (Dietz et al., 2000; Neumann and Ward, 1999; Trasande et al., 2010). Human exposure to mercury occurs primarily via the consumption of contaminated fish (Trasande et al., 2005), although rice (Feng et al., 2008; Zhang et al., 2010) and even direct exposure to mercury vapor (Global Mercury Assessment, 2013) can be locally significant pathways. There is a robust literature on the human health effects of mercury exposure.

In multiple longitudinal studies prenatal exposure to methylmercury has been documented to produce extreme fetal abnormalities and significant decrements in neurological and cognitive outcomes, independent of confounding factors, including fish consumption (Grandjean et al., 1997; Kjellstrom et al., 1986, 1989; Oken et al., 2005). Available data suggests that moderate exposure to Hg can be associated with decrements in memory, attention, language development, and visual motor skills (National Research Council, 2000). Recent research also suggests that low levels of Hg exposure can impact the cardiovascular and immune systems in both children and adults (Karagas et al., 2012). Increased awareness about the negative impacts of Hg exposure on both human health and the environment motivated the international community to develop a new global, legally binding treaty on mercury, the Minamata Convention on Mercury (United Nations Environment Programme, 2013a). The treaty represents a global consensus that mercury poses a threat to human health and environment and that global action is required. Key anthropogenic sources of mercury air emissions covered by the treaty include ASGM, coal combustion, production of non-ferrous metals, cement manufacturing, large-scale gold mining, consumer product waste, contaminated sites, and chlor-alkali plants (United Nations Environment Programme, 2013a).

Knowledge of pollution sources, accompanying exposures, and information on the cost of inaction can be key drivers for promoting chemicals management and treaty implementation into national policies (United Nations Environment Programme, 2013b). However, many developing countries and countries with economies in transition have limited or no information about exposures near anthropogenic mercury sources or estimates of the economic impacts of mercury pollution.

Previous estimates of economic impacts of mercury exposure in developed countries show substantial economic costs, especially in terms of lost economic productivity. In the United States, these costs totaled $5.1 billion in 2008 (Trasande and Liu, 2011), while in the European Union losses of up to €9 billion ($11.9 billion) have been identified (Bellanger et al., 2013). Pacyna et al. have estimated that global lost economic productivity from mercury pollution could reach $29.4 billion in 2020 (Pacyna et al., 2008). Studies have also suggested substantial economic benefits to mercury pollution prevention in the US and globally (Sundseth et al., 2010; Trasande et al., 2006). Yet, no studies have quantified costs of mercury pollution or economic benefits to mercury pollution prevention in developing and transition countries, which would inform implementation of the global mercury treaty.

In this study, we analyzed hair samples from exposed subpopulations in developing countries most likely to benefit from treaty implementation, and estimated economic costs related to mercury exposure in these communities.

2. Methods

2.1. Site selection

Mercury sources listed in the Minamata Convention provided a guide to the selection of sites. Listed sources in this study include chlor-alkali plants (Article 5); artisanal small-scale gold mining (ASGM) (Article 7); coal-fired power plants, waste incineration, non-ferrous metal smelting, and cement plants (Article 8); wastes (Article 11); and contaminated sites (Article 12). The United Nations Environment Programme (UNEP) inventory of mercury sources includes large-scale gold mining as a source of global mercury emissions to air. Several sites with mixed sources were included in the study since these represent the reality of emission sources encountered in most countries. Finally, one Small Island Developing State without industrial sources was included to reflect mercury sources from global deposition.

2.2. ASGM sites

ASGM sites are primary contributing mercury sources at sites in Indonesia, Kenya, and Tanzania. In Indonesia, samples were collected near two ASGM sites. Sekotong is a large site with more than 35,000 miners and more than 200 ball mill plants. Poboya contains approximately 5000 miners and 100 ball mill plants. Miners at both sites amalgamate gold using mercury, then burn off the mercury to leave the gold. Processing occurs in the backyards of residences or near rice fields. The miners process contaminated tailings further using cyanide leaching or dump wastes directly into rivers. In Kenya, the ASGM sites are located in Masara in the Mogori District. At peak mining times, more than 20,000 miners work in the area using mercury to amalgamate gold and then wastes are dumped in rivers that serve as main food sources for the surrounding communities. The Tanzanian ASGM sites are in Matundasi and Makongolosi. Mercury is used to amalgamate gold, and then burned off. The wastes along with water used for sluicing end up in the Lupa River which flows into Lake Rukwa, an important support for livelihoods in southern Tanzania and located on the border of an Ugandan game reserve.

2.3. Chlor-alkali plant sites

Current or former chlor-alkali plants are a primary contributing mercury source at study sites located in Albania, India, Russia, and Uruguay. In Albania, a currently abandoned chlor-alkali and PVC plant operated from 1967 to 1992 using mercury-cell technology. The factory discharged mercury-containing waste directly into Vlora Bay and dumped polluted sludge by the seashore. Vlora Bay is an important fishing area and fish from the area are distributed to all cities in Albania. The former Vlora Bay facility is currently a contaminated site. The chlor-alkali plant in India is located in Ganjam Province in the state of Orissa. The plant utilized mercury cell technology from 1967 to 2011 and discharged wastes into the nearby estuary which supplies fish to the surrounding communities. The chlor-alkali plant in Volgograd, Russia uses both mercury cell technology and diaphragm processes. Mercury-containing wastes are discharged into local waterways and also stored in drums outside the plant. Mercury is also released during incineration of mercury-containing lamps. In Uruguay, the chlor-alkali plant using mercury cell technology is located in San Jose province near the mouth of the Santa Lucia River. The river is a principal waterway in Uruguay that feeds into the large Rio de la Plata which runs between Argentina and Uruguay and serves as an important fishing area.

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2.4. Mixed use sites

Sites that contain an assortment of mercury sources reflect a common reality in many countries. In this study, more than one likely source of mercury occurs at the sites in Bangladesh, Belarus, Cameroon, Mexico, Nepal, and Sri Lanka. The Bangladesh sites are located in Dhaka and include a hazardous waste landfill and high capacity cement kilns. The landfill is situated close to a river and residential area and contains a mixture of industrial, medical, and municipal waste. The cement kilns are also located along a river with a combined production capacity of 7400 MT per day. In Minsk, Belarus, the Academy of Science identified mercury sources including incineration, cement production, and metal smelting. These facilities are located in industrial and urban areas in the Svisloch River valley, which runs through the city. Douala, Cameroon, is a large city with a dense industrial center containing a cement plant, waste incinerator, polyurethane production, metal recycling, and various dumpsites. These facilities in the city are located next to the Wouri River, a major location for fishing. The sites in Mexico are in the Coatzacoalcos – Minatitlan area and include a chlor-alkali plant and burning of vinyl chloride monomer wastes in incinerators located within a large petrochemical complex. The area also contains a large oil and gas refinery which was upgraded in 2011 to process 350,000 barrels a day of crude oil. These facilities are located along the Coatzacoalcos River which flows into the Gulf of Mexico. Pokhara is the second largest city in Nepal and many industries drain into Phewa Lake, an important source of fish. Mercury sources are not well-characterized except for mercury-containing medical products, thermometer breakage, and mercury spills. In Sri Lanka, the Negombo lagoon area is the destination of waste from industrial zones and garbage dumps.

2.5. Coal fired power plant site

The Tha Tum site in Thailand contains 75 factories including a coal fired power plant consuming 900,000 tons/year of coal. The Shalongwaeng canal runs adjacent to the plant near open-air storage of coal and fly ash from the power plant. The community commonly eats fish from the canal.

2.6. Global deposition site

The Cook Islands are located in the South Pacific and do not contain any obvious possible point sources of mercury. Instead, mercury in fish results from atmospheric deposition. Samples were taken in the Ngatangiia village area of Raratonga.

2.7. Hair sample collection and analysis

A standardized hair sampling protocol for all countries was developed to ensure samples were collected in a uniform fashion. Public interest organizations participating in the IPEN network collected hair samples. Little to no notice was given to possible participants about the sampling (a few days at most) and no information was provided about how to possibly raise or lower their mercury content before the sample was collected. More complete information was provided at the sampling itself. A single representative from the public interest organization in each country collected hair samples. A small bunch of hair was cut from the occipital region of the head using stainless steel scissors and tied with unwaxed dental floss to mark the proximal end. Samples were shipped by expedited international shipping to Biodiversity Research Institute's Mercury Research Laboratory for analysis in the US. Samples were analyzed on a Milestone DMA 890, using U.S. EPA SW-846 Method 7473. Two samples from Cameroon and two samples from Tanzania were excluded from the data analysis as outliers since they were the only samples with extremely high mercury concentrations of over 200 ppm, considered to be likely compromised by external mercury contamination. The age ranges and gender ratio of the participants is described in Table 1. Participants were informed of their results in writing in the local language by the relevant public interest organization.

2.8. Ethics

Dr. Trasande's participation in this project represented non-human subjects research as per 45 CFR 43, as documented by completion of and signature on an NYU School of Medicine Institutional Review Board attestation form. Biodiversity Research Institute obtained IRB approval for the analysis of mercury concentrations in human hair from the University of Southern Maine's Office of Research Integrity and Outreach (IRB 020912-04).

2.9. Estimation of lost IQ

Mercury values were first log-transformed and the average and standard deviation of the log-transformed mercury concentration across samples from each location were calculated. These values were used to estimate the percentage of the population within specific ranges (<0.5, 0.5–1, 1–2, 2–4, 4–8, 8–16 and >16) using the LOGNORMDIST function in Excel (Microsoft Corp., Redmond, WA, USA). We assumed that the group with levels <0.5 had no mercury exposure, and that the population in each range had a concentration corresponding to the lower end of the range (e.g., 0.5 for the population in the range 0.5–1). Hair mercury levels in these adults were modeled on the premise that their distribution would be similar in pregnant women, resulting in fetal exposure and subsequent child IQ loss.

We used linear dose-response relationships from an integrative analysis by Axelrad and colleagues, who identified a 0.18 IQ point decrement per ppm increase in hair mercury (Axelrad et al., 2007). We modeled two scenarios, a base case scenario assuming a reference level of 1 ppm, and a second scenario assuming no reference level. These steps produced IQ losses across proportions of the populations of births in 2010, which were then multiplied by births as they were estimated to occur in 2010.

Births for the appropriate area were calculated by multiplying the birth rate for the specific country (World Bank data) (World Bank, 2014) by the estimated population at risk. Population

Table 1
Demographic characteristics of study participants.

Country	n	Ratio male/female	Age range (years)	Average age (years)
Albania	15	2/13	21–75	44
Bangladesh	15	8/7	25–65	47
Belarus	11	5/6	22–60	42
Cameroon[a]	17	7/10	18–65	26
Cook Islands	9	3/6	56–75	65
India	17	15/2	19–58	32
Indonesia	20	9/11	18–57	32
Kenya	7	3/4	21–70	36
Mexico	22	12/10	21–85	47
Nepal[b]	15	7/6	25–62	37
Russia	28	9/19	20–64	38
Sri Lanka[c]	16	6/9	19–79	42
Tanzania[a]	14	14/0	16–38	25
Thailand	20	13/7	18–72	47
Uruguay	10	5/5	19–59	44

[a] Two samples with extremely high values were excluded from the calculations.
[b] Personal data available for 13 individuals.
[c] Personal data available for 15 individuals.

values were obtained from census data for relevant locations in Albania (Vlora, 79,948) (Albania, 2011), Bangladesh (areas of Dhaka including Hazaribagh, Gazaria, Matlab, and Munshiganj, 1,999,337) (Bangladesh, 2011a, 2011b), Belarus (Minsk, 1,885,067) (Belarus, 2011), Cameroon (Douala, 1,907,479) (Cameroon, 2011), Cook Islands (14,974) (Cook Islands, 2011), India (Ganjam, 3,524,451) (India, 2011), Indonesia (Poboya, 19,255, and Sekotong 49,858) (Indonesia, 2011), Kenya (Nyatike District in Migori, 563,033) (Kenya, 2011), Mexico (Coatzacoalcos, Minatitlan, and Ixhuatlan del Sureste, 478,003) (Mexico, 2011a, 2011b, 2011c), Nepal (Pokhara, 300,000) (Nepal, 2011), Russia (Krasnoarmeyskaya District and Raygorod, 174,950) (Russia, 2011a, 2011b), Sri Lanka (Negombo, 144,551) (Sri Lanka, 2011), Tanzania (Chunya District, 206,615) (Tanzania, 2011a, 2011b), Thailand (Tha Tum, 14,769) (Thailand, 2011), and Uruguay (Delta de Tigre y Villas, 20,240) (Uruguay, 2011).

2.10. Increases in intellectual disability and lost Disability-Adjusted Life Years (DALY)

Assuming that IQ is normally distributed with a mean of 100 and standard deviation of 15, shifts in IQ were modeled in each proportion of the population to estimate increases in IQ < 70 (intellectual disability). The percentage increase in intellectual disability was aggregated and multiplied by the births for the appropriate area. For each case of intellectual disability, a 0.36 disability weight was applied, following the approach used in the Global Burden of Disease (World Health Organization, 2008) project for mild intellectual disability, and multiplied for thirty-five years, representing a conservative estimate of the lifespan during which that disability would be experienced.

2.11. Economic analysis

Following approaches taken by previous authors (Attina and Trasande, 2013; Bellanger et al., 2013; Trasande and Liu, 2011) each IQ point was valued at $19,269 2010 US dollars, updating the estimate by Gould (Gould, 2009) from 2005 dollars using the US General Consumer Price Index (US Department of Labor, 2014). The $19,269 value was then multiplied by the ratio of each country's Purchasing Power Parity (PPP) adjusted per-capita Gross Domestic Product (GDP), available from Eurostat (Eurostat, 2012) to that of the US to produce a country-specific estimate of the value of an IQ point that accounts for differences in GDP. Finally, the country-specific value of an IQ point was then multiplied by the IQ points lost.

DALY losses due to intellectual disability were valued at $50,000 and multiplied by the ratio of each country's Purchasing Power Parity (PPP) adjusted per-capita GDP (Eurostat, 2012) to that of the US, using the same procedure described above.

3. Results

3.1. Sampling sites

Sites in 15 countries represented a variety of mercury sources listed in the mercury treaty including chlor-alkali plants, ASGM, coal-fired power plants, waste incineration, non-ferrous metal smelting, cement plants, wastes, and contaminated sites. One Pacific Island country without industrial sources was included to reflect mercury sources from global deposition. Country locations of the sites included Albania, Bangladesh, Belarus, Cameroon, Cook Islands, India, Indonesia, Kenya, Mexico, Nepal, Russia, Sri Lanka, Tanzania, Thailand, and Uruguay. More information about the sites

Table 2
Mercury levels in human hair from sites in 15 countries.

Country	Relevant mercury source(s) at site	n	Range (ppm)	No. samples >0.58 ppm (%)[a]	Average mercury concentration (ppm ± SD)
Albania	Contaminated site from former chlor-alkali plant	15	0.14–2.06	4 (27%)	0.54 ± 0.53
Bangladesh	Mixed sources including wastes and cement kilns	15	0.20–2.68	6 (40%)	0.67 ± 0.60
Belarus	Mixed sources including incineration, cement kilns, and metal smelting	11	0.16–2.44	4 (36%)	0.64 ± 0.78
Cameroon[b]	Mixed sources including cement kiln, waste incineration, polyurethane production, metal recycling, and various dumpsites	17	0.90–3.77	17 (100%)	1.93 ± 1.07
Cook Islands	Non-point sources/global deposition	9	0.94–5.00	9 (100%)	3.29 ± 1.37
India	Chlor-alkali plant	17	0.05–0.73	4 (24%)	0.48 ± 0.20
Indonesia	Artisanal small-scale gold mining	20	0.82–13.30	20 (100%)	4.32 ± 3.28
Kenya	Artisanal small-scale gold mining	7	0.82–5.63	5 (71%)	1.35 ± 1.92
Mexico	Mixed sources including incineration, oil and gas refinery, chlor-alkali plant	22	0.29–4.32	20 (91%)	1.75 ± 1.07
Nepal	Mixed sources including wastes	15	0.34–1.72	13 (87%)	1.06 ± 0.39
Russia	Chlor-alkali plant	28	0.00–5.47	23 (82%)	1.93 ± 1.51
Sri Lanka	Mixed sources including wastes	16	0.78–4.45	16 (100%)	2.00 ± 1.25
Tanzania[b]	Artisanal small-scale gold mining	14	0.42–13.15	9 (64%)	2.74 ± 3.43
Thailand	Coal-fired power plant	20	1.63–12.76	20 (100%)	4.60 ± 2.69
Uruguay	Chlor-alkali plant	10	0.05–2.09	2 (20%)	0.48 ± 0.77

[a] Percentage of the total number of samples with mercury levels >0.58 ppm.
[b] Two samples with extremely high values were excluded from the calculations.

is provided in Materials and Methods. The estimated population at risk of mercury exposure near these 15 sites was 11,302,582.

3.2. Participants

A total of 236 people from 15 countries provided hair samples for analysis. Gender ratios varied at each site but the overall ratio of male to female participants was 1.03. Ages ranged from the late teens to mid-eighties with an overall average age of 40.

3.3. Mercury levels in hair

Mercury levels in the hair of community participants across all sites and countries ranged up to 13.30 ppm (Table 2). Average mercury levels ranged from 0.48 ppm–4.60 ppm. Sixty-one percent of all the participants had hair mercury concentrations greater than 1 ppm, the level that approximately corresponds to the USA EPA reference dose (Rice et al., 2003). Updated calculations of this value have led to limit value of 0.58 ppm (Bellanger et al., 2013; Grandjean and Budtz-Jorgensen, 2007). Seventy-three percent of the participants had mercury hair levels equal to or greater than 0.58 ppm.

All the sites contained some fraction of participants with hair mercury levels greater than 0.58 ppm ranging from 20% to 100%. Average mercury concentrations above 0.58 ppm were observed in participants near 12 sites (81%) including Bangladesh, Belarus, Cameroon, Cook Islands, Indonesia, Kenya, Mexico, Nepal, Russia, Sri Lanka, Tanzania, and Thailand.

3.4. Estimates of cognitive loss, intellectual disability and social costs

Table 3 presents the 262,230 births estimated to occur annually in each of the 15 contaminated areas. Applying a 1 ppm reference level, 72,160 IQ points are lost, whereas 107,228 are lost in the scenario without a reference level. An additional 1310 cases of intellectual disability are identified annually (4110 assuming no reference level), resulting in 16,501 lost DALYs (51,809 assuming no reference level). A total of $77.4 million in lost economic productivity was identified, which is an annual cost insofar as exposures persist at similar levels ($130 million assuming no reference level). Lost DALYs, assuming a $50,000 value before correction for country GDP, also cost an additional $46.1 million ($149 million if no reference level is assumed).

4. Discussion

The Minamata Convention on Mercury targets a variety of anthropogenic mercury sources including emissions and releases from chlor-alkali plants, ASGM, coal-fired power plants, waste incineration, non-ferrous metal smelting, cement plants, wastes, and contaminated sites. Measurements of residents in communities near these sources revealed significant mercury exposures, with average levels above 0.58 ppm in 73% of the participants at 12 sites located in Bangladesh, Belarus, Cameroon, Cook Islands, Indonesia, Kenya, Mexico, Nepal, Russia, Sri Lanka, Tanzania, and Thailand. These sites represent a variety of mercury sources including wastes, cement kilns, incineration, metal smelters, chlor-

Table 3
Populations affected, estimated loss of IQ, increase in intellectual disability, lost disability adjusted life years and costs.

Country	Relevant mercury source(s) at site	Estimated no. of births	IQ points lost, reference level of 1 ppm (no reference level)	Annual lost economic productivity, 2010 $, reference level of 1 ppm (no reference level)	Additional cases of intellectual disability, reference level 1 ppm (no reference level)	DALY loss, reference level 1 ppm (no reference level)	Annual cost of DALYs, 2010 $, reference level 1 ppm (no reference level)
Albania	Contaminated site from former chlor-alkali plant	1039	5 (53)	$16,400 ($191,000)	0 (0)	0 (0)	$0
Bangladesh	Mixed sources including wastes and cement kilns	39,987	146 (2739)	$102,000 ($1,920,000)	3 (10)	37 (126)	$67,100 ($228,000)
Belarus	Mixed sources including incineration, cement kilns, and metal smelting	22,621	552 (1837)	$3,310,000 ($11,000,000)	10 (46)	130 (579)	$2,020,000 ($9,010,000)
Cameroon	Mixed sources including cement kiln, waste incineration, polyurethane production, metal recycling, and various dumpsites	68,669	60,952 (80,025)	$54,700,000 ($71,800, 000)	1105 (3362)	13,928 (42,358)	$32,400,000 ($98,600,000)
Cook Islands	Non-point sources/global deposition	210	56 (114)	$699,000 ($1,420,000)	1 (3)	13 (37)	$416,000 ($1,190,000)
India	Chlor-alkali plant	77,538	191 (3785)	$297,000 ($5,880,000)	4 (84)	52 (1056)	$209,000 ($4,250,000)
Indonesia	Artisanal small-scale gold mining	1244	520 (885)	$961,000 ($1,630,000)	9 (26)	115 (327)	$550,000 ($1,570,000)
Kenya	Artisanal small-scale gold mining	20,832	2521 (4942)	$1,710,109 ($3,350,000)	45 (149)	570 (1874)	$1,000,000 ($3,300,000)
Mexico	Mixed sources including incineration, oil and gas refinery, chlor-alkali plant	9082	803 (2459)	$5,150,072 ($5,150,000)	15 (60)	195 (750)	$3,250,000 ($12,500,000)
Nepal	Mixed sources including wastes	7200	67 (1018)	$37,600 ($572,000)	1 (23)	19 (287)	$27,200 ($418,000)
Russia	Chlor-alkali plant	2274	699 (1090)	$6,270,000 ($9,790,000)	13 (38)	158 (484)	$3,670,000 ($11,300,000)
Sri Lanka	Mixed sources including wastes	2602	268 (792)	$600,000 ($1,770,000)	5 (19)	66 (241)	$382,000 ($1,400,000)
Tanzania	Artisanal small-scale gold mining	8471	5300 (7344)	$3,200,000 ($4,400,000)	95 (289)	1203 (3644)	$1,880,000 ($5,710,000)
Thailand	Coal-fired power plant	177	77 (133)	$278,000 ($480,000)	1 (4)	17 (46)	$157,000 ($431,000)
Uruguay	Chlor-alkali plant	283	3 (13)	$19,300 ($76,700)	0 (0)	0 (0)	$0 ($0)
Total		**262,230**	**72,160 (107,228)**	**$77.4 million ($130 million)**	**1310 (4110)**	**16,501 (51,809)**	**$46.1 million ($149 million)**

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alkali plants, ASGM, and oil and gas refining. The three highest average mercury levels were measured near a coal-fired power plant (Thailand), ASGM mining community (Indonesia), and in residents of the Cook Islands who are exposed to mercury through global deposition and a diet rich in fish.

To our knowledge, this is the first study providing data on hair mercury levels in Belarus, Cameroon, Cook Islands, Nepal, Sri Lanka, and Uruguay. Previous studies measured hair mercury levels in Albania, Bangladesh, India, Kenya, Mexico, Russia, and Thailand but did not target communities located near the types of mercury sources studied here. In Indonesia and Tanzania, previous studies showed similar hair mercury levels in communities near ASGM sites, with some studies showing even higher levels at some sites in Indonesia (Baeuml et al., 2011; Bose-O'Reilly et al., 2010; Krisnayanti et al., 2012).

The data presented here indicates that communities near mercury sources named in the Minamata Convention have significant mercury exposures. The treaty outlines actions for reducing and eliminating such exposures, but monitoring is needed to identify and characterize them. Indeed, mercury monitoring data can provide an impetus for ratification of the Treaty, help quantify the effectiveness of pollution reduction measures during the implementation of the Treaty, and guide decision-making process in development planning.

Previous studies have demonstrated significant economic impacts of mercury pollution in developed countries such as the United States and Member States of the European Union. The data presented here indicate that mercury pollution could also have a significant economic impact in developing and transition countries. Mercury exposures at the relatively small of number of sites presented in this study is associated with a total of $77.4 million in lost annual economic productivity, assuming a 1 ppm reference level, and $130 million if no reference level is used. To our knowledge, this is the first estimate of the potential economic impact of mercury pollution in developing and transition countries.

Estimates of the economic losses are based on the loss of IQ and its impact on earning potential. This includes lower cognitive capacities and, also, indirect effects due to diminished educational achievements and reduced labor force participation. Of note, seemingly small IQ losses at an individual level can be extremely significant at the population level as they shift the distribution of IQ and increase the number of individuals who are below the normal range (Bellinger, 2012).

There are important limitations to this analysis. The potential impacts of atmospheric mercury emissions may range from local impacts to global impacts due to the long-range transport, but assessing mercury transport was beyond the scope of our study. We sampled a modest proportion of the population from each area, and we did not perform formal tests to evaluate population representativeness. IQ loss relationships with lifetime economic productivity were also modeled based upon data from the US. Technological change associated with economic growth increases the impact of IQ on productivity (Salkever, 1995) and, given that technological growth in low- and middle-income countries (LMICs) is probably faster, we are likely to have underestimated the lost economic productivity due to methylmercury exposure. We also appreciate that there is significant variability in technological growth rates across LMICs, and so there is potential for significant uncertainty introduced by using an input from a single, industrialized nation.

We also extrapolated individual-level lifetime economic productivity from US data, applying a PPP GDP correction factor, but the higher rates of growth in GDP per capita in some LMICs makes annual productivity gains most likely higher than in the U.S, further adding to the uncertainty of the estimates presented here.

Due to resource constraints, we were not able to include a control group in our study, comprised of subjects living away from industrial sites. Future studies addressing this area are warranted.

Costs associated with reducing and eliminating mercury pollution should also take into account the health and economic benefits derived from reducing exposure, which is a strong argument for ratification and full implementation of the Minamata Convention. Nongovernmental and governmental funding entities should consider the cost of mercury pollution as an area of ongoing concern which deserves immediate action.

5. Conclusions

Significant mercury exposures occur in developing and transition country communities near sources named in the Minamata Convention. Our estimates suggest that loss of IQ from mercury exposure and its impact on earning potential at the 15 sites examined amount to $77.4 million in lost annual economic productivity. Since this study only examines a very small number of sites, our findings suggest that a large economic burden in developing and transition countries could be avoided by timely implementation of measures to prevent mercury exposures.

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References

Albania, 2011. Vlora. Population Estimates. http://en.db-city.com/Albania–Vlor%C3%AB–Vlor%C3%AB–Vlora (accessed 18.08.15.).
Attina, T.M., Trasande, L., 2013. Economic costs of childhood lead exposure in low- and middle-income countries. Environ. Health Perspect. 121, 1097–1102.
Axelrad, D.A., Bellinger, D.C., Ryan, L.M., Woodruff, T.J., 2007. Dose–response relationship of prenatal mercury exposure and IQ: an integrative analysis of epidemiologic data. Environ. Health Perspect. 115, 609–615.
Baeuml, J., Bose-O'Reilly, S., Gothe, R.M., Lettmeier, B., Roider, G., Drasch, G., Siebert, U., 2011. Human biomonitoring data from mercury exposed miners in six artisanal small-scale gold mining areas in Asia and Africa. Minerals 1, 122–143.
Bangladesh, 2011a. Dhaka. Population Estimates. http://www.bbs.gov.bd/Census2011/Dhaka/Dhaka/Dhaka%20at%20a%20glance%20General.pdf (accessed 18.08.15.).
Bangladesh, 2011b. Munshiganj. Population Estimates. http://www.bbs.gov.bd/Census2011/Dhaka/Munshiganj/Munshiganj%20Community%20General.pdf (accessed 18.08.15.).
Belarus, 2011. Minsk. Population Estimates. http://belstat.gov.by/en/bgd/katalog-

publikatsii/public_compilation/index_134/ (accessed 18.08.15.).
Demo/Cophes Bellanger, M., Pichery, C., Aerts, D., Berglund, M., Castano, A., Cejchanova, M., Crettaz, P., Davidson, F., Esteban, M., Fischer, M.E., Gurzau, A.E., Halzlova, K., Katsonouri, A., Knudsen, L.E., Kolossa-Gehring, M., Koppen, G., Ligocka, D., Miklavcic, A., Reis, M.F., Rudnai, P., Tratnik, J.S., Weihe, P., Budtz-Jorgensen, E., Grandjean, P., 2013. Economic benefits of methylmercury exposure control in Europe: monetary value of neurotoxicity prevention. Environ. Health. http://dx.doi.org/10.1186/1476-069X-12-3.
Bellinger, D.C., 2012. A strategy for comparing the contributions of environmental chemicals and other risk factors to neurodevelopment of children. Environ. Health Perspect. 120, 501–507.
Bose-O'Reilly, S., Drasch, G., Beinhoff, C., Rodrigues-Filho, S., Roider, G., Lettmeier, B., Maydl, A., Maydl, S., Siebert, U., 2010. Health assessment of artisanal gold miners in Indonesia. Sci. Total Environ. 408, 713–725.
Cameroon, 2011. Douala. Population Estimates. http://www.statistics-cameroon.org/downloads/Rapport_de_presentation_3_RGPH.pdf (accessed 18.08.15.).
Cook Islands, 2011. Population Estimates. http://www.cookislands.org.uk/2011census (accessed 18.08.15.).
Dietz, R., Riget, F., Cleemann, M., Aarkrog, A., Johansen, P., Hansen, J.C., 2000. Comparison of contaminants from different trophic levels and ecosystems. Sci. Total Environ. 245, 221–231.
Eurostat, 2012. Methodological Manual on Purchasing Power Parities. OECD, Paris. https://www.oecd.org/std/prices-ppp/PPP%20manual%20revised%202012.pdf (accessed 19.08.15.).
Feng, X., Li, P., Qiu, G., Wang, S., Li, G., Shang, L., Meng, B., Jiang, H., Bai, W., Li, Z., Fu, X., 2008. Human exposure to methylmercury through rice intake in mercury mining areas, Guizhou province, China. Environ. Sci. Technol. 42, 326–332.
Global Mercury Assessment, 2013. Sources, Emissions, Releases and Environmental Transport. UNEP Chemicals Branch, Geneva, Switzerland. http://www.unep.org/PDF/PressReleases/GlobalMercuryAssessment2013.pdf (accessed 19.08.15.).
Gould, E., 2009. Childhood lead poisoning: conservative estimates of the social and economic benefits of lead hazard control. Environ. Health Perspect. 117, 1162–1167.
Grandjean, P., Weihe, P., White, R.F., Debes, F., Araki, S., Yokoyama, K., Murata, K., SØRensen, N., Dahl, R., JØRgensen, P.J., 1997. Cognitive deficit in 7-year-old children with prenatal exposure to methylmercury. Neurotoxicol. Teratol. 19, 417–428.
Grandjean, P., Budtz-Jorgensen, E., 2007. Total imprecision of exposure biomarkers: implications for calculating exposure limits. Am. J. Ind. Med. 50, 712–719.
Guimaraes, J., Ikingura, J., Akagi, H., 2000. Methyl mercury production and distribution in river water-sediment systems investigated through radiochemical techniques. Water Air Soil Poll. 124, 113–124.
India, 2011. Ganjam. Population Estimates. http://www.censusindia.gov.in/2011-prov-results/data_files/orissa/Data%20Sheet-%20Orissa-Provisional.pdf (accessed 18.08.15.).
Indonesia, 2011. Poboya and Sekotong. Population Estimates. https://www.google.com/fusiontables/DataSource?docid=1OlmGuziakXDKU7EB-By-xUZH_2YiQdTGP5HWMohG#rows:id=6 (accessed 20.08.15.).
Karagas, M.R., Choi, A.L., Oken, E., Horvat, M., Schoeny, R., Kamai, E., Cowell, W., Grandjean, P., Korrick, S., 2012. Evidence on the human health effects of low-level methylmercury exposure. Environ. Health Perspect. 120, 799–806.
Kenya, 2011. Migori. Population Estimates. https://opendata.go.ke/facet/counties/Migori (accessed 20.08.15.).
Kjellstrom, T., Kennedy, P., Wallis, S., Mantell, C., 1986. Physical and Mental Development of Children with Prenatal Exposure to Mercury from Fish. Stage I: Preliminary Tests at Age 4. National Swedish Environmental Protection Board, Solna, Sweden. http://agris.fao.org/agris-search/search.do?recordID=SE8710767 (accessed 20.08.15.).
Kjellstrom, T., Kennedy, P., Wallis, S., Stewart, A., Friberg, L., Lind, B., 1989. Physical and Mental Development of Children with Prenatal Exposure to Mercury from Fish. Stage II: Interviews and Psychological Tests at Age 6. National Swedish Environmental Protection Board, Solna, Sweden. http://agris.fao.org/agris-search/search.do?recordID=SE19910039355 (accessed 20.08.15.).
Krisnayanti, B.D., Anderson, C.W., Utomo, W.H., Feng, X., Handayanto, E., Mudarisna, N., Ikram, H., Khususiah, 2012. Assessment of environmental mercury discharge at a four-year-old artisanal gold mining area on Lombok Island, Indonesia. J. Environ. Monit. 14, 2598–2607.
Mexico, 2011a. Ixhuatlan del Sureste. Population Estimates. http://www.veracruz.gob.mx/finanzas/files/2015/05/Ixhuatl%C3%A1n-del-Sureste.pdf (accessed 20.08.15.).
Mexico, 2011b. Minatitlan. Population Estimates. http://www.veracruz.gob.mx/finanzas/files/2015/05/Minatitl%C3%A1n.pdf (accessed 20.08.15.).
Mexico, 2011c. Coatzacoalcos. Population Estimates. http://www.veracruz.gob.mx/finanzas/files/2015/05/Coatzacoalcos.pdf (accessed 20.08.15.).
National Research Council, 2000. Toxicological Effects of Methylmercury. http://dels.nas.edu/Report/Toxicological-Effects-Methylmercury/9899 (accessed 20.10.13.).
Nepal, 2011. Pokhara. Population Estimates. http://www.pokharacity.com/about-pokhara/ (accessed 20.08.15.).
Neumann, R.M., Ward, S.M., 1999. Bioaccumulation and biomagnification of mercury in two warmwater fish communities. J. Freshw. Ecol. 14, 487–498.
Oken, E., Wright, R.O., Kleinman, K.P., Bellinger, D., Amarasiriwardena, C.J., Hu, H., Rich-Edwards, J.W., Gillman, M.W., 2005. Maternal fish consumption, hair mercury, and infant cognition in a US cohort. Environ. Health Perspect. 113, 1376–1380.
Pacyna, J.M., Sundseth, K., Pacyna, E.G., Munthe, J., Åström, S., Panasiuk, D., 2008. Socio-economic Costs of Continuing the Status-quo of Mercury Pollution [Internet]. Nordic Council of Ministers, Copenhagen. http://www.norden.org/sv/publikationer/publikationer/2008-580/at_download/publicationfile (accessed 20.08.15.).
Rice, D.C., Schoeny, R., Mahaffey, K., 2003. Methods and rationale for derivation of a reference dose for methylmercury by the U.S. EPA. Risk Anal. 23, 107–115.
Russia, 2011a. Raygorod. Population Estimates. http://czn.volgadmin.ru/struct/rotdel.aspx (accessed 20.08.15.).
Russia, 2011b. Krasnoarmeyskaya District. Population Estimates. http://www.bankgorodov.ru/place/inform.php?id=38206 (accessed 20.08.15.).
Salkever, D.S., 1995. Updated estimates of earnings benefits from reduced exposure of children to environmental lead. Environ. Res. 70, 1–6.
Sri Lanka, 2011. Negombo. Population Estimates. http://www.negombo.mc.gov.lk/Muncipal.html (accessed 20.08.15.).
Sundseth, K., Pacyna, J.M., Pacyna, E.G., Munthe, J., Belhaj, M., Astrom, S., 2010. Economic benefits from decreased mercury emissions: projections for 2020. J. Clean. Prod. 18, 386–394.
Tanzania, 2011a. Chunya District. Population Estimates. http://en.wikipedia.org/wiki/Chunya_District (accessed 20.08.15.).
Tanzania, 2011b. Population Estimates. http://nbs.go.tz/nbs/sensa/PDF/2012%20PHC%20POPULAR%20VERSION.pdf (accessed 20.08.15.).
Thailand, 2011. Tha Tum. Population Estimates. http://stat.bora.dopa.go.th/xstat/p5525_03.html (accessed 20.08.15.).
Trasande, L., Landrigan, P.J., Schechter, C., 2005. Public health and economic consequences of methyl mercury toxicity to the developing brain. Environ. Health Perspect. 113, 590–596.
Trasande, L., Schechter, C., Haynes, K.A., Landrigan, P.J., 2006. Applying cost analyses to drive policy that protects children: mercury as a case study. Ann. N.Y. Acad. Sci. 1076, 911–923.
Trasande, L., Cortes, J., Landrigan, P., Abercrombie, M., Bopp, R., Cifuentes, E., 2010. Methylmercury exposure in a subsistence fishing community in Lake Chapala, Mexico: an ecological approach. Environ. Health. http://dx.doi.org/10.1186/1476-069X-9-1.
Trasande, L., Liu, Y., 2011. Reducing the staggering costs of environmental disease in children, estimated at $76.6 billion in 2008. Health Aff. 30, 863–870.
United Nations Environment Programme, 2013a. Minamata Convention on Mercury. http://www.mercuryconvention.org (accessed 31.10.13.).
United Nations Environment Programme, 2013b. Costs of Inaction on the Sound Management of Chemicals. UNEP Chemicals Branch, Division of Technology, Industry and Economics, Geneva, Switzerland. http://www.unep.org/chemicalsandwaste/Mainstreaming/CostsofInactionInitiative/tabid/56397/Default.aspx (accessed 20.08.15.).
Uruguay, 2011. Delta de Tigre y Villa. Population Estimates. http://www.ine.gub.uy/censos2011/resultadosfinales/sanjose.html (accessed 20.08.15.).
US Department of Labor, 2014. Bureau of Labor Statistics. Consumer Price Index, Medical Care. http://data.bls.gov/cgi-bin/surveymost?cu (accessed 08.05.14.).
World Bank, 2014. Birth Rate, Crude (Per 1,000 People). http://data.worldbank.org/indicator/SP.DYN.CBRT.IN?order=wbapi_data_value_2010+wbapi_data_value+wbapi_data_value-first&sort=asc (accessed 03.01.14.).
World Health Organization, 2008. Global Burden of Disease 2004 Update: Disability Weights for Diseases and Conditions. http://www.who.int/healthinfo/global_burden_disease/GBD2004_DisabilityWeights.pdf?ua=1 (accessed 01.07.14.).
Zhang, H., Feng, X., Larssen, T., Qiu, G., Vogt, R.D., 2010. In inland China, rice, rather than fish, is the major pathway for methylmercury exposure. Environ. Health Perspect. 118, 1183–1188.

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