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Socioeconomic cost of dredge boat gold mining in the Tapajós basin, eastern Amazon

Julia Queiroz[a,*], Pedro Gasparinetti[a], Leonardo B. Bakker[a], Felipe Lobo[b], Gustavo Nagel[c]

[a] Conservation Strategy Fund, CSF - Av. Churchill, 129, RJ, 20020-050, Brazil
[b] Center for Technological Development (CDTec), Universidade Federal de Pelotas (UFPel), Pelotas, 96010-610, RS, Brazil
[c] School of Ocean and Earth Science, University of Southampton, Southampton, SO17 1BJ, UK

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ABSTRACT

With the rapid expansion of artisanal small-scale gold mining (ASGM) in the Brazilian Amazon, an increasing number of studies have attempted to estimate the impacts and socio-environmental costs of ASGM using economic valuation methods. However, most studies focused on alluvial gold mining and few examined dredge boat mining, leading to an under-estimation of the overall impact of ASGM in some regions. The objective of the present study was to develop a methodology for assessing the socio-environmental costs of dredge boat mining in the Tapajós watershed. We developed a method linking the type of gold mining, type of pump, motor power required, time spent in exploration, and mercury use with the average socioeconomic cost. We identified 13 boats in the Tapajós basin in 2020 using satellite images. The total socioeconomic cost of dredge boat mining was US $6.4 million in 2020 (i.e., US $142,556 per kilogram of gold or US $588,887 per ferry). The estimated dredging impact cost may reach US $14.7 million for an optimistic scenario, which would reach US $443.9 million when considering accumulated impact over 30 years. These findings can contribute to a more accurate economic valuation of illegal dredge boat mining, providing valuable information for estimating compensation fines and planning law enforcement investments to prevent illegal ASGM.

1. Introduction

In recent years, illegal artisanal small-scale gold mining (ASGM) has been expanding in the Brazilian Amazon, leading to significant social, economic, and environmental impacts in the region (BRASIL, 2020). The upward trend is explained by increasing gold prices and new policies to relax the current environmental regulations. In 2019, deforestation in the Amazon region caused by ASGM reached the highest values since the beginning of its computation in 2015. Illegal small-scale miners favor low-cost techniques, typically associated with the use of mercury, which affects forests, soils, watersheds, animals, and humans, generating both short- and long-term consequences.

Gold mining (both alluvial and dredge boats gold mining) leads to erosion and siltation and significantly affects water bodies and watersheds (Moreno-brush et al., 2020; Veiga and Hinton, 2002). In addition, anthropogenic disturbances in aquatic environments (particularly in headwater streams) affect the ichthyofauna of the main rivers and their tributaries (Araújo, 1998; Meyer et al., 2007). Furthermore, increased erosion and siltation produce adverse on- and off-site effects in rivers (Mol and Ouboter, 2004). Suspended and deposited sediments increase water turbidity, altering the structure of fish assemblages (Dias and Tejerina-Garro, 2010); negatively affecting the development of fish embryonic, feeding behavior, and species richness (Chapman et al., 2014) as well as microcrustaceans and sessile organisms (Villardi, 2017); and causing eutrophication of waterways and reservoirs (Colombo and Calatrava, 2002), among many other impacts. However, the measurement of these impacts and the consequent social costs is rather complex. There is no direct link between gold extraction processes and soil erosion and sedimentation, as these specific ecosystem impacts depend on many variables, such as context specificity (climate, water type, slope, and biodiversity) and measurement methods.

Given its importance, an increasing number of studies have attempted to estimate the impacts and socio-environmental costs of ASGM using economic valuation methodologies (CID, 2011; Steckling

Abbreviations: ASGM, artisanal small-scale gold mining; RAISG, Amazon Network of Georeferenced Socioenvironmental Information; DALY, disability-adjusted life year; USLE, Universal Soil Loss Equation.

* Corresponding author.
E-mail address: julia@conservation-strategy.org (J. Queiroz).

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et al., 2014; Kahhat et al., 2019). However, most of these studies focused on alluvial gold mining (Meaza et al., 2017; Gulley, 2017; Green et al., 2019), and few examined dredge boat mining (Bezerra et al., 1996). Consequently, there remains a methodological gap related to the impact assessment of dredge boat mining, resulting in the underestimation of the total impact of ASGM in certain regions, such as the Tapajós basin in the Brazilian Amazon.

Most studies quantifying the impact of artisanal gold mining have focused on alluvial exploration (CID, 2011; Miranda, 2019), and there is incipient literature on the assessment of dredge boat gold mining and its association with gold exploration processes and ecosystem impacts. For instance, Lobo et al. (2016) demonstrated a direct relationship between gold mining in the Crepori River (in the Tapajós basin) and increased suspended solids concentration in the water. However, the authors did not estimate the socioenvironmental impact of gold mining in this region. Furthermore, only a few studies have addressed the productivity of dredge boat mining (Bezerra et al., 1996).

The use of dredge boats leads to physical changes in aquatic habitats (Smokorowski and Pratt, 2007; Araújo, 1998; Meyer et al., 2007), negatively affecting fish embryonic development, feeding behavior, and species richness (Chapman et al., 2014) as well as water circulation and current patterns (Harvey et al., 1998). Other impacts are related to increases in the concentration of suspended solids and turbidity (Wenger et al., 2016), reduction in light penetration (Jones et al., 2016), resuspension of nutrients and organic matter (Bridges et al., 2008), and changes in water quality (Fischer et al., 2015; Mol and Ouboter, 2004).

The relationship between the biophysical impacts of dredge boats and their monetary values remains unclear. There is no direct link between gold extraction processes and soil erosion and sedimentation, as these specific ecosystem impacts depend on many variables, such as pump motor power (Porto, 2006), plowed material volume (UPAN, 1989, Embrapa Pantanal, Sd), raft operation time (da Silva et al., 2012), and gold productivity (Bezerra et al., 1998; Cooperativa dos Garimpeiros da Amazônia –, 2013; Amade and Mota de Lima, 2009).

In this context, the objective of the present study is to estimate the socioeconomic costs of dredge boat gold mining impacts. The specific objectives are to identify what are these impacts, quantify them and estimate a related economic value. The hypothesis is that the social and environmental costs of dredge boat gold mining are greater than its private economic benefits. In order to do that, we present a methodology for estimating the impacts and socioeconomic costs of gold exploration through illegal dredge boat mining in the Tapajós watershed. The present study complements Gasparinetti et al. (in press), who developed a methodology to calculate the socioeconomic impacts of artisanal alluvial gold mining in the Brazilian Amazon. Our findings partially fill the gap in the literature concerning the quantification and economic valuation of dredge boat mining impacts. We hope that the quantification and economic valuation of dredge boat mining impacts presented here will aid public and private decision-making regarding gold exploration and law compliance, thus avoiding irreversible damage to the environment and human health.

2. Material and methods

2.1. Study area

With a total area of 528,756.12 km2, the Tapajós hydrographic basin is located mainly in the Brazilian state of Pará and represents approximately 10% of Brazil's Legal Amazon. Its population is 2.4 million inhabitants, based in 76 municipalities, accounting for 8% of the total population of Brazil's Legal Amazon.

The most populous city in the basin is Santarém (Pará), with 306,480 inhabitants, followed by Altamira (Pará) with 115,969 and Itaituba (Pará) with 101,300 inhabitants. There are seven federal protected areas[1] covering a total area of 59,092.58 km^2 (ICMBio, 2021), falling entirely within the basin, and 15 indigenous lands (IL), which are home to inhabitants who directly depend on the region's natural resources (ISA, 2021).

Illegal gold mining is a relevant issue among various environmental threats in this region. In the primary rivers and their tributaries, many dredge boats operate in search of gold. With their large-scale and deep dredgers, ferries continuously remove soil from the rivers, dredging their sediments and leaving trails of destruction along their path. In dry land, powerful soil-digging machines advance along the narrow ways of the forest to search for gold at the riverside or in soil deposits (alluvial mining). They pave roads and create craters in the middle of the forest, leaving a chessboard drawn in the landscapes of the many protected areas and indigenous lands in the Tapajós Basin.

Based on data from the Amazon Network of Georeferenced Socio-environmental Information (RAISG) in Portuguese (RAISG, 2018), there have been 2,571 outbreaks of illegal alluvial gold mining on the mainland in Legal Amazon. Of these outbreaks, 964 occurred in the Tapajós basin, with 334 in conservation units (UCs) and 442 in Munduruku (IL) (Fig. 1 shows the points on the map). The RAISG data do not include dredge boat points because of the complexity of identifying and mapping these non-fixed gold exploration sites.

Itaituba, also called the "Gold City," is one of the main municipalities impacted by illegal gold mining. Although requests regarding concession for legal gold exploration have decreased, mineral production continues to grow in the city.[2] According to the National Gold Association, 500–600 kg of gold is extracted from the "Gold City" in a month, but only 20% of that amount comes from legalized areas. In 2014, approximately 70% of the inhabitants of Itaituba lived directly or indirectly off gold mining activities (ENRIQUEZ,).

In addition, in both dredge boats and alluvial mines, part of the mercury used to extract gold enters the water and soils of the Tapajós Basin. When lost, mercury enters the food chain following

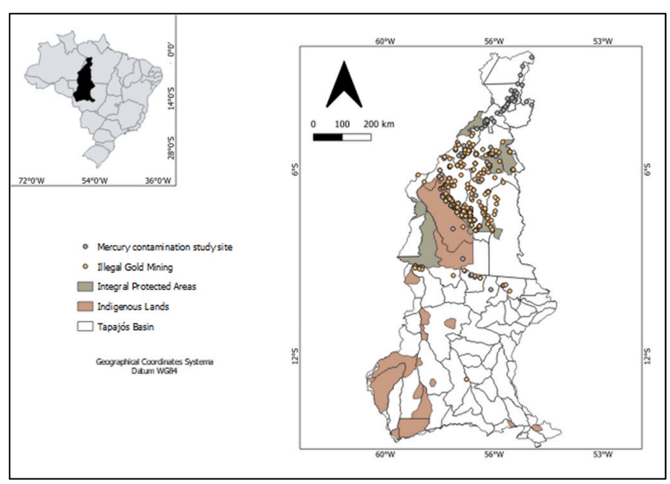

Fig. 1. Protected areas, indigenous lands, and illegal mining points in the Tapajós basin.
Source: Elaborated by the authorsbased on data from RAISG and Mercury Observatory (2021).

[1] There are eight other federal protected areas that are partially located in the basin.

[2] High gold price boosts illegal mining in the Amazon. Portal Gazetaweb.com. Available at: <https://gazetaweb.globo.com/portal/noticia/2020/08/alta-no-preco-do-ouro-impulsiona-garimpo-ilegal-na-amazonia_112936.php>.

bioaccumulates in fish. Mercury becomes extremely toxic upon transformation to methylmercury, and frequent ingestion of contaminated fish by indigenous and riverside communities may lead to severe health problems. Additionally, as the Tapajós basin is one of the principal water sources in the Amazon region, these toxic contaminants can spread to the urban areas within the basin.

2.2. Dredge boat mapping

To calculate the socioeconomic impacts of dredge boat mining, we assumed two potential impacts: mercury and siltation. The methodology comprises four steps: dredge boat mapping; assessment of siltation impact; economic valuation method development; and development of mercury valuation method. We detail these steps in sections 2.2 to 2.5.

We mapped dredge boats in the Tapajós River (the main river in the Tapajós basin) and its tributaries from June to August 2020 (a period with less cloudy images) using Sentinel 2 satellite images available on the Google Earth Engine cloud computing platform. Subsequently, we created and overlapped a heat map to identify the areas most dredged for gold extraction.

We used original color bands with a spatial resolution of 10 m. Because the small size of the boats prevents the identification of vessel contours, we developed a specific methodology to characterize the operation of these ferries in clearwater rivers (such as the Tapajós river). The ferry activities in these locations lead to sediment resuspension, increasing water turbidity.[3] This turbidity contrasts with the characteristic of clear rivers, which appear in dark color on images due to the high radiometric absorption of water. In this context, ferry sites have a high reflectance point (white spot), followed by a plume of sediment downstream (Fig. 2, example 1).

This plume sediment may start homogeneously and dissipate downstream in more linear flows (Fig. 2, example 2), or it may start generating vortices in the regions of more turbulent flow (Figs. 2 and 3). In the shallow parts of the river, the spectral responses of submerged sandbanks may resemble those of sediment plumes. Of note, however, due to depth variations, sandbanks present a non-continuous spectral reply and can therefore be differentiated from sediment plumes (Fig. 2, example 3).

2.3. Siltation measurement

We assumed that the median dredge plowing (water + sediment) capacity is 300 m^3 h^{-1} (i.e., 7,200 $m^3 \cdot day^{-1}$ or 216,000 m^3 $month^{-1}$) (DNIT, 2021; 2021 Allonda,). Based on literature (Amade; Lima, 2009; Bezerra et al., 1996; Cooperativa dos Garimpeiros da Amazônia –, 2013), the average gold production of dredge boats is 0.48 kg $month^{-1}$, that is, 5.71 kg $year^{-1}$. When we divide the production value by dredge plowing capacity, the productivity of the dredge boats is 0.0022 ($g \cdot m^{-3}$).

Therefore, the amount of sediment and gold produced per month must be calculated, depending on the boat pump power. We used the pump power equation to estimate the total mud plowed (Q) and the association between the power and flow of the hydraulic pump (equation (1)) (Porto, 2006). In equation (1), we express pump power in horsepower (Pcv), the specific gravity of fluid in Kgf·m-3, pump flow in m-3 ·s −1, manometric height (Hm) in meters, and pump efficiency in %.

$$Q = (Pcv \times n \times 75) / (\gamma \times Hm) \qquad \text{Equation 1}$$

where

Q = Flow in $m^3 \cdot s^{-1}$

Pcv = Pump power in cv (1 cv = 0.98 hp)

Hm: Head loss (Hc − m) + suction height (Hs − m)

γ: Specific weight ($Kgf \cdot m^{-3}$)

n: Pump yield (%)

Based on the equation, we can establish the association between power and mudflow per second (m3 ·s −1) and month (m3 ·month-1). Considering that 10% of one cubic meter of mud is composed of solids (sediments) (Poloski et al., 2009; Addie et al., 2005), the mudflow was multiplied by 0.1 to calculate sediment flow per month. Then, we multiplied this value by gold productivity (0.0022 g·m-3) to estimate the amount of gold extracted per month from the pumped sediment. We multiplied the sediment volume (m3 ·month-1) by the density of 2.76 (Klein, 2002; Lima et al., 2007) to estimate the sediment production in tons per month (ton·month-1) through the mining activity.

The parameters of equation (1) were estimated to represent the average conditions of gold mining activity, thus ensuring that the equation can be applied to all gold mining rafts operating in the Amazon. Because mining activities typically use old pumps with little maintenance, 40% yield has been stipulated (Porto, 2006). This performance is associated with the hydraulic and mechanical losses within the pump, which dissipate energy. Considering that the extracted mud contains 10% sediment and 90% water, we assumed the density of mud to be 1.14 (Willard, 2009) and specific weight to be 11,142 $Kgf \cdot m^{-3}$ (specific weight of the mud = specific weight of the water × density). We considered the specific weight of water to be 10.000 kN m^{-3}.

Manometric height (Hm) is associated with the energy required by the pump to transport the fluid at a given flow rate to the point designated by the pumping system. This value is associated with the height difference between the beginning and end of the pipe (suction height), its resistance, and its components (head loss). In the case of gold mining rafts, we stipulated an average suction height value of 10 m, which corresponds to the depth of the Tapajós and Madeira rivers (de Cortes et al., 2021). We measured pressure loss in meters per meter of pipe (m·m-1). This value depends on several variables, such as the flow rate of the fluid and the type, state, length, and the number of curvatures and valves of the pipe (Porto, 2006).

Because of the difficulty in obtaining this parameter, we calculated head loss from a reverse account. Using gold production data in the field obtained by Bezerra et al. (1996) for low- (35.5 hp), moderate- (54.7 hp), and high-power pumps (73 hp) (Table 1), reverse counting was performed, and head loss was estimated (dependent variable) to be equal to the gold production calculated by Imazon (tabulated).

Using this methodology, we estimated a head loss of 0.28 m m^{-1}, or 2.8 m in a 10-m-long pipe (Table 2). To calculate monthly values, the daily workload was considered to be 12 h. Of note, the parameters in Table 2 are fixed and should not be changed to suit individual situations (unless there are data for new calibration of the parameters).

Table 3 and Graph 1 show the relationship of pump power with the calculated and observed gold production. The reference (Bezerra et al., 1996) and calculated (obtained by hydraulic equations) gold values are similar because of the calibration of input parameters (Table 2) in the pump power equation (equation (1)). Consequently, the calculated gold production tends to be below the reference value for higher powers (Graph 1). This underestimation is desirable for the application of fines for illegal mining activities.

Table 3 demonstrates a linear relationship between gold production and engine power. All values obtained by dividing gold production by motor power[4] were close to 0.006, which we adopted as a fixed parameter. In other words, by multiplying the engine by 0.006, we obtain the value of gold production per month. Based on this value, we calculated total gold production in any context depending on the

[3] The identification of dredge boats is considerably simpler in clear than in white waters due to easier observation of suspended sediment.

[4] If the engine power is 35.5, gold production will be 2.57. If the power is 3.97, gold production will be 0.33.

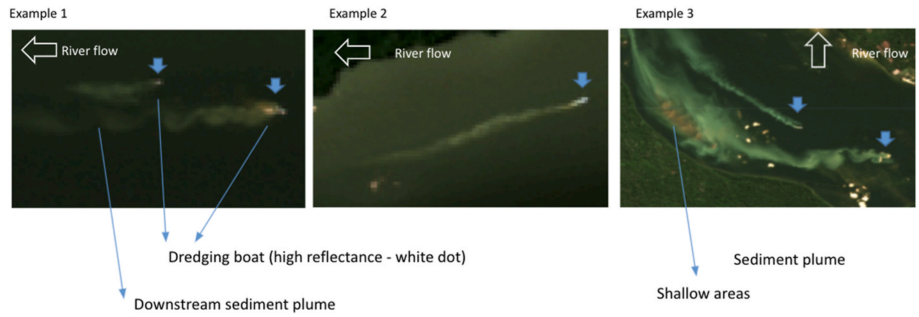

Fig. 2. Dredge boats in the Tapajós River.
Source: Elaborated by the authors

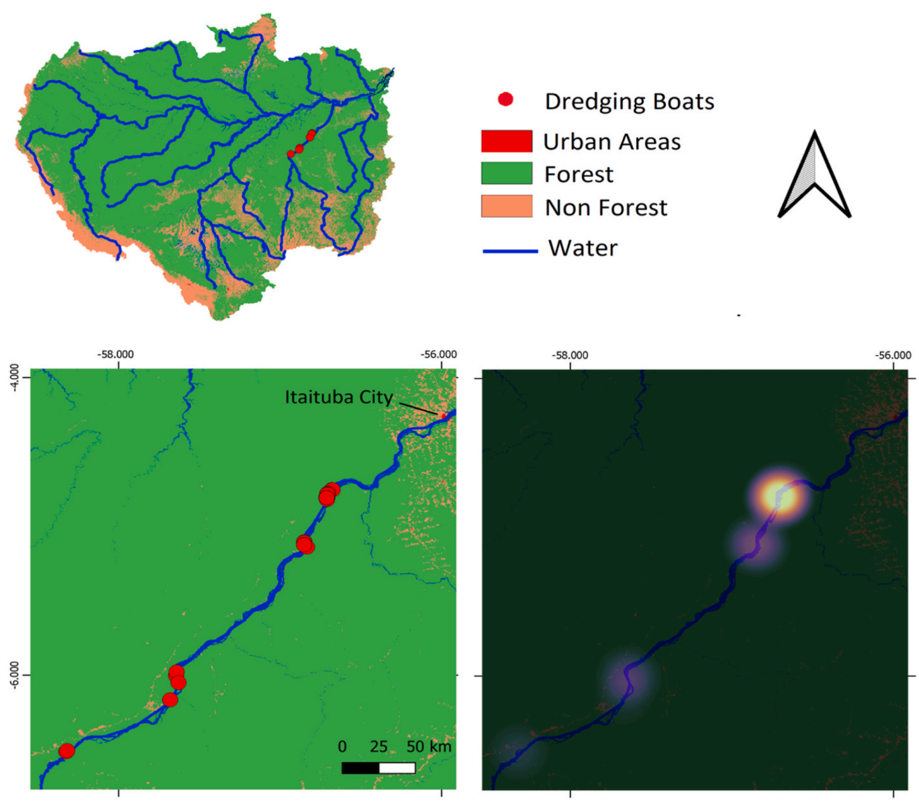

Fig. 3. Identification of gold mining ferries in the Tapajós River in 2020.
Source: Elaborated by the authors

Table 1
Relationship between pump power and gold production in the Tapajós region, Pará.

Pump power	Low (<35.5 cv)	Moderate (35.5–54.7 cv)	High (>73cv)
Production (g/year)	2.577 ± 1.902)	3.723 ± 1.668)	7.190± 7.080)

Source: Elaborated by the authors

Table 2
Parameters used and calculated to estimate the flow of gold mining pumps.

Pump Yield	40%
Suction height	10 m
Head loss	2.28 m in a 10 m of pipe
Y (specific weight)	11.172 Kgf·m-3

Source: Elaborated by the authors

number of months the ferry operated at each location. To calculate the amount of mined material, we divided gold production by the productivity of 0.0022 that we calculated initially.

As a dredge sucks only 10% of sediment and the rest is water, we can also calculate the total dredged sediment using the following equation:

$$Ts = 0.1 \times [(M \times E \times 0.006 \times 1{,}000) / 0.0022)] \quad \text{Equation 2}$$

where

Ts = Total sediment (m^3)
M = Months of dredge boat operation
E = Engine power (cv)

However, operators deposit most residual sediment discarded from mining activity in the river at that location or nearby. At the time of

Table 3
Calculated and observed pump power and gold production.

Pump power (cv)	Q1 flow rate ($m^3 \cdot s^{-1}$)	Q2 flow rate ($m^3 \cdot s^{-1}$)	Sediment ($ton \cdot year^{-1}$) (Q2 × 0.1)	Estimated gold ($kg \cdot year^{-1}$) (sediment × 0.0022 × 12 months)	Reference gold (Bezerra et al., 1998)	Observed error
35.5	0.08	97348.49	26868.18	2.57	2.57	0.00
54.7	0.12	150194.81	41453.77	3.97	3.72	6.50
73	0.15	200259.75	55271.69	5.29	7.19	−26.47

Source: Elaborated by the authors

residual sediment disposal, a large part of this material is deposited at the river bottom, while a small part (1%–5% of sediment) the river transports to its downstream (Bokuniewicz and Gordon, 1980; Gordon, 1974. In this sense, sediments that turn into plumes generated by the mining activity must be multiplied by 0.05 (because of the clear water) to represent the portion of sediments with potential impact on the river downstream. We convert the sediment into tons by multiplying by a density of 2.76 (Klein, 2002; Lima et al., 2007).

Further dividing the sediment (in tons) by the months for which the dredge boats had been operating at the site and the engine power, we obtained another fixed parameter of 38.82. The latter represents the relationship between these variables. Using this methodology, we developed simple formulas to calculate the production of gold and plume sediment (i.e., sediment that causes direct damage to the environment). The equations used to obtain the parameters and final formulas are as follows:

$$\delta = [(Ts \times 0.05) \times 2.76)] / (E \times M) \quad \text{Equation 3}$$

$$Tg = M \times E \times 0.006 \times 1{,}000 \quad \text{Equation 4}$$

$$Ps = M \times E \times 38.82 \quad \text{Equation 5}$$

where

δ = Plume sediment parameter
Tg = Total gold production (g)
Ps = Plume sediment (ton)

Employing this method, we estimated the total gold and plume sediment produced by the mapped dredge boats in the Tapajós basin. We estimated the average engine power of boats operating in the basin to be 57 cv (Bezerra et al., 1996). We believe that plume sediment is an element that should be taken into consideration when estimating the economic value of environmental impacts considering the marginal turbidity generated in the Tapajós River.

2.4. Economic valuation methodology for siltation impact

The assessment of siltation caused by dredge boat mining is based on a benefit transfer methodology related to erosion control estimation and its values. The idea is to estimate how many hectares of degraded land can generate the same amount of plume sediment as the dredge boats; For this assessment, using the economic valuation method, we can calculate the benefits transfer of erosion control cost.

According to Borrelli et al. (2017), the average annual erosion level is 0.16 t $ha^{-1} \cdot year^{-1}$ in an intact forest and 12.70 t $ha^{-1} \cdot year^{-1}$ in cropland. Thus, assuming the erosion in croplands as the proxy for erosion in gold-mining areas, the difference in erosion between forested land to gold-mining land would be 12.54 t $ha^{-1} \cdot year^{-1}$. In other words, an area impacted by mining activities would generate 12.54 t $ha^{-1} \cdot year^{-1}$ more sediment than an intact forest. Based on this value, the equivalence of impacted hectares (how many hectares of the degraded area can generate the same amount of erosion as the dredge boats) can be calculated by dividing the plume sediment amount (Ps) by 12.54.

In monetary values, the costs of erosion control were obtained from the meta-analysis by De Groot et al. (2012), who estimated the value of US$15 per hectare in tropical forests[5] - which its update led to the US $17.18·per hectare in 2020.[6] Thus, we multiplied the equivalence of impacted hectares by the erosion control cost (the US $17.18·ha-1) to calculate the value of siltation impact caused by dredge boats.

$$Eq = Ps / 12.54 \quad \text{Equation 6}$$

$$Cs = Eq \times 17.18 \quad \text{Equation 7}$$

where

Eq = Equivalence of impacted hectares
Cs = Cost of siltation impact (US$)

2.5. Mercury valuation method for dredge boat mining

Mercury valuation for dredge boat mining followed the same methodology as that for alluvial mining developed by Gasparinetti et al. (in press) and detailed by Bakker et al. (in press). The authors used disability-adjusted life year (DALY) to calculate the health impacts and productivity loss of people exposed to mercury contamination.

Here, we made only one modification related to mercury loss. In alluvial mining, the authors assumed that mercury loss occurred in rivers and soil; In dredge boat mining, we assumed mercury loss was released directly into the rivers. Therefore, we summed the values for soil and river. Table 4 shows the values for alluvial and dredge boat mining.

We used moderate values for mercury spill. Thus, we assumed that 21.8% of the mercury used in illegal dredge boat mining is released into rivers. We converted this mercury to methylmercury, which bioaccumulates in fish. Through such contaminated fish, humans may be at

Table 4
Mercury loss for alluvial and dredge boat mining.

Scenario	Alluvial mining		Dredge boat mining
	Soil	Water	Water
Low	5.6%	7%	12.6%
Moderate	8.8%	13%	21.8%
High	14%	21%	35%

Source: Elaborated by the authors

[5] Among the various studies reviewed by the authors, some calculated the cost of erosion control as the cost of agricultural production loss and increase in agricultural cost, damage to hydroelectric plants and increase in the cost of energy production, damage to fishing resources and travel time of the population from villages to clean water sources.

[6] For the update we used the Consumer Price Index (U.S. Bureau of Labor Statistics, 2021).

risk of mercury exposure.

The phases of mercury contamination upon release into rivers caused by dredge boat mining follow the same phases of contamination caused by alluvial mining as described by Gasparinetti et al. (in press) to calculate the economic impacts of mercury. Instead of selecting a specific municipality as proposed by the authors to estimate the total population possibly impacted by mercury, we used the total population of the Tapajós Basin (2.4 million inhabitants). This modification is justified as most dredge boats operate near large urban centers (such as Itaituba) and as mercury impact can spread over several kilometers from the source (Diringer et al., 2015; Scarlat, 2013; Roulet et al., 1998).

3. Results

On average, we identified 11 different dredge boats along the Tapajós River from June to August 2020, and we did not detect dredge boats in the tributaries.[7] Fig. 3 shows the distribution of ferries, their total in the study period, and the density of the points for the Tapajós River. The number of points collected is on the left side of the image, and their density is on the right side (warm colors represent high density). Even if dredge boats can operate on permission for alluvial gold extraction, we assumed all mapped dredge boats to be illegal because of the historical illegality of the activity in this region.

Fig. 3 shows the areas with a greater concentration of the identified points. We assumed that these areas have a higher concentration of ferries because they have a higher concentration of gold in the riverbed or are close to the urban centers, which would reduce travel costs. For instance, we observed a high concentration of ferries near the city of Itaituba.

We assumed that the dredge boats identified from June to August 2020 have been exploring gold in the region for long periods because of the lack of police inspection prohibiting their activity. Thus, for the subsequent calculations, we considered that these boats explored gold throughout 2020. For the final estimation, we calculated impact of 1-year operation (12 months) per boat and then multiplied the final costs by 11, or we used the total of 132 months (i.e., 11 ferries operating for 12 months each).

Tables 5 and 6 present the non-monetary and monetary impacts of illegal dredge boat gold mining in the Tapajós Basin.[8]

We identified 11 dredge boats, and assuming that each operated for 12 months, we can calculate the total impact over 132 months. Overall, the ferries produced 45.44 kg of gold during this period (i.e., 292,086 cubic meters of plume sediment). For this amount, the total cost of siltation damage was US $288,726. Furthermore, to produce 45 kg of gold, 118 kg of mercury was required, of which 25.8 kg was released into the Tapajós River, potentially impacting 3,563 people. In this context, we estimated 24.9 people at an increased risk of developing cardiovascular diseases, with a social cost of this impact at US $5.4 million.

This level of mercury contamination potentially causes a loss of over 2 IQ points in 1,013 live births in 2020. In other words, we estimated the social cost of mercury contamination at the US $73,004, calculated in terms of DALY and productivity loss. Furthermore, 88 miners were estimated to be at risk of developing neuropsychological symptoms, and we estimated the social cost of this damage at the US $677,417. Finally, we calculated the total socio-economic cost of illegal dredge boat mining for gold at the US $6.4 million for 2020 (i.e., US $142,556 per kilogram of gold or the US $588,887 per ferry).

Over 95% of the socio-economic cost of dredge boat mining we attributed to the health recovery costs (the US $6,169,027) for neuropsychological symptoms, cardiovascular diseases, and mild mental retardation among miners and inhabitants exposed to mercury contamination, and the remaining 5% is attributed to dredge boat siltation (the US $288,726). This cost would increase even further, considering the maximum values for mercury loss (as described in Table 4). Thus, assuming the mercury loss of 35%, the health recovery and productivity loss cost would increase from the US $6.1 million to US $13.4 million, and the amount of mercury released into rivers would increase from 25 to 41.4 kg.

Assuming the gold price of US $59.095 per kilogram (Gold Price, 2021), if we incorporate the social cost in conventional economic analysis of dredge boat mining, the activity will not be economically viable. In addition, Bezerra et al. (1996) have estimated a profit margin of approximately US$2.6 (per gold gram). Therefore, for 45.44 kg of gold produced in the Tapajós basin, the profit would be the US $118, 144, which can cover only 1.82% of the total impact cost of dredge boat mining in the region, further asserting the assumption of socioeconomic non-feasibility of this activity.

Table 5
Non-monetary impacts of illegal dredge boat gold mining in the Tapajós Basin.

Non-monetary impacts of dredge boat mining (2020)	
Number of dredge boats	11
Total months of gold extraction (11 ferries operating for 12 months each)	132
Gold production (kg)	45.44
Plowed material (m^3)	58,417,276
Sediments removed (m^3)	5,841,728
Sediment that generates plume (impact) (m^3)	292,086
Mercury used (kg) (2.6 kg per kg of gold)	118.1
Mercury spilled into rivers (kg) – (21.8%)	25.8
Population of the Tapajós basin	2,400,000
Population potentially affected by methylmercury ingestion	3,563
Population with additional cardiovascular disease risk caused by mercury contamination	24.9
Number of live births that can lose at least 2 intelligence coefficient (IQ) points due to high average maternal mercury contamination	1,013
Number of illegal miners with neuropsychological symptoms	88

Source: Elaborated by the authors

4. Discussion

To the best of our knowledge, there is no study assessing the impacts of dredge boat mining. Lele (2009) has highlighted that establishing a single value or a range of values for watershed services is highly complicated given the biophysical complexity of river basins as well as the relationship of these values with the type of services provided, such

Table 6
Monetary impacts of illegal dredge boat gold mining in the Tapajós basin.

Monetary impacts of dredge boat mining (2020)	US$
Siltation impact	288,726
Mining-related neuropsychological symptoms	677,417
Live births with IQ loss	73,044
Mining-related Cardiovascular disease risk	5,438,566
Total cost	6,477,753

Source: Elaborated by the authors

[7] In 2020, we did not detect dredge boats along the Tapajós tributaries using Sentinel 2 images in 2020.

[8] The monetary values were converted at an exchange rate of 5.22 R$ per US $, verified on May 11, 2020.

as irrigation, power generation, health, and water supply. For example, the effect of sedimentation on hydroelectric power generation may vary from $4·to $2,000·year-1 ha[1]1.

Based on the Universal Soil Loss Equation (USLE), Macedo et al. (2014) estimate that the cost of environmental impact sedimentation reached US $18.94 ha −1 ·year-1, which is similar to the value reported by De Groot et al. (2012) (the US $17.18 ha −1 ·year-1) used in our study. Although our methodology is not as specific as USLE, our formula delivers results even when the estimation does not include all context variables, which is relevant, for instance, to Brazil's Federal Police, when writing technical reports regarding dredge boat operations, as they do not have time and material to collect specific data.

The economic valuation of erosion control mainly concerns agriculture, with methods using nutrient loss replacement costs, observed damage costs (as a consequence of flooding), and production costs (Alam, 2008; Hacisalihoglu et al., 2010).[9] The values found in the literature are consistent with the erosion control impact of dredge boat mining used in the present study, based on De Groot et al. (2012). Alam (2018) has underscored the need to determine a (distance) decay function depending on the context (climatic conditions and decline[10]). For dredge boat mining, this estimation is even more complex as the ferries move along the river, and siltation caused by the ferries depends on motor power, location, and climate conditions, among other factors. In the face of the current impossibility of establishing a (distance) decay function, our methodology based on the estimation of plume sediment to calculate the economic value relative to the equivalence of impacted hectares offers a solution for this measurement.[11]

The mercury impact values are alarming, as inhabitants from all parts of the Tapajós basin are exposed to a high level of mercury contamination. Mercury is a global pollutant with known toxic properties, and the World Health Organization considers it is one of the ten most hazardous chemicals for human health (Bjørklund et al., 2017). Thus, even though people in Santarém (one of the largest cities in Pará) consume lower average amounts of fish than riverside communities or indigenous populations, big cities have more people (i.e., higher demographic density) consuming contaminated fish. Among indigenous populations and riverside communities, this scenario is worse because fish is the fundamental source of protein for these populations.[12] In a study with the World Wild Fund for Nature, Fiocruz (2020) showed that the indigenous peoples in Munduruku (located in the middle of the Tapajós watershed) are exposed to high levels of mercury contamination.[13]

According to the recent Mercury Observatory (2021) database, 75 studies have addressed mercury contamination in the Tapajós basin. Without control of the dredge boat mining, the potential impact on rural and urban areas and indigenous lands can be enormous. Bakker et al. (2021) have reported estimates for the indigenous population in Yanomami (located in the Brazilian state of Rondônia) and discussed the enormous socioeconomic impact and economic value of this issue.

5. Conclusion

The present study developed an innovative methodology to link even the initial processes of dredge boat mining to the valuation of its impacts. We considered the type of gold mining, pump specificities, and motor power, time spent in exploration in the socioeconomic costs of mining estimation, as these variables are some of the main factors determining sediment amount. However, as we could not specify the type of environmental service affected by siltation, we opted for a methodology of benefit transfer valuation based on erosion equivalent hectares.

Despite being innovative, our methodology has some important limitations. Our model does not capture many specificities in a biophysical context. We did not consider factors that are extremely important for the erosion and siltation estimation, such as river length, decline, climatic variations, fish assemblage composition, and suspended solid variations depending on the level of natural turbidity. Moreover, we only calculated the economic cost of siltation from plume sediment. We also did not assess the effects of soil movement on microorganisms and river flow and the consequent ecosystem impacts. Thus, we may have underestimated the total economic cost of dredge boat mining calculated using the proposed methodology. Even though the contribution of dredge boat gold mining to the overall value is small for the Tapajós region,[14] it is still significant compared with the economic value of alluvial ASGM.

In the present study, we developed a methodology (which we can apply in different contexts[15]) that provides robust estimates of economic values and highlighted the higher potential for mercury contamination in dredge boat mining than in alluvial mining. In case of limited resources and time to develop a case study, our methodology can fill the literature gap on the economic valuation of the impacts of dredge boats mining. In an upper-bound scenario, the cost of dredging impacts will be US $14.7 million. It will reach US $443.9 million, considering accumulated impact over the 30 years, and billions of dollars in just a year if we combine the latter cost with the alluvial mining one.

Therefore, our methodology to estimate the cost of dredge boat mining can be considered the first step toward calculating the total cost of illegal mining and providing inputs to combat these illegal activities. This information may be useful for Federal Police when writing technical reports, for public prosecutors when estimating damage fines for mining, and for policymakers when enacting restrictions on illegal mining activities. Although these costs do not take into consideration the individual choice of economic agents because of illegality, while there is a lack of punishment, law compliance remains weak, and there are no credible systems for gold sale, in addition to many other factors promoting this illegal activity, dredge boat mining will remain a severe threat to watershed ecosystems and human health. In other words, the most accurate economic valuation of illegal dredge boat mining would provide the most reliable information for decision making.

Author statement

All authors have seen and approved the final version of the manuscript being submitted. The article is the authors' original work. It hasn't

[9] The authors used fertilizer prices to calculate replacement costs and estimated the average cost of soil loss at the US $59.54·ha-1 ·year-1 for pasture lands and US $102.36 ha-1 ·year-1 for agricultural lands.

[10] The author also emphasized little empirical evidence on this issue.

[11] Another parameter for the valuation of the impacts of erosion and siltation is fisheries loss, which may be assessed using willingness to pay for the maintenance of the species (Ressurreição et al., 2011), or replacement or production cost (Van Beukering et al., 2003). However, we did not have enough elements to establish a function between ASGM siltation and fisheries loss.

[12] For instance, riverside communities along Tapajós consume an average of 189 g of fish per day (Hacon et al., 2020). Meanwhile, indigenous people consume up to 100 g of fish per day (Fiocruz, 2020), since they hunt for other animals, in addition to fishing. Urban populations such as Belém (Pará) also follow a relatively diversified diet and rely on other protein sources; therefore, their average fish consumption is only 57 g per day (Mangas et al., 2016).

[13] Among the participants of their hair collection survey to estimate mercury contamination, 57.9% presented mercury levels exceeding 6 μg g -1—the maximum safety limit established by health agencies. In communities closer to mining rivers, this percentage was even higher. Furthermore, children presented high contamination levels, with 15.8% exhibiting problems on neurodevelopmental tests.

[14] According to Gasparinetti et al. (in press), the impact cost of alluvial gold mining was US $1.4 billion in 2020.

[15] Mainly where ferries dominate gold production (e.g., Madeira River in the Amazon Region).

received prior publication and isn't under consideration for publication elsewhere.

Data availability

Data will be made available on request.

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