# Life Cycle Inventories of Gold Artisanal and Small-Scale Mining Activities in Peru

## Toward Indicators for South America

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**Key words:**
artisanal mining
industrial ecology
life cycle assessment (LCA)
mercury
metals
resource extraction

## Summary

No life cycle assessment (LCA) of artisanal and small-scale mining activities (A&Sma) has been identified as of today, and there are limited studies about large-scale mining and alluvial mining. The A&Sma are relevant economic sectors in countries with large reserves of mineral resources. Gold is the most representative metal mined with these practices and is used not only in jewelry but also in several electronics appliances. South America accounted for 17% of the total worldwide gold extraction in 2005; A&Sma occurred mostly in Colombia, Peru, and Brazil.

The aim of this study is to estimate environmental indicators using methodologies for life cycle inventories (LCIs) in one of the two largest producers of gold through A&Sma in South America, Peru, and to discuss possible indicators for A&Sma in South America. Different functional units were used for each case study, as gold with different concentrations was produced and it was not possible to collect data for downstream processes for both bases. The product systems start in the mining and end with the gold production. Data were collected in two mining sites and, later on, related to the functional units. The results showed the amount of energy and water consumed as well as mercury used and released, carbon dioxide ($CO_2$) emissions, and solid wastes for each type of gold produced.

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## Introduction

Comprehensive life cycle inventories (LCIs) of large-scale mining have already been performed in Australia, Sweden, Canada, the United States, Chile, Papua New Guinea, and Peru (Classen et al. 2007), and one study was conducted about alluvial mining in Peru (Valdivia 2005). Although the artisanal and small-scale mining activities (A&Sma) are relevant economic sectors in countries with large reserves of mineral resources, no life cycle assessments of these products have been accomplished as of 2010. Among the minerals that are extracted according to these practices, gold is the most representative; it accounts for about 20% to 30% of all the extracted gold in the world (UNIDO 2007).

A great percentage of A&Sma workers use amalgamation (US EPA 1994). In this process, gold is trapped by mercury and is responsible for the release worldwide in 2005 of approximately 350 tonnes[1] of this metal—18% of the total amount of anthropogenic emissions of mercury in 2005, estimated to be 1,930 tonnes—ultimately causing damage to ecosystems and human health throughout the world (Telmer and Veiga 2009; Pacyna et al. 2010). The main source of anthropogenic emissions of mercury in 2005 was the combustion of fossil fuels (mainly coal in utility, industrial, and residential boilers), as shown in figure 1; it accounted for 46% of the total amount released. Other sources were ferrous and nonferrous metal production, including large-scale gold production (13%), and cement production (about 10%; De Lacerda 2003; Hylander and Meili 2003; Telmer and Veiga 2009; Pacyna et al. 2010.

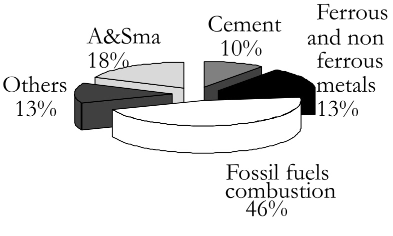

**Figure 1** Contribution to mercury emissions in 2005 (Pacyna et al. 2010).

In 2005, the extraction of gold in South America accounted for 17% of the total worldwide extraction (USGS 2005), which gives an indication of the relevance of this region for gold production worldwide. Of an average of 390 tonnes of gold produced in the region per year, between 80 and 89 tonnes come from A&Sma, which represents about 20% to 23% (Valdivia 2009). Colombia, Peru, and Brazil account for the highest levels of gold extraction through A&Sma: 29%, 20%, and 14%, respectively (Valdivia 2009). Table 1 provides more detailed information about gold production in ten countries of the region from 2003 to 2005.

The manner of exploitation is a parameter that defines the A&Sma type. In South America, the alluvial and underground exploitation practices were found to be dominant (Valdivia 2009). Both types exist in Ecuador and Peru, which is not the case in Suriname, French Guiana, the Cooperative Republic of Guiana, and Brazil, where alluvial mining constitutes almost 100% of the A&Sma (in Brazil, called *garimpo*; Lowe 2005). In Peru, the most prominent subregion with alluvial mining is the Amazonian Madre de Dios, which produces 1.2 kilograms (kg)[2] per miner every year (Medina et al. 2007).

An extensive list of studies on A&Sma served as input in the present study to confirm the relevance of and urgency to complete research efforts. An international effort with important highlights and pathways for A&Sma concluded in 2005 with the launch of the *MMSD Final Report—Breaking New Ground: Mining, Minerals and Sustainable Development* (IIED 2002). Especially regarding the Latin American region, Veiga (1997; Veiga et al. 2006, 2009) has been prolific during the last decades, generating valuable information and promoting better practices in this regard (see also Pantoja and Alvarez 2000). Several authors have produced relevant detailed national reports: Gallarday and Tomás (2006), Medina and colleagues (2007), and Valdivia (2005) described the problems around the Peruvian A&Sma; we found additional relevant literature for other South American countries, such as Ecuador (Velásquez-López et al. 2010), Colombia (Amichoco et al. 1999), Guianas (Vieira 2006), Bolivia (Vizcarra and Molina 1997), and

**Table 1** Gold production in South America, 2003–2005 (kilograms)

| | 2003 | | 2004 | | 2005 | |
|---|---|---|---|---|---|---|
| *Country* | *National production*[a] | *Production from A&Sma*[b] | *National production*[a] | *Production from A&Sma*[b] | *National production*[a] | *Production from A&Sma*[b] |
| Argentina | 29,749 | 19 | 28,466 | 19 | 30,000 | 19 |
| Bolivia | 9,362 | 3,664 | 6,951 | 2,720 | 8,906 | 3,486 |
| Brazil | 40,416 | 15,000 | 47,596 | 19,088 | 41,154 | 11,212 |
| Chile | 38,954 | 3,225 | 39,986 | 2,199 | 40,447 | 2,106 |
| Colombia | 46,515 | 30,235 | 37,738 | 24,530 | 35,783 | 23,259 |
| Ecuador | 3,020 | 4,819 | 5,158 | 5,128 | 5,416 | 5,338 |
| Peru | 172,619 | 13,553 | 173,224 | 16,018 | 207,822 | 16,481 |
| Co-operative Republic of Guiana | 12,441 | 2,488 | 12,441 | 2,488 | 12,441 | 2,488 |
| Suriname | 11,559 | 5,779 | 12,739 | 6,369 | 12,739 | 6,369 |
| French Guiana | 13,296 | 10,000 | 12,564 | 10,000 | 12,500 | 10,000 |
| Venezuela | 8,190 | Not known | 9,690 | Not known | 10,000 | 5,000[c] |
| Total in South America | 387,671 | 88,782 | 388,311 | 88,560 | 420,208 | 85,758 |
| | | 23% | | 23% | | 20% |
| Total worldwide | 2,560,000 | 512,000 | 2,444,000 | 488,000 | 2,470,000 | 494,000 |
| % of global production in South America | 15% | 17% | 16% | 18% | 17% | 17% |

[a] USGS (2003, 2004, 2005).

[b] Valdivia (2009). Estimations were obtained thanks to the contribution of individuals acknowledged at the end of this article.

[c] Veiga and colleagues (2005).

Venezuela (Veiga et al. 2005). We identified no literature for A&Sma in Paraguay or Uruguay.

Due to the relevance of A&Sma for gold extraction in South America, in this study we aim to estimate environmental indicators using the LCI methodology (ISO 2006a, 2006b) in Peru, one of the two largest producers of gold through A&Sma in South America, considering the two types of extraction. Furthermore, this study discusses possible indicators for South America and highlights hotspots identified in light of existing results from large-scale gold mining activities.

## Methodology

This section describes the methodologies used to create the LCIs of two case studies in Peru, including the estimation of an indicator that could help in estimating the magnitude of mercury emitted by A&Sma. In Case 1, we analyzed a small-scale extractive alluvial mining and concentration activity in Mazuko, Madre de Dios, Peru and in case 2, we examined an artisanal underground mining and concentration activity in Ayacucho, Peru.

### *Life Cycle Inventories*

The functional unit was the production of 1 kg of gold with 99.5% purity in Case 1 and the production of 1 kg of gold with 80.0% purity in Case 2. It must be highlighted that the results are not directly comparable, as the functional units are different. For future comparison, the stages of transport and gold refining to obtain concentrated gold (99.5% gold [Au]) should be added.

The system boundary used to develop the LCI was cradle to gate: extraction, transportation, and concentration. Practices related to treatment and waste were not analyzed due to insufficient data availability.

To obtain primary data, at first, we established direct contacts with managers of operations in Peru. They agreed to participate in a survey once they understood that an LCI is a useful tool to estimate consumption from the operations and, hence, their costs. We developed a questionnaire to obtain the necessary information on the basis of data from 2004 and 2005, including the type of extraction adopted and the amount of gold extracted. On the basis of the information gathered through the questionnaires, we visited one of the sites to complete data collection about environmental flows (resources consumption and emissions) and product flows (flows from or to other processes). For missing data, we made some estimates (through observation, comparison with similar cases, or calculation by using emission and consumption factors). We then processed the data and presented the LCIs to be reviewed by the owners. In LCIs presented here, only estimated and observed information was used; existing commercial databases were not used, except for the case of greenhouse gas emissions.

### The Mercury Footprint

As for the purpose of this study, the mercury footprint (MF) is defined as the overall amount of mercury emitted to the environment associated with the concentration of gold extracted either by alluvial or by underground mining. The chemical forms of mercury include elemental mercury ($Hg^0$), methylmercury ($CH3Hg^+$), mercuric ion ($Hg^{2+}$), mercurous ion ($Hg^+$), and mercury sulfide (HgS).

## Case 1: Life Cycle Inventory of Alluvial Gold Mining and Concentration by a Small Scale Activity

### Background Information

The first LCI of gold is based on the processes of a small-scale company in Mazuco, Peru, over a period of 12 months (January 2005–December 2005), during which 43.2 kg of gold (99.5%) was extracted (Valdivia 2005). The extraction follows the alluvial process. The concentration of gold in the area is low (10,046.6E-04 grams [g]$^3$ of gold in 15 cubic meters [m$^3$]$^4$ of sand).

Mazuko is the capital of the Inambari district (Tambopata province, Madre de Dios, in Peru) and is located in the southeastern part of the country. This area is considered tropical rainforest with abundant rain year-round and with land mainly consisting of sand. A&Sma in Mazuko are located in the buffer area of the national reserve of Tambopata, which increases environmental risks in the reserve. This protected area is also on the border of Brazil. Mazuko is a small village consisting of 389 houses and 1,899 inhabitants who mainly live off gold mining, directly or indirectly (Ecsa Ingenieros 2007).

To illustrate the setting in which operations are carried out and their environmental impacts occur, we must mention that Mazuko does not have a controlled waste management system, and, therefore, all solid wastes (including household wastes) of the city and of the mines are dumped in open spaces, which damages the fragile natural environment.

Energy is cogenerated and based on diesel (D2). The consumed water comes from the river or aquifers, and the total occupied area per year is 16,125 square meters (m$^2$).$^5$

### Description of the Processes to Obtain Gold

To obtain gold, the mining companies used five processes: excavation and extraction, the initial separation of the material, amalgamation, the second separation of the material, and the concentration of the gold and recovery of mercury. Two other processes were also taken into account: transportation and electricity generation, as shown in the product system in figure 2.

#### *Excavation and Extraction*

The excavation is an open-pit mining process. Before the gold is extracted, the biomass (trees and vegetation) must be cut, which amounts to an area equivalent to 1.6 hectares per year to obtain 17,628 kg biomass per gram of gold, or 761.53 tonnes of biomass per year (USEPA 2004). Intensive alluvial extractions up to 40 meters deep are then carried out. The annual volume of removed soil is estimated at 0.1032 million tonnes.

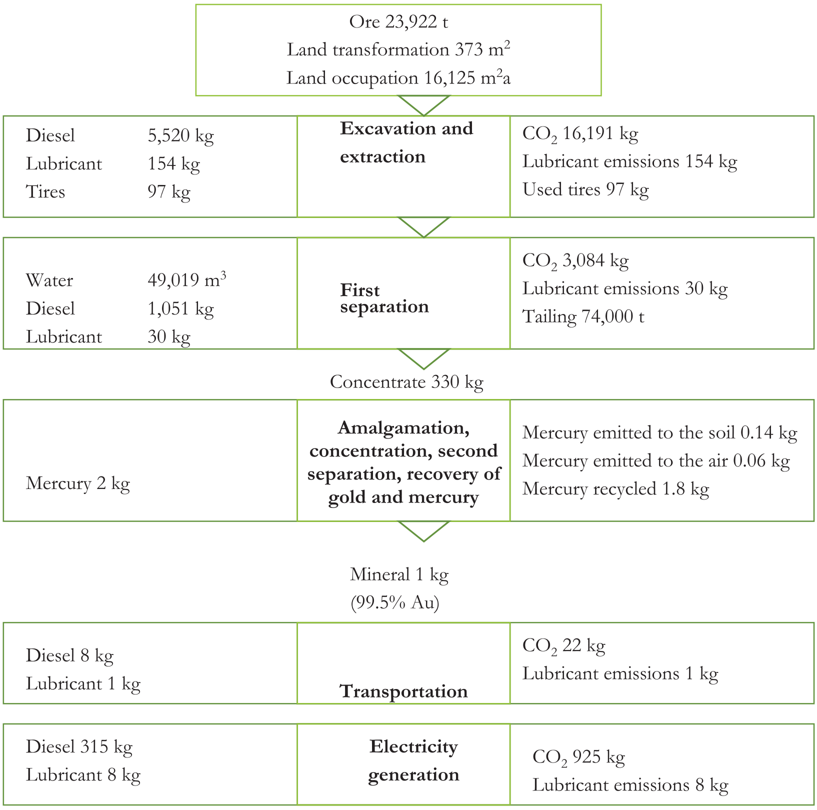

**Figure 2** Product system with inputs and outputs to obtain 1 kilogram of gold concentrate (99.5% gold): Case 1. t = tonne; $m^2$ = square meter; $m^2a$ = square meter years; kg = kilogram; $CO_2$ = carbon dioxide; Au = gold.

### *First Separation*

Next, the mining company conducts the initial separation by washing the extracted material with water pumped from rivers or aquifers, on woolen mats or carpets that are placed on an inclined ladder. As indicated by the interviewed operation manager, the total quantity of water used per year is 2,177,640 $m^3$, which is not recycled. The mat retains about 55% of the gold in the sand. At the end of a day, the mats are brushed out, and the heavy sediments containing the gold are separated.

### *Amalgamation and Concentration*

The third process, the amalgamation, consists of the mixture of mercury with the previously obtained sediments. The mercury particles adhere to the fine gold particles in the sediments. It is estimated that 2 g of mercury are necessary to extract 1 g of gold, as indicated by the interviewed operation manager. About 90% of the mercury is recycled, so the final consumption of mercury is equivalent to 0.2 g per gram of gold. From the mercury released, the 30% generated by A&Sma is evaporated directly into the atmosphere, whereas the remaining 70% is discharged into soil, tailings dams, rivers, and lakes (UNIDO 2007).

### *Second Separation*

Then the company performs the second separation of the material by tossing the sediments into a drum and, thus, separating the mercury and gold on the basis of the differences in the densities. Water is then added to the separated sediments. Those with a high concentration of gold are separated by centrifugation. These daily products are accumulated, and gold and the mercury are recovered every weekend.

### Mercury Recovery

Finally, as indicated by the operations manager, the preconcentrated mineral is heated up to 700 °C with a burner and a torch for melting metals. The mercury evaporates, and 90% of it is recovered, equivalent to 1.8 kg Hg per kilogram of gold. Nonrecovered mercury is emitted to the environment or is inhaled by the workers and amounts to about 8.6 kg per year. The obtained gold has a very high purity (99.5%) and is sold directly to jewelry makers.

### Transportation

The energy necessary for the water pumps and to remove and transport the equipment is obtained from diesel motors. Diesel (D2) necessary for the equipment (one backhoe, one front loader, and two trucks) is 78,800 gallons (gal)[6], or 297,910 kg, during the year. The amount of fuel used by the burner (for the concentration of the gold and separation of the mercury) is insignificant and was not included in the calculation. The lubricating oil for the motors (motor oil) used for the extraction equipment in one year was 8,343 kg.

In this phase, the following wastes or emissions were identified and included in the LCI: motor oil emissions (8,343.2 kg per year) and tires from the machines (4.2 tonnes per year are abandoned in areas owned by the company). Other solid wastes, such as household garbage, were not considered in the study and have therefore not been inventoried.

Thirteen tonnes of sand per gram of gold is removed and disposed of in an open space. No planned or appropriate destination is available. Practices of water and waste treatment were not analyzed due to lack of data. Results are shown in table 2.

## Case 2: Life Cycle Inventory of Artisanal Underground Gold Mining and Concentration

### Background Information

The period of analysis was 12 months (September 2004—August 2005). The association extracts between 25 and 30 kg of gold (80.0% concentration) per year. This study examines a group of artisanal mining activities in the Sancos district (Lucanas province, Ayacucho) in the south-central area of Peru. This small town is located 2,400 m above sea level. The area is 574 kilometers (km)[7] from Lima and is accessible by public transportation by land. Each member works about 240 days per year, and they are broken into groups of five to 8 members. The activities are organized under a workers' association called the Sociedad de Trabajadores Mineros de Santa Filomena (SOTRAMI; Association of the Mining Workers of Santa Filomena), which has about 160 members and 240 external cooperators, including the relatives.

The areas of mining and extraction are semiarid, with almost no precipitation at all. The land is dry and sandy; vegetation is scarce and mainly includes desert bushes. Climatic conditions are a mix of strong hot fronts and slight cold fronts.

The energy used is cogenerated and is based on diesel (D2). Water is transported more than 10 km from the river Laytaruma. A volume of 10,000 liters (L) is consumed per year in the process of concentration and cleaning, and another 6,000 L is used for general services.

### Description of the Processes to Obtain Gold

To obtain gold in this mine, the company performed the following processes: drilling and blasting, first selection, transportation, second selection, grinding, milling, amalgamation, panning, and concentration, as shown in figure 3

### Excavation, Drilling, Explosion, and Extraction

Electric drills (each drill can extend up to a depth of 0.5 m) or manual methods are used to drill into the soil, where dynamite is then laid and exploded. This operation weakens the rocks and allows for the opening of tunnels of 0.8 m width and 1.6 m height. The water is used before and after the drillings to clean the dust.

### First Selection

On the basis of the miners' experience, a first selection of the mineral with higher concentration of gold is done inside the mine before the materials are transported to the next selection area.

**Table 2** Inputs, emissions, and resources recovered from 1 kilogram gold concentrate (99.5% gold) produced: Case 1

| *Impact parameters* | *Unit* | *Category* | *Excavation* | *Extraction* | *Concentration, amalgamation, recovery of Au and Hg* | *Transportation* | *Electricity generation* | ***Total*** |
|---|---|---|---|---|---|---|---|---|
| Lubricants | kg | Raw material | 154 | 30 | N/A | 1 | 8 | **193** |
| Mercury | kg | Raw material | 0 | 0 | 2 | 0 | 0 | **2** |
| Diesel consumed | kg | Raw material |  | 5,520 | 1,051 | 8 | 315 | **6,894** |
| Fresh water consumed | t | Resource, from river | 0 | 49,019 | 0 | 0 | 0 | **49,019** |
| Land transformed | $m^2$ | Resource, from forest to mining |  | 373 | 0 | 0 | 0 | **373** |
| Mined ore | t | Resource |  | 23,922 | 0 | 0 | 0 | **23,922** |
| Gold | kg | Product | 0 | 0 | 1 (99.5%) | 0 | 0 | **1 (99.5%)** |
| Mercury | kg | Recovered | 0 | 0 | 1.8 | 0 | 0 | **1.8** |
| Mercury (kg) | kg | Emissions to soil | 0 | 0 | 0.14 | 0 | 0 | **0.14** |
| Mercury (kg) | kg | Emissions to air | 0 | 0 | 0.06 | 0 | 0 | **0.06** |
| $CO_2$ | kg | Air emission |  | 16,191 | 3,084 | 22 | 925 | **20,223** |
| Used tires | kg | Soil emission | 0 | 0 | 0 | 97.2 | 0 | **97.2** |
| Tailings | t | Soil emission | 0 | 74,000 | 0 | 0 | 0 | **74,000** |
| Oil spills | kg | Soil emission | 150 | 30 | 0 | 1 | 8 | **189** |

*Note*: Au = gold; Hg = mercury; kg = kilogram; t = tonne; $m^2$ = square meter; $CO_2$ = carbon dioxide.

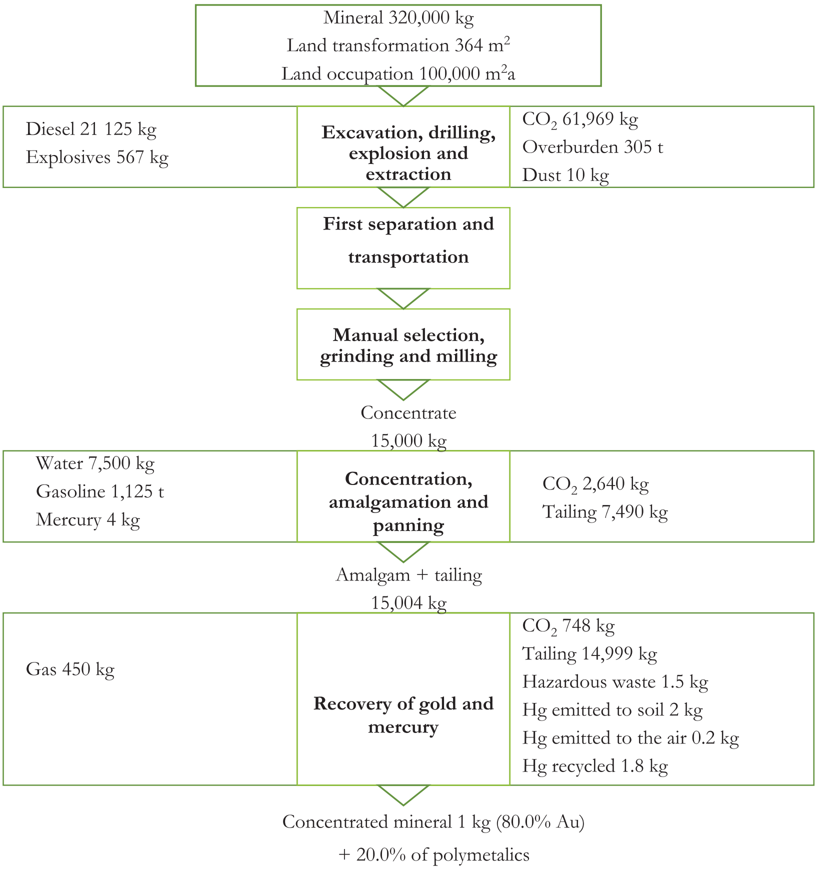

**Figure 3** Product system with inputs and outputs to obtain 1 kilogram of gold concentrate (80.0% gold): Case 2. kg = kilogram; $m^2$ = square meter; $m^2a$ = square meter years; $CO_2$ = carbon dioxide; t = tonne; Hg = mercury.

### *Transportation*

The workers carry about 20 kg of the selected mineral in their backpacks from the area of extraction to the area of selection outside the mine. Until 2004, this work was also done by children, who carried a smaller quantity of the material. Child labor has ceased since 2006, thanks to the awareness efforts of the Gama (Environmental Management in Artisanal Mining) project in Peru (Gama 2008).

### *Manual Selection of Materials, or Pallaqueo*

In this phase, women of mining families separate the mineral according to size before the grinding process. Women protect their respiratory system with a simple cloth mask and wear metal gloves to protect their hands when dealing with sharp rocks. About 50% of the material is removed as overhead and is partially reintroduced into the mine as a method of final disposal. The concentration of gold obtained is 133 g per ton.

### *Grinding*

The selected materials are ground with machines or large hammers in family mills to reduce their size. The daily production of each family is a metal drum containing about 30 kg of concentrated ore.

### *Milling*

Families share a number of ball mills with a capacity of 220 to 450 kg, which are powered with a diesel engine and reduce the size of the ore to 2 centimeters (cm) in diameter. Water from the Laytaruma River is used for the operation of these mills.

#### *Concentration and Amalgamation*

*Quimbaletes* (or rocking grinders) are used to concentrate the gold. Each *quimbalete* consists of a stone placed on a large tray. The stone is in continuous movement through a mechanism that allows workers to balance themselves on top. Another worker adds mercury during the process, pressing and mixing the ore with mercury. The amalgamation process lasts an average of 20 minutes.

#### *Panning*

The ore is thrown in a pan with mud, which leaves some mercury remaining on top. The ore concentrate, known as alloy, is then separated due to its high concentration of gold (one-third of the alloy is gold, and two-thirds is mercury).

#### *Concentration of Gold and Recovery of Mercury (Refogado)*

The family heats the filtered mixture to produce evaporation to recover the mercury and obtain the gold concentrate. Each family uses about 2.0 kg of mercury and recovers 1.6 kg daily (0.4 kg of new mercury is needed each day).

### *Tailings and Wastes*

The mud waste is called tailing and contains 10 to 43 grams of gold per ton and traces of mercury. Therefore, these wastes are sold to intermediate processing centers in the region that carry out additional concentration processes, such as cyanidation. The color of the tailing produced varies from red to white or black, depending on the composition of the soil.

No data were obtained about the generation of used tires. The amounts of lubricants used and oil spills could not be estimated here. The results are shown in table 3.

## Calculating Carbon Dioxide Emissions

With respect to the calculation of carbon dioxide ($CO_2$) emissions from diesel equipment, 29,334.31E-4 kg $CO_2$ per kilogram of diesel was used as the emission factor, on the basis of stoichiometry that uses $C_{10}H_{20}$ (cyclodecane) without complete combustion (80% of the carbon was converted into $CO_2$). A factor of 80.0% was applied for gasoline (US EPA 2005) to the emission factor estimated previously. On the basis of stoichiometry, 1.497 kg $CO_2$ per kilogram of gas methane was used as the emission factor. We recognize that these values are only estimations and that further analysis is required for valid $CO_2$ totals.

## Discussion of Results

It is important to remember that the results of the LCIs produced (Cases 1 and 2) are not comparable because of the different functional units and thus the discussion below does not aim to compare them. With the exception of mercury emissions, a high uncertainty exists, caused by a lack of formal information and the fact that obtained data were available for only 1 year of operation.

It seems relevant to discuss findings of Cases 1 and 2 in the light of results from studies on large-scale gold mining activities. Fonseca (2010) highlighted the evolution of reporting in view of corporate social responsibility in mining activities; however, no quantitative data were presented for the purpose of an analysis or for LCIs. Conversely, Classen and colleagues (2007), the Ecoinvent Centre (2007), and Mudd (2007) provided quantitative indicators, especially for large-scale mining activities. It is worth noting that Mudd (2008) analyzed a large sample of big mining companies but addressed only a limited number of environmental indicators (water consumption, $CO_2$, and mercury emissions, where available). Classen and colleagues (2007) and the Ecoinvent Centre (2007) analyzed a rather small sample of large mining sites (nine countries in North America, South America, Africa, and Australia/Oceania) but provided detailed LCIs according to ISO 14040 (ISO 2006a) and 14044 (ISO 2006b) standards.

All LCIs presented in these studies were related to the production of 1 kg of gold. Classen and colleagues (2007) and the Ecoinvent Centre (2007) provided the degree of the gold produced,

**Table 3** Inputs, emissions, and resources recovered from 1 kilogram gold concentrate (80.0% gold) produced: Case 2

| *Impact parameters* | *Unit* | *Category* | *Excavation and extraction* | *Concentration and amalgamation* | *Recovery of Au and Hg* | ***Total*** |
|---|---|---|---|---|---|---|
| Mercury | kg | Raw material | 0 | 4 | 0 | **4** |
| Explosives | kg | Raw material | 567 | 0 | 0 | **567** |
| Diesel | kg | Raw material | 21,125 | 0 | 0 | **21,125** |
| Gasoline | kg | Raw material | 0 | 1,125 | 0 | **1,125** |
| Gas | kg | Raw material | 0 | 0 | 450 | **450** |
| Fresh water consumed | kg | Resource, from river | 7,500 | 0 | 0 | **7,500** |
| Land transformed | $m^2$ | Resource | 364 | 0 | 0 | **364** |
| Mined ore | kg | Resource | 320,000 | 0 | 0 | **320,000** |
| Gold | kg | Product | 0 | 0 | 1 (80.0%) | **1 (80.0%)** |
| Mercury | kg | Recovered | 0 | 0 | 1.8 | **1.8** |
| Overburden | kg | Emissions to soil | 305,000 | 0 | 0 | **305,000** |
| Tailings | kg | Emissions to soil | 0 | 7,490 | 14,999 | **22,489** |
| Mercury | kg | Emissions to soil | 0 | 0 | 2 | **2** |
| Mercury | kg | Emissions to air | 0 | 0 | 0.2 | **0.2** |
| Hazardous waste | kg | Emissions to soil | 0 | 0 | 1.5 | **1.5** |
| Dust | kg | Air emissions | 0 | 10 | 0 | **10** |
| $CO_2$ | kg | Air emissions | 61,969 | 2,640 | 748 | **65,357** |
| Dust | kg | Air emissions | 10 | 0 | 0 | **10** |

*Note*: Au = gold; Hg = mercury; kg = kilogram; $m^2$ = square meter; $CO_2$ = carbon dioxide.

which is not the same in all cases. It is possible to verify that the order of magnitude varies a lot among all the studies, as shown in figure 4.

Both studies performed in A&Sma resulted in a much higher amounts of diesel consumption and emissions of $CO_2$ per kilogram of gold than the amounts presented by Classen and colleagues (2007) for large-scale mining activities. Water consumption was also much higher in Case 1 because there was no water recycling. In Case 2, the water restriction in the region resulted in much less consumption and therefore lower figures, similar to the case of the large-scale gold mining activity in Peru.

All information obtained to develop the LCIs of gold from A&Sma suggests that each mining activity is different from the other and, furthermore, different from large-scale mining.

The average land transformation caused by large-scale mining activities is 110.5 $m^2$ per kilogram of gold, according to Classen and colleagues (2007) and the Ecoinvent Centre (2007), with a standard deviation of 111.0, which suggests that each mine is different from the other. Land transformation might be a very important issue, especially in rainforest areas; nevertheless, it was not possible to discuss the differences or commonalities between LCIs of large-scale gold mining and of A&Sma due to the lack of data.

Mercury releases to the environment per kilogram of gold extracted in Cases 1 and 2 varied from 0.2 to 2.2 kg. These values are consistent with results found in the literature. A selection of mercury emissions to environment is presented in table 4.

As for mercury, even though it was recycled, the amounts released to the environment per gram of gold in Cases 1 and 2 were also higher than amounts released by big companies. The accounting of mercury emissions is to be considered relevant information at national and local levels for future policy-making processes dealing with the abatement and consumption reduction of this toxic metal in the upcoming United Nations Environment Programme Mercury International Treaty (UNEP 2009).

Regarding the possibility to extrapolate captured information on mercury emissions to the South American region, the variation is

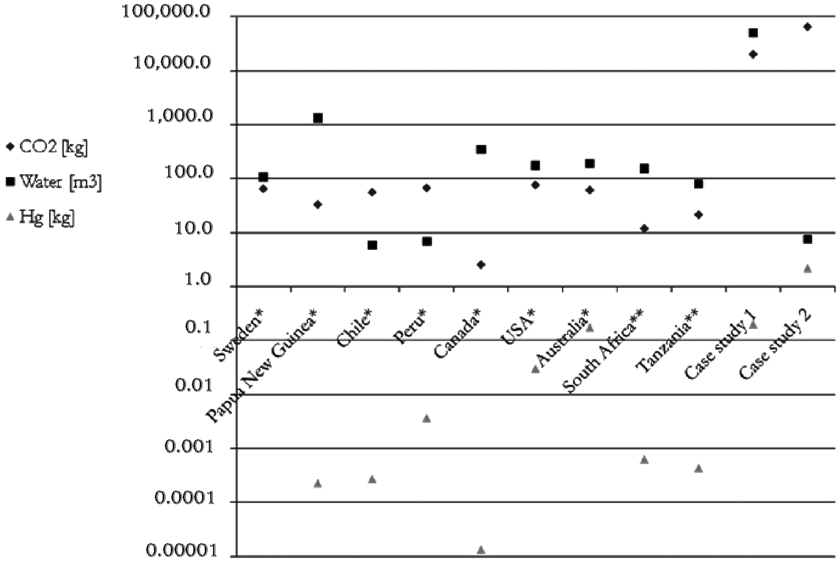

**Figure 4** Comparison of carbon dioxide ($CO_2$) emissions, water consumption, and mercury emission per kilogram of gold in large mining operations in various countries and Cases 1 and 2 of this study. Source: *Classen et al. (2007), **Ecoinvent Centre (2007). $CO_2$ = carbon dioxide; kg = kilogram; $m^3$ = cubic meter; Hg = mercury.

significant, and we do not recommend using the data as averages. Mercury footprints estimated per kilogram of gold vary from 0 to 10 kg for all technologies available or from 0.2 and 2.2 kg in case mercury recovery takes place.

**Table 4** Mercury emissions in artisanal and small-scale gold mining activities (Wotruba et al. 2004)

| *Mining: metallurgical approach or process* | *Grams of mercury emissions per kilogram of gold concentrated*[a] |
|---|---|
| Amalgamation in open flow | 1,000 to 10,000 |
| Amalgamation in closed circuit with mercury recovery | 10 to 1,000 |
| Gold-mercury splitting process (especially for the open burning of the amalgam) | 500 to 2,000 |

[a] The concentration of gold was not indicated.

## Conclusions and Recommendations

The present study shows the LCI of gold extracted in two A&Sma in Peru and verifies that very few data are available for A&Sma compared to large-scale mining activities. Even so, some important data concerning mercury and its effect on water consumption and land transformation were obtained for different processes located in regions with different ecosystems.

### *Application of Results*

Findings presented in this article can contribute to improved understanding by stakeholders of A&Sma's implications.

- International initiatives and organizations are increasing the number of activities and resources invested to reduce environmental and health impacts of A&Sma. A leading organization in this area is the Chemicals Branch of UNEP, which is leading the mercury program toward an international mercury treaty in the coming years (UNIDO

2007). For example, baseline estimates of mercury use and emissions are created to plan future reduction targets, and, hence, a good-quality accounting is needed.
- Local and central government representatives need more training on and awareness of the critical aspects of A&Sma, how to enhance and implement national environmental programs, and how to support the implementation of international treaties, such as the upcoming mercury treaty. Government entities may strengthen in this way their capacities to enhance local mechanisms for eliminating mercury, reducing emissions, recovering soil and watersheds affected, and so on.
- A&Sma mining associations and owners of mining and concentration installations need more awareness and training to better relate the implications of their decisions on the A&Sma activities for the workers and their families and adapt their technologies to avoid negative impacts.

The best decision is the one based on the best available information. A limited number of indicators can support a robust national environmental policy (UNEP 2008a, 2008b). Thousands of LCIs provide data; however, bridges to decision makers for a broader use and understanding are still lacking (Sonnemann et al. 2011), especially in developing countries. The approach suggested for data collection can support the development of databases of unit processes of gold A&Sma. Furthermore, although the results of Cases 1 and 2 may seem limited, decision makers are encouraged to use them and to generate more indicators on the basis of the methodologies suggested for the benefit of the societies concerned.

### *Further Research Needs*

Except for the A&Sma indicator on mercury, there are not sufficient data to generate other indicators to allow a discussion on their extrapolation to a South American context. Only after obtaining a better understanding of the amount of gold extracted by means of the different existing technologies in South America, on the basis of a representative sample of studies, can researchers eventually propose and analyze a regional mercury footprint. In this sense, we propose to improve the representativeness of the sample of activities of A&Sma in the region by conducting more case studies of gold A&Sma and extending the data collection to other countries, including Colombia, Ecuador, Bolivia, and Brazil.

If differences are identified between the main gold concentration processes as well as between small and large-scale operations, a South American database could be improved. Unit processes could be appropriately documented, including estimations of amounts of gold produced per type of technology (amalgamation, cyanidation, and other chemical-free processes, e.g., the Green Gold [Oro Verde] Program in Chocó, Colombia; Amichoco et al. 1999), amounts of mercury recovered in case of amalgamation processes, amounts of water used, and pollutants and $CO_2$ emissions generated.

Another improvement that should be highlighted in further studies of the A&Sma is the generation of enhanced specific data related to land use aspects, due to their relationships with different environmental impact categories, such as the biodiversity. In addition, researchers should investigate the environmental impacts caused by these activities, considering the different characteristics of the regions where they are located. Finally, to facilitate potential comparison of LCIs, more research is needed regarding the sensitivity of results in relationship to the degree of the concentrated gold produced.

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## Notes

1. One tonne (t) = $10^3$ kilograms (kg, SI) ≈ 1.102 short tons.
2. One kilogram (kg, SI) ≈ 2.204 pounds (lb).
3. One gram (g) = $10^{-3}$ kilograms (kg, SI) ≈ 0.032 troy ounces.
4. One cubic meter ($m^3$, SI) ≈ 35.3 cubic feet ($ft^3$).
5. One square kilometer ($km^2$, SI) = 100 hectares (ha) ≈ 0.386 square miles ≈ 247 acres.
6. One gallon (gal) ≈ 3.79 liters (L).
7. One kilometer (km, SI) ≈ 0.621 miles (mi).

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