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Mercury contamination from artisanal gold mining in Antioquia, Colombia: The world's highest per capita mercury pollution

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ABSTRACT

The artisanal gold mining sector in Colombia has 200,000 miners officially producing 30 tonnes Au/a. In the Northeast of the Department of Antioquia, there are 17 mining towns and between 15,000 and 30,000 artisanal gold miners. Guerrillas and paramilitary activities in the rural areas of Antioquia pushed miners to bring their gold ores to the towns to be processed in Processing Centers or *entables*. These Centers operate in the urban areas amalgamating the whole ore, i.e. without previous concentration, and later burn gold amalgam without any filtering/condensing system. Based on mercury mass balance in 15 *entables*, 50% of the mercury added to small ball mills (*cocos*) is lost: 46% with tailings and 4% when amalgam is burned. In just 5 cities of Antioquia, with a total of 150,000 inhabitants: Segovia, Remedios, Zaragoza, El Bagre, and Nechí, there are 323 *entables* producing 10–20 tonnes Au/a. Considering the average levels of mercury consumption estimated by mass balance and interviews of entables owners, the mercury consumed (and lost) in these 5 municipalities must be around 93 tonnes/a. Urban air mercury levels range from 300 ng Hg/m^3 (background) to 1 million ng Hg/m^3 (inside gold shops) with 10,000 ng Hg/m^3 being common in residential areas. The WHO limit for public exposure is 1000 ng/m^3. The total mercury release/emissions to the Colombian environment can be as high as 150 tonnes/a giving this country the shameful first position as the world's largest mercury polluter per capita from artisanal gold mining. One necessary government intervention is to cut the supply of mercury to the *entables*. In 2009, eleven companies in Colombia legally imported 130 tonnes of metallic mercury, much of it flowing to artisanal gold mines. *Entables* must be removed from urban centers and technical assistance is badly needed to improve their technology and reduce emissions.

1. Introduction

Worldwide, artisanal gold miners (AGM) are the main consumers of mercury, using and losing almost 1000 tonnes of metallic mercury per annum or more than 30% of all mercury annually used by different industrial applications (Swain et al., 2007). Mercury emitted to the atmosphere and released to the environment has serious environmental and health implications. As the price of gold has been increasing, more artisanal miners are mining and processing gold using rudimentary procedures. There are now about 10 to 15 million artisanal and small gold miners worldwide. Their operations span more than 70 countries and they produce in the range of 350 tonnes of gold annually (Telmer and Veiga, 2008). Hilson (2006) and Hilson et al. (2007) suggested that organizations which aim to mitigate mercury releases require deeper understanding of mine community dynamics Hilson (2006) and Hilson et al. (2007) suggested that organizations which aim to mitigate mercury releases require deeper understanding of mine community dynamics, the organization of processing activities, the needs of operators and the nature of the ore. This paper provides an overview of these, while highlighting the alarming scale of contamination within densely urban mining centres in remote, insecure, and mountainous region of Antioquia, Colombia.

The UN Human Development Report (UNDP, 2010) revealed that 16% of Colombians still live with less than US$ 1.25 per day. The social tensions and presence of various armed groups have agglomerated the terrorized rural population into towns. The rural areas have also witnessed an increasing number of illegal plantations of coca with less or virtually no cattle farms. Only 26% of the 45.6 million Colombians live in the rural areas. In spite of a gradual reduction of poverty over recent years, the Colombian statistics department, DANE, estimates that in 2006, at least 62% of the rural population lived in poverty (Perfetti, 2009). Gold mining is thus a natural option for the rural inhabitants in Colombia. Without technical assistance, gold mining

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started in a very rudimentary fashion and has been generating huge environmental and health impacts.

Mercury vapour impacts public health most directly, causing problems with the respiratory tract in short-term exposure to high levels of mercury vapour. Symptoms include chest pains, dyspnoea, cough, haemoptysis, impairment of pulmonary function and interstitial pneumonitis (Stopford, 1979; Levin et al., 1988). Exposure to high levels of mercury vapours such as 1,200,000 to 8,500,000 ng/m^3 of Hg, can be fatal (Jones, 1971). WHO (2000) suggests a LOAEL (lowest-observed-adverse-effect-level) of 15,000 to 30,000 ng/m^3. The recommended health-based exposure limit for metallic Hg is 25,000 ng/m^3 for long-term exposure (TWA — time weighed average concentration for a normal eight hour day and forty hour workweek, to which nearly all workers can be repeatedly exposed without adverse effect). The normal atmospheric levels of Hg in rural areas are about 2–4 ng/m^3, and in urban areas about 10 to 20 ng/m^3 (Veiga and Baker, 2004).

The World Health Organization sets the limit of chronic and tolerable mercury exposure to an annual average of 200 ng/m^3 and 1000 ng/m^3 respectively. Tschakert and Singha (2007), Tschakert (2010), Howard et al. (2011), and numerous others have also shown mercury to accumulate in sediments, ecosystems, and to impact local human health with similar long-term neurological and renal degeneration. While direct vapour exposure has been linked to physiological effects in miners (Tomicic et al., 2009), less is known about the effect of casual vapour exposure on non-miners.

The large majority of mining activities in Antioquia (Fig. 1) are illegal, as they lack permits either from the mining or the environmental authorities. As a result of the presence of guerrilla groups in the rural area, gold ore mined in the surrounding hills is processed in the urban environment. Miners accumulate as little as 2 tonnes of ore to take to the processing centers, or '*entables*', which are located beside residences, schools and stores. Commonly miners in *entables* do not pre-concentrate the ore, and mercury is added to the whole high grade material in small ball mills, known as *cocos* (Fig. 2). This whole ore amalgamation process maximizes mercury losses in tailings and effluent. The *entables* charge the miners a nominal fee of US$ 0.5 to $1.00 per *coco* with the condition that the miners leave their tailings to be further leached with cyanide. Miners obtain only the gold extracted by amalgamation, which leaves significant residual gold for the *entable* owners. Some *entables* have 5 to 10 *cocos* and others as many as 80. These steel ball mills are locally made with capacity of processing 50 to 70 kg of ore. We estimate that there are between 2500 and 2700 *cocos* in 323 *entables* at the 5 municipalities studied in Antioquia (Table 1).

Fig. 1. Map of Colombia indicating the gold mining region at the Northeast of the Department of Antioquia. Source: virtualamericas.net.

Fig. 2. *Cocos* are small ball mills to grind and amalgamate the whole ore.

The mercury contamination in Colombia by artisanal gold mining has been recognized by a number of researchers and local authorities for over a decade (Ingeominas, 1995; Veiga, 1997; Olivero et al., 2002; Marrugo-Negrete et al., 2008). Telmer and Veiga (2008) estimated that the annual mercury emissions from artisanal gold miners in Colombia in 2007 were between 50 and 100 tonnes, however given recent gold value increases and gold rush activity, current mercury emissions are likely much higher. Colombia is likely the world's 3rd largest source of mercury emissions from AGM after China (240 to 650 tonnes of Hg/a) and Indonesia (130 to 160 tonnes of Hg/a) (Telmer and Veiga, 2008) and is the world's highest per capita mercury polluter.

In Antioquia, miners do not use retorts to recover mercury because they believe that gold is lost in the process and because the price of mercury is low in the region (US$ 56/kg).

The five municipalities in this study produce the majority of gold in the Antioquia region, and the purpose of this work is to obtain more information about gold production methods and pathways for mercury release to the environment in these towns. This is part of the efforts of the UNIDO (United Nations Industrial Development Organization) Colombia Mercury Project, that, in partnership with the Government of Antioquia, are assessing the gold production and mercury pollution in the region in order to demonstrate cleaner production technologies. The data presented here were collected through interviews with miners and local authorities, and confirmed with direct observations and other sources of information.

Table 1
Number of *entables* in the 5 municipalities in Antioquia. (Data from the UNIDO Colombia Mercury Project).

Municipality	Number of entables
Remedios/La Cruzada	24
Segovia	94
Zaragoza	47
El Bagre	123
Nechi	35
Total	323

2. Materials and methods

Data about imports and sales of mercury in Colombia, and specifically in the five municipalities were obtained from the Colombian Ministry of Commerce (Bogotá), the UN COMTRADE (United Nations Commodity Trade Statistics Database) and direct interviews with mercury vendors and consumers.

Interviews with *entable* owners were conducted over a two year period in Segovia and Remedios/La Cruzada (the largest mercury consumers in the region) in order to obtain self-report data on the amount of mercury purchased per month by each *entable*. There are a total of 118 *entables* located within the municipalities of Remedios/La Cruzada) and Segovia. In Segovia, 69 out of 94 *entables* were visited and in Remedios/La Cruzada, 20 out of 24. These *entables* provide mercury to the miners, and occasionally use mercury to process their own ores if they have their own mine. Thus, when attempting to arrive at the value of mercury purchased (which is a direct indicator of mercury consumption) per month, one can expect the values to be higher than reported due to the fact that some miners buy mercury from a separate distributor and bring it to the *entables*. Another source of error is the fact that people would be naturally inclined to underreport their consumption of mercury.

In order to check the self-report data, a mass balance of mercury losses was conducted in 15 *entables*. Mercury was weighed before and after amalgamation using a scale with detection limit of 0.01 mg. The losses by evaporation were measured by the weight of the amalgam before and after burning. These data underestimate the true value as *doré* commonly retains 2 to 5% of residual mercury after amalgam burning (Veiga, 1997). Based on these self-report and mass balance data, it is possible to estimate the mercury consumption rates for the remaining *entables* that were not interviewed in these and other municipalities.

Mercury concentrations in air were measured using the LUMEX RA 915+ (from University of British Columbia, CERM3) and the Jerome 431X (from CORANTIOQUIA) spectrometers. The LUMEX RA 915+ is a portable cold vapour atomic absorption analyzer, with a low detection limit of 2 ng/m^3 of mercury in air. The LUMEX uses a Zeeman process (Zeeman Atomic Absorption Spectrometry with high frequency modulation of light polarisation ZAAS-HFM) that eliminates interferences and does not use a gold trap. The Jerome Hg analyzer uses a thin gold film that, in the presence of mercury vapour, increases the electrical resistance in proportion to the concentration of mercury vapour in the air sample. It has the lower detection limit around 1000 ng/m^3 and the upper limit around 999,000 ng/m^3. The Jerome was used for high concentration measurements such as at the outlet of a mercury fume hood during an amalgam burn or inside gold shops, and the Lumex was used to measure lower concentrations such as mercury in exhaled air and for measuring local background levels.

A preliminary survey of airborne mercury concentrations was conducted in each of the target municipalities. Where possible, measurements were taken in streets near and far from mercury sources, inside gold shops, *entables*, as well as inside businesses not directly related to mining. In practice, security/health concerns and highly variable receptiveness of business owners and miners required that an opportunistic sampling program be adopted instead of a more systematic approach. Nevertheless, these measurements provide an impression of the acute exposures in a variety of settings during five days of sampling in the region.

3. Results and discussions

3.1. Mercury imports and sales

Mercury can be legally imported to Colombia, but local miners in Antioquia have also reported buying mercury from illegal suppliers who bring the metal from Peru. According to the data obtained from the Colombian Ministry of Commerce and confirmed by the UN COMTRADE, 130.39 tonnes of metallic mercury were imported by Colombia in 2009. In 2001, this amount was around 57 tonnes.

The countries exporting mercury into Colombia are outlined in Table 2, with the majority of exports originating from the Netherlands and Germany.

Two companies, Insuminer S.A and Villa Estrada Jose Santiago, are responsible for 64% of total mercury (Table 3). The former reported that the final use of mercury is for “small and large scale mining”. Other importers indicate that mercury is being sold to manufacturers of chlorine and alkali (4.14 tonnes), rubber, plastic, and agricultural chemicals or is used in dental, pharmaceutical, or analytical chemistry industries.

The five major vendors in Segovia, the largest gold producing town in Antioquia, reported sales of 1502 kg of mercury per month (Table 4), or 18.02 tonnes per annum, exclusively to gold mining. Mercury is sold to miners for around US$ 56/kg, which is inexpensive compared to prices in artisanal mining sites elsewhere in Latin America (Sousa et al., 2011).

Based on interviews, in total, 1.37 tonnes of mercury is purchased monthly by all 69 *Segovia entables* investigated in this study. Thus on average each *entable* purchases and releases approximately 19.86 kg of mercury per month to the environment. By using this average, the total mercury purchased across all 94 *entables* in Segovia would be approximately *22.40 tonnes/a*. This estimate differs from that of the mercury vendors by 4.38 tonnes. The difference could be attributable to self-reporting errors or omissions, to mercury brought from outside the *entable* by individual workers, and to the consumption of the nearby municipality of Remedios where mercury from Segovia is also sold. There are 5 *entables* that consume more than 100 kg Hg/month or 73% of all mercury used in gold mining in Segovia.

With respect to *Remedios/La Cruzada*, the reported amount of mercury purchased by 20 *entables* collectively is 0.567 tonnes per month, thus on average each *entable* is purchasing approximately 28.35 kg of mercury/mo/entable. Using this amount, it follows that total consumption of all 24 *entables* within Remedios/La Cruzada is *8.21 tonnes/a*. It is important to highlight that two *entables* consume 250 kg/mo and 104 kg/mo respectively or 62% of the mercury consumed in Remedios.

If we assume that the average Segovia/Remedios/La Cruzada *entable* consumption of 24.10 kg/mo is a reasonable estimate for all 323 active *entables* in the 5 municipalities in Antioquia being studied, then the total amount of mercury released is around *93.4 tonnes/a*. This estimate assumes that the *entables* do not stockpile any mercury, i.e. all mercury purchased monthly is lost to the environment as vapour (when amalgam are burned in the gold shops), or in the tailings.

3.2. Mercury losses

Assessment of 15 *entables* revealed that, on average, 60 kg (range 47 to 73) of ore is added to each *coco* together with 80 g (range 50 to 110 g) of mercury. The pH of the pulp is adjusted with quick lime (Ca

Table 2
Countries exporting metallic mercury in 2009 to Colombia. (Colombian Ministry of Commerce data, 2010).

Country	Tonnes of Hg/a
Netherlands	47.95
Germany	35.58
Mexico	24.76
Spain	14.49
United Kingdom	4.14
United States	3.44
Italy	0.6
Total	130.96

Table 3
Main Companies importing metallic mercury in 2009 to Colombia. (Colombian Ministry of Commerce data, 2010).

Company	Tonnes of Hg/a
Insuminer S.A	52.96
Villa Estrada Jose Santiago	30.33
Distribuidora de Quimicos Industriales S.A	18.29
Ferreteria El Pedalista Luis Alberto Velasquez Y CIA. Limita	7.76
Productora Y Comercializadora Ondontologica New Stetic S.A	6.89
Pacific Chemicals Corporation LTDA	6.17
Brinsa S.A	4.14
Baux Chemical LTDA	3.79
Merck S.A	0.05
Quimicos Y Reactivos Limitada	0.0006
Elementos Quimicos LTDA	0.0002
Total	130.39

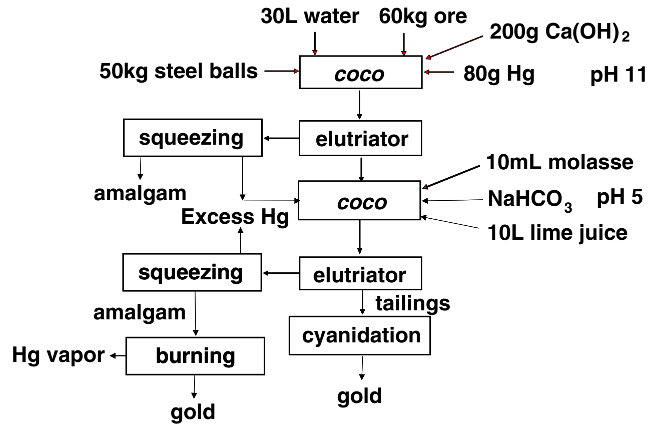

Fig. 3. Flow sheet of a typical whole ore amalgamation in *cocos*.

$(OH)_2$) resulting in pH 11 and run on average for 4 h. Then, the material is discharged, washed and the amalgam is recovered either by panning or by a locally made elutriator. The excess mercury is squeezed off in a piece of fabric and the resulting amalgam is burned in a fume hood with no filter or condenser. If the ore is too rich in gold, the tailings are collected for a second amalgamation for 1 or 2 h but the pH is reduced to 5 with lime juice. Molasses and sodium bicarbonate are also added to the mixture together with mercury recycled from the first amalgamation. It seems that the change in pH provides some coalescence to mercury droplets, however mercury loss is visible when the final tailing is panned. During the grinding process, a portion of mercury is pulverized, oxidized and loses coalescence. This whole procedure varies depending on the *entable* and type of ore being processed (rich or poor in gold, more or less sulphide, coarse or fine gold, etc.). Some people add guava leaves, toothpaste, detergents, and other ingredients they believe avoid mercury losses. The amalgamation tailing, contaminated with mercury, is then collected in a concrete pool, naturally drained off, to be leached with cyanide by percolation (Fig. 3).

The mercury mass balance (Table 5) reveals that around 50% of excess mercury is recovered by squeezing the amalgam, i.e. filtration with a piece of cloth. This is an indication that the miners add too much mercury into the *cocos*. On average, 46.3% of mercury pulverized during grinding is lost with tailings (this ranges from 26 to 82%). The amount of mercury lost when amalgams are burned without retorts is 3.76% of the initial mercury added into the *cocos*. It was extremely difficult to know who uses retorts, but it is assumed for the purposes of this study that evaporated mercury is not recovered. This is reasonable, as most local miners bring raw amalgam to the gold shops, and most shops have no mercury recovery devices, and the devices that exist are insufficient at best.

An alternative calculation of the mercury consumption in the region can be obtained based on the data from Table 5. Considering that there are 2600 *cocos* in the 5 municipalities studied and each coco receives in average 78 g of mercury and loses 50% (average in Table 5) and considering that each *coco* runs twice, and in some cases, three times per day in 360 days per annum, then *the mercury loss (consumption) might be between 73 and 110 tonnes/a* in the 5 municipalities studied.

The average $Hg_{lost}:Au_{produced}$ ratio obtained for Segovia was around 15 which is compatible with operations in other countries using similar process of grinding the whole ore with mercury (Veiga, 2003; Castilhos et al., 2006). This ratio has been used as a parameter to quantify Hg releases from artisanal gold mining operations (Veiga and Baker, 2004). The ratio $Hg_{los}t:Au_{produced}$ cannot be used as an individual measure due to fluctuations in gold production that can result in overestimation, but it is adequate as an average over many operations.

3.3. Gold shops and atmospheric pollution

The most amazing observation in Antioquia is that amalgams with 40 to 50% of mercury are burned in gold shops in densely populated urban areas without any condensing systems. In the 5 municipalities studied, there are about 98 gold shops (Remedios = 14, Segovia = 57, Zaragoza = 12, El Bagre = 10, and Nechi = 5). Amalgams are burned and sometimes melted under the scrutiny of the miners. Another type of business (*fundición*), also located in urban areas, charges miners to burn the amalgam to evaporate the mercury and melt the gold before selling it to a gold shop. This gives the miners a clearer idea of the purity of their gold (based on colour) and thus a stronger position when bargaining a price with the gold shops. Two *fundiciónes* have filters with an intricate system of condensers and cellulose filters (those used for water filtration). Despite the goodwill of these individuals, the exhaust from these shops still has 100 times higher mercury concentration than the levels allowed by World Health Organization (WHO, 2000) for public exposure (1000 ng/m^3).

Artisanal miners elsewhere in the world commonly burn amalgam in the field either with retorts or in open pans, and therefore only *doré* (burned gold that contains only 2–5% mercury) is re-burned in gold shops. However, even with these low levels of mercury, the *doré* must be melted under fume hoods with condensers and filters to avoid mercury emissions. In a Segovia gold shop that uses a rudimentary condenser (Table 6), burning a 200 g amalgam with 100 g of mercury, still produced exhausted air containing 100,000 ng/m^3. In other words, even if the mercury abatement system had efficiency of >95%, mercury concentrations would be intolerably high.

The mercury levels analyzed in the ambient air in some of the 5 municipalities studied are shown in Table 6. It is clear that the levels

Table 4
Vendors of metallic mercury within the municipality of Segovia. (self-report data).

	Vendor 1	Vendor 2	Vendor 3	Vendor 4	Vendor 5
Quantity of Hg sold/month (kg)	238	240	690	130	204
Number of regular clients	40	Unknown	30	Unknown	Unknown
Sale price of Hg (US$/kg)	55.76	55.76	58.55	58.55	55.76

Table 5
Mass balance of Hg losses in 15 entables in Segovia.

Entables	Mass of mineral (kg)	Initial Hg (g)	Overall Hg lost (g)	% Total Hg lost	Gold (g) produced	Ratio Hg lost: Au produced	%Hg lost with tailings	%Hg recovered squeezing	%Hg lost by burning
1	54.0	52.0	29.5	56.7	0.65	45.5	54.1	43.3	2.60
2	62.0	74.8	32.1	47.7	4.03	8.0	42.9	52.3	4.79
3	47.0	95.0	30.0	35.8	4.00	7.5	31.6	64.2	4.21
4	61.0	86.0	39.3	46.5	1.30	30.2	45.7	53.5	0.81
5	60.0	92.3	46.7	56.7	3.30	14.2	50.6	43.3	6.07
6	60.0	59.8	21.0	37.5	2.00	10.5	35.0	62.5	2.42
7	58.0	79.0	35.6	51.3	2.90	12.3	45.1	48.7	6.20
8	53.2	109.0	28.2	32.1	4.50	6.3	25.9	67.9	6.24
9	53.2	114.0	93.2	87.9	6.30	14.8	81.8	12.1	6.14
10	63.0	98.0	39.1	40.4	0.60	65.2	39.9	59.6	0.51
11	63.0	87.0	55.5	69.5	5.40	10.3	63.8	30.5	5.75
12	73.0	50.9	19.0	38.9	0.80	23.8	37.3	61.1	1.57
13	63.0	61.2	22.1	37.3	0.60	36.8	36.1	62.7	1.14
14	63.0	51.7	26.6	53.0	0.40	66.5	51.5	47.0	1.55
15	63.0	61.2	25.5	43.2	0.50	51.0	41.7	56.8	1.50
Average	59.8	78.1	36.1	50.0	2.48	14.6	46.3	50.0	3.76

of mercury on the streets are commonly far above the WHO guidelines. The simple use of mercury in the ball mills emits significant amounts of mercury vapour from the *cocos*. The employees of the gold shops, working in extremely contaminated sites are likely the most intoxicated individuals, but toxicological and neuropsychological exams have not yet been performed.

In the town of Caucasia, in Antioquia, there is no mining activity or *entables*, but miners bring amalgams from other municipalities to gold shops in this town. This causes not only loss of royalties by the municipality where the gold is mined but also significant pollution in a very populated city (second largest in Antioquia). Table 6, shows high levels of mercury in the air of 'Calle 21' street in Caucasia. This is a poorly ventilated street canyon, and the levels of mercury are very high everywhere; including inside a pharmacy on the same side of the street as the gold shops.

In Caucasia, it was demonstrated to a gold shop owner that the levels of mercury inside the shop were around 200,000 ng/m^3 when nobody was burning amalgam. The owner did not believe in the measurements and said that he had recently analyzed his urine and the levels of mercury came back to "normal" after two weeks of treatment with diuretics in Bogotá. It was explained to him that mercury in urine can decrease to a background level (for example 5 μg/L) in less than fifteen days, but this does not mean that there is no mercury already in his brain. What he did not know is that the total mercury levels in urine would not be expected to correlate with neurological findings even once exposure has stopped (Veiga and Baker, 2004).

Mercury concentrations inside *entables* and *fundiciones* often exceed the detection limit of the Jerome (>999,000) which suggests that workers' exposure at times approaches fatal levels (Jones, 1971). Experiments with animals indicate that continuous (chronic) exposure to Hg above 300 ng/m^3 of air may present a health hazard. The long-term exposure to low levels of mercury vapour can derive less pronounced symptoms of fatigue, irritability, loss of memory, vivid dreams and depression (WHO, 1991a) which in many cases are hard to correlate with mercury intoxication once miners are hard alcohol drinkers and are subjected to all types of tropical diseases (Cassidy and Furr, 1978; WHO, 1991b; Asano et al., 2000).

The seriousness of the situation in Antioquia is evident. Neuropsychological tests will only confirm the high level of intoxication of the population living near the gold shops and *entables*.

3.4. Cyanidation of Hg-contaminated tailings

The rudimentary amalgamation process performed in the *cocos* is not efficient since mercury is pulverized and lost with tailings when the whole ore is ground with mercury. According to local operators, only 40 to 50% of the gold in the ore forms amalgam and is recovered. The main environmental problem is that on average 46.3% (and in some cases as much as 82%) of the mercury introduced in the system is lost with tailings (Table 5). Tailings with up to 5000 mg/kg of Hg were analyzed in one *entable* in Segovia. The tailings, with residual gold, are then subjected to cyanidation in vat leaching with subsequent gold precipitation with zinc shavings. This usually happens in the *entables* where owners excavate tanks on the ground and line them with permeable cotton rags to allow filtration of the cyanide solution. The filtered solution passes through a wooden box or PVC pipes filled with zinc shavings where gold and residual mercury are precipitated. The operators in Antioquia do not pay attention to the re-dissolution of gold when the zinc precipitation is not conducted under vacuum and usually a part of the gold is lost with the effluents. After gold precipitation on the zinc shavings, the solution is pumped back to the percolation tank. This leaching cycle occurs from eight to thirty days, depending on the grade of the tailings. This is far too long and indicates a lack of aeration in the vat. The amount of mercury retained by the zinc is not known, but in similar operations in Ecuador, it was observed that about 28% of the mercury in the tailings introduced in the cyanidation tanks is precipitated on the zinc shavings (Velasquez et al., 2011). At the end of the leaching process, when miners visually notice that there is no more gold being precipitated on the zinc shavings (it does not turn black), they discharge the pulp with gold-barren cyanide solution, which is still rich in zinc and mercury, into local creeks. The zinc shavings, rich in gold, are burned in open-gas furnaces spreading zinc vapour to a wider area. Mercury, lead and other heavy metals in the tailings, partially leached by cyanide and precipitated by the zinc, are also released into the urban air when the zinc is evaporated. This process could be done safely using acid (e.g. hydrochloric) to dissolve and recycle zinc as well as mercury. After burning the zinc off, gold is melted and sold to the gold shops.

This inefficient process of whole ore amalgamation followed by cyanidation has also been witnessed in Brazil, Ecuador, Indonesia, Mozambique, Peru and Zimbabwe.

In the cyanidation process, mercury, as gold and other metals, forms soluble complexes with cyanide, such as $[Hg(CN)_4]^{2-}$ which is stable at pHs above 8.5 and $Hg(CN)_2$ (aq), stable at pH below 7.8 (Flying and Mc Gill, 1995). Velasquez et al. (2011), studied dissolution of mercury in a gold leaching agitated tank and revealed that while more than 92% of the gold is dissolved in five days, only 27% of mercury becomes soluble with cyanide. As observed by these authors in Ecuador, mercury dissolves in cyanide slower than gold. In this case the tailings dumped into the rivers still contain mercuric–cyanide complexes in solution as well as metallic mercury droplets.

Table 6
Atmospheric mercury in selected parts of Remedios, Segovia, and Zaragoza.

Location	Hg (ng/m^3)	Remarks
Remedios		
Remedios-Segovia road	10–20	Background: rural area 5 km from Segovia, no residences or mines.
Main plaza	100–400	On a holiday, few gold shops were working
Inside the City Hall	100–200	The mayor and employees inhale 10 times more Hg than the background.
Calle Real (on the street)	500–5000	On a holiday; there were 6 gold shops on this street but they were not working.
In front of a gold shop (on the street)	3000–5000	Same as above.
Inside a gold shop	5000–60000	Gold shop not working.
Inside a bakery	200–300	On a holiday; the bakery is beside a gold shop that was closed for the day.
La Cruzada (on the street)	5000–10000	In front of an elementary school.
La Cruzada (on the street)	500–900	In front of a working *entable*.
La Cruzada (on the street)	1000–3000	In front of a series of 6 *entables*.
Segovia		
Main plaza	100–200	On a holiday, no *entable* was working.
Calle Real (on the street)	150–300	Same as above.
Calle 48 (on the street)	1000–1500	Same as above.
Entable Guamo	15,000–20,000	At the door of this entable; about 40 *cocos* were working at the time.
Entable Guamo	Up to 80,000	Measured near a *coco*.
Inside another *entable*	Up to 943,000	Near a *coco*; probably somebody had burned amalgam inside the *entable*.
Calle Castillos	Up to 40,000	Near an elementary school.
In front of gold shop (on the streets)	3000–5000	Gold shops were not burning amalgam at the time.
"Fundicion" Calle 47A (on the street)	3000–5000	Amalgam being burned in a fumehood with a "new" mercury condensing system.
At the door of this *fundición*	20,000–30,000	Same as above.
Inside this *fundición*	40,000	The operators believe that the filters are retaining ALL mercury vapour.
Near the nose of the operator (in the same *fundición*)	60,000	A child was sleeping near this worker while he was burning amalgam.
At the exhaust of the condensing system	100,000	This shows how inefficient the filtering and condensing system is.
When zinc precipitate is evaporated	616,000	All Hg precipitated on the zinc is also emitted to the atmosphere.
Zaragoza		
Main plaza	40–50	Measurements on the street; no amalgam was being burned.
Main Street with 4 gold shops	1000–3000	Same as above.
Street with no gold shop	800–1000	Parallel to main street; no gold shop was burning amalgam at the time.
Inside a gold shop	Up to 80,000	The gold shop was not burning amalgam.
Expired air (*entable* worker)	Up to 2500	Miner exhaled air into the LUMEX.
Clothes of this worker	5000	
Hands of this worker	6000	
Expired air (non workers)	50–500	Kids not involved in mining showed high levels of mercury in breath.
Caucasia		
Streets (no gold shop)	30–40	There is no gold shop in these streets.
Calle 21 (5 gold shops)	4000–5000	Measurements on the street where there are 5 gold shops.
Inside the gold shops	100,000–200,000	No amalgam was being burned.
Inside a pharmacy	5000	Other side of the street from the above gold shop; no amalgam burning at the time.

Any cyanidation of Hg-contaminated tailings is a likely source of mercury cyanide formation and release to the environment. It is well known that mercuric species are easily methylated (Jensen and Jernelov, 1969), but it is not well-understood whether the mercury cyanide species are methylated in the sediments or directly bioaccumulated in aquatic organisms. However, in many sites where Hg-contaminated tailings are leached with cyanide, fish contain high levels of mercury (McDaniels et al., 2010). Rodrigues-Filho et al. (2004) analyzed 31 samples of carnivorous fish from a small lagoon at the Brazilian Amazon that was receiving effluents from a heap-leaching cyanidation operation. The average total mercury concentration of the samples was 4.16 ± 5.42 mg/kg and a small fish (15 cm) sample showed levels of 21.9 mg Hg/kg, probably a new world record (Sousa and Veiga, 2009). In Antioquia, the creeks adjacent to the *entables* have no aquatic life.

4. Conclusion

Inhalation of Hg vapour is the primary exposure pathway for miners, gold shop workers and people living near areas where mercury and amalgams are handled in the five municipalities studied in Antioquia, Colombia. Usually more attention is given by authorities and researchers to the effects of ingestion of fish contaminated with methylmercury. This is understandable since methylmercury is much more toxic than metallic mercury and the worldwide events related to consumption of contaminated fish left a legacy of thousands of deaths or impaired individuals (e.g. Minamata, Iraqi, etc.). In addition, fish is not only consumed by rural population but also by people living in large cities who usually have more political clout to pressure authorities to find solutions for fish pollution. In many cases, mercury vapour pollution is perceived as a restricted occupational exposure, i.e. to workers like miners and gold shop employees. Information about mercury contamination of neighbours living near processing centers or gold shops has been limited to a few cases. Information about long-range transport of mercury vapour emitted by gold miners is also limited. Rural communities living in towns that depend on artisanal gold mining activities have also little interest in ending the sole economic activity of the region, even if this activity is polluting the whole town.

The health and environmental effects caused by the misuse of mercury and cyanide in Antioquia would not have the same public repercussion as the economic impacts if all gold *entables* are closed. In this case, it is advised to start a strong educational intervention in Antioquia showing how "new" cleaner mercury-free techniques can increase the gold production. This is the first step to earn the confidence of miners. A priority must be given to stop the insane practice of bringing mercury to the urban environment, either to amalgamate the whole ore in *cocos* or to burn amalgams in gold shops. NO MERCURY CONDENSING SYSTEM OR FILTER in the world will be capable of reducing the levels of mercury in the Colombian towns if tonnes of mercury continue being burned and dispersed into the urban atmosphere. Retorts are badly needed and have been introduced in Antioquia by the UNIDO Colombia Mercury Project to be used in the field. Condensing systems for gold shops must be installed to trap ONLY residual mercury (around 2–5%) when retorted gold *doré* is melted.

The environmental problems caused by this huge release of mercury and cyanide with tailings to the local aquatic systems have not been evaluated yet but all creeks in the Antioquia municipalities visited are silted with tailings and likely have no aquatic life. The mobility of mercury with tailings must also be investigated.

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