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Eleven years monitoring the modern gold rush in the southern Amazon

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ABSTRACT: Gold mining has been increasing in Brazil and worldwide since 2000, causing negative effects on the environment and surrounding communities due to deforestation of open mines and the degradation of soil and rivers. This activity is historically important in the northern Brazilian state of Mato Grosso, Southern Amazon, but integrated studies are lacking. The current research sought to map areas of active alluvial gold mining in this region from 2009 to 2019, relating it to fluctuations in the national gold market as a tool for inspection, prevention and mitigation of related environmental damage. The study was carried out by remote sensing with LANDSAT and IRS satellite images in six stages, ranging from the survey of gold mines found *in loco* to the analysis of the relationship between the evolution of exploited areas and the price of gold. Eight mining zones were identified. The exploited areas were dimensioned by year and mining zone, indicating an overall 195% growth. This growth was not homogeneous among the mining zones. The true price per gram of gold increased by 56.62% during the study period. Mining fronts have approached and/or encroached on conservation units and indigenous lands. The relationship between price variation and the area exploited was significant and positive in the eight zones (α=0.05). This was the first detailed mapping of gold mines at the regional level in eleven years to support effective public policies in overcoming persistent socio-environmental conflicts related to the activity.
Keywords: Amazonian rivers from the Brazilian Shield; deforestation; conservation units; indigenous lands; small-scale mining; Tapajos basin.

Onze anos monitorando a moderna corrida do ouro no sul da Amazônia

RESUMO: A mineração de ouro vem aumentando no Brasil e no mundo desde 2000, causando efeitos negativos ao meio ambiente e às comunidades do entorno devido ao desmatamento para abertura de minas e à degradação do solo e dos rios. Essa atividade carrega importância histórica no norte do estado brasileiro de Mato Grosso, sul da Amazônia, mas há uma carência de estudos integrados a respeito. A presente pesquisa buscou mapear áreas de mineração de ouro aluvial ativa nessa região de 2009 a 2019 relacionando-a às flutuações do mercado nacional de ouro como ferramenta de fiscalização, prevenção e mitigação de danos ambientais relacionados. O estudo foi realizado por sensoriamento remoto com imagens de satélite LANDSAT e IRS em seis etapas, abrangendo desde o levantamento das minas de ouro encontradas in loco até a análise da relação entre a evolução das áreas exploradas e o preço do ouro. Oito zonas de mineração foram identificadas. As áreas exploradas foram dimensionadas por ano e zona de mineração e indicaram um crescimento geral de 195%. Esse crescimento não foi homogêneo entre as zonas de mineração. O preço real por grama de ouro aumentou 56,62% durante o período do estudo. Frentes de lavra mineral se aproximaram e/ou invadiram unidades de conservação e terras indígenas. A relação entre variação de preço e área explorada foi significativa e positiva nas oito zonas (α=0,05). Este foi o primeiro mapeamento detalhado de minas de ouro em onze anos em nível regional para embasar políticas públicas efetivas na superação de conflitos socioambientais persistentes relacionados à atividade.
Palavras-chave: Rios Amazônicos do Escudo Brasileiro; desmatamento; unidades de conservação; terras indígenas; mineração em pequena escala; bacia do Tapajós.

1. INTRODUCTION

The exploitation of gold through artisanal and small-scale mining (ASGM) is carried out by around 16 million miners in developing countries in tropical regions, accounts for 17 to 20% of all the gold mined in the world and provides income for many poor communities (SECCATORE et al., 2014). Large areas of densification of this type of gold mining have been reported in South American countries encompassing parts of the Amazon, such as in the regions of Madre de Dios in Peru (Plenge et al., 2012), Bene in Bolivia (Coelho et al., 2013), Portovelo-Zaruma in Ecuador (Miserendino et al., 2013), Mojana in Colombia (Pinedo-Hernández et al., 2015), Guayana in Venezuela (Lozada 2017), Guyana (Hook 2018), French Guiana and Suriname

(Dedieu et al., 2015). The ASGM in the Brazilian Amazon expanded during the 1970s, with the most traditional area being the Tapajós basin in Pará but with later advancement to the southeast of that state and in northern Mato Grosso. This growth had negative consequences for the environment, such as the conversion of primary forests into mining fronts (Swenson et al., 2011; Asner et al., 2013; Kalamandeen et al., 2018), as well as siltation, erosion of banks and the discharge of untreated effluents into rivers (LOBO et al., 2016; KEITA et al., 2018). Chemical pollution due to the uncontrolled use of mercury in gold purification has contaminated workers and Indigenous communities via inhalation of inorganic mercury vapor and consumption of contaminated fish (TELMER et al., 2007; ASHE, 2012; GIBB et al., 2014; CASTILHOS et al., 2015). In addition, working conditions are often unhealthy and have a high risk of accidents, generating conflicts between operations owners and their workers (SALMAN et al., 2017).

The construction of the Cuiabá-Santarém highway drove gold mining in the Southern Amazon, BR-163, inaugurated in 1976 (HOGAN et al., 2002). At its peak, between 1984 and 1987, this region produced ten tons of gold a year, reaching 20% of all gold mined in the Brazilian Amazon (WANDERLEY, 2015). Production in the region declined in the 1990s with the depletion of deposits, restrictions imposed by the federal government and the fall in the price of gold. Beginning in the 2000s, the price of gold rose again, reaching historic highs (VEIGA et al., 2002; WANDERLEY, 2015). The valorization of gold followed the disorderly expansion of ASGM, causing increased damage to the environment and the health of workers and residents of adjacent communities in developing countries (SWENSON et al., 2011). The rise in the price of gold from 1999 to 2012 was responsible for a 400% expansion in deforested areas to open new mines in the region of Madre de Dios in Peru (Asner et al., 2013) and 50% in the area exploited by ASGM enterprises in the region of Tapajós river basin in Brazil (LOBO et al., 2016). Kolen et al. (2013) identified a movement between 1990 and 2010, due to the recent rise in the price of gold, towards recolonizing regions in the Brazilian Amazon with gold deposits that were previously considered depleted, leading to an increase in the number of gold miners from approximately 20,000 to 200,000.

The small-scale gold mining in the Amazon is characterized by great mobility and illegality, making control by inspection and regulatory bodies extremely difficult (WANTZEN et al., 2013). Little is known about aspects of this activity, such as the area covered, type and scale of mining, and socio-environmental impacts, with a large part of this lack of knowledge stemming from a lack of a precise mapping of mining areas (LOBO et al., 2018). Studies of ASGM in the Southern Amazon in Brazil have reported specific cases of impacts on the environment and the health of local populations, such as: environmental degradation on the banks of the Rio Peixoto de Azevedo (SOUZA et al., 2008), encroachments of conservation units and indigenous lands, proliferation of the vector of malaria due to water accumulated in abandoned pits (Maciel et al., 2014; Galardo et al., 2013), exposure of pregnant women to mercury (Hacon et al., 2000) and technological and cultural aspects of the ASGM world (MASSARO et al., 2018).

Our study, as far as we know, is the first to map and monitor areas of ASGM over eleven years in the Southern Amazon in the Amazonian Rivers from the Brazilian Shield using satellite images from 2009 to 2019. It aims to identify zones of occurrence, characteristics regarding the pace of opening mining fronts and the association of the area and age of ASGM with fluctuation in the national gold market. Our findings will be integrated to outline trends in economic activity and the associated environmental impacts in the short and medium term.

2. MATERIAL AND METHODS

The methodology used involved six steps: (1) survey of records of gold mining sites located in northern Mato Grosso, Southern Amazon; (2) identify and demarcate active ASGM areas using satellite images (3); validate demarcated areas based on control points in the field; (4) identify mining zones and dimension active ASGM areas by year and zone of occurrence; (5) survey average annual gold prices on the market; and (6) analyze the relationship between the area of active ASGM and the average gold price per year.

The geoprocessing, georeferencing and construction of geographic maps were performed with the Geographic Information System (GIS) programs Arcmap 10.1® of the Environmental Systems Research Institute (ESRI) and TerraView® 5.3.3 of Instituto Nacional de Pesquisas Espaciais (INPE), using the SIRGAS 2000 horizontal projection datum on the 21S zone.

2.1. Study area

The study area was established based on a survey of gold mining sites addressed by expert examinations carried out by the criminal expertise unit in the Federal Police headquarters of the city of Sinop, state of Mato Grosso, Brazil (UTEC/DPF/SIC/MT), which occurred from 2009 to 2019. These locations are all located in the Northern Region of Mato Grosso as defined in state law (Mato Grosso 2015), with an area of 95,850 km², covering 15 municipalities in the Juruena, Teles Pires and Xingu river basins, tributaries of the Amazon river basin as shown in Figure 1.

According to the digital map on the Ministry of the Environment (MMA) website, this area is in the southern portion of the Amazon biome. The climate is warm and humid equatorial, with average temperatures above 18°C and two to three dry months during the year. The vegetation comprises transitional forest formations between the Cerrado and Amazon biomes. The soil of the dystrophic Red Yellow Argisols and dystrophic Red Latosols predominate (Empresa Brasileira de Pesquisa Agropecuária 2011).

2.2. Survey and characterization of ASGM areas

Areas of occurrence of ASGM activity were obtained from expert reports produced by UTEC/DPF/SIC/MT, for which *loco* inspections were carried out. The occurrence of alluvial gold mining activity was verified for all the surveyed locations according to the standard extraction and processing model divided into five stages as recommended by Centro de Tecnologia Mineral (Rodrigues et al. 1994): (1) stripping; (2) hydraulic disassembly; (3) repression; (4) concentration; and (5) carpet washing/amalgamation.

These operations are perceived by satellite images as follows: (a) areas with the recent exposure of quartz and sand material from subsurface layers produced by excavations and the deposition of tailings from ore concentration cause the appearance of high reflectance pixels in the bands of wavelengths between red and medium infrared, forming spots of bright white color; (b) the advance of mining fronts based on an intuitive search for gold deposits gives these spots an irregular contour; (c) the formation of water bodies in the abandoned pits leads to the occurrence of low-reflectance pixels in the infrared and red bands, forming darkly pointed spots often accompanying the land drainage line as associated with alluvial deposits; (d) bodies of water with suspended sediments increase the reflectance of the water in the infrared bands making the pixels acquire a lighter color. Figure 2 shows that the more recent the gold mining exploration, the greater the reflectance given by the exposure of the quartz material still free from the cover of herbaceous plants (white spots) and the greater the turbidity of the bodies of water due to suspended sediments not fully decanted (light blue pixels).

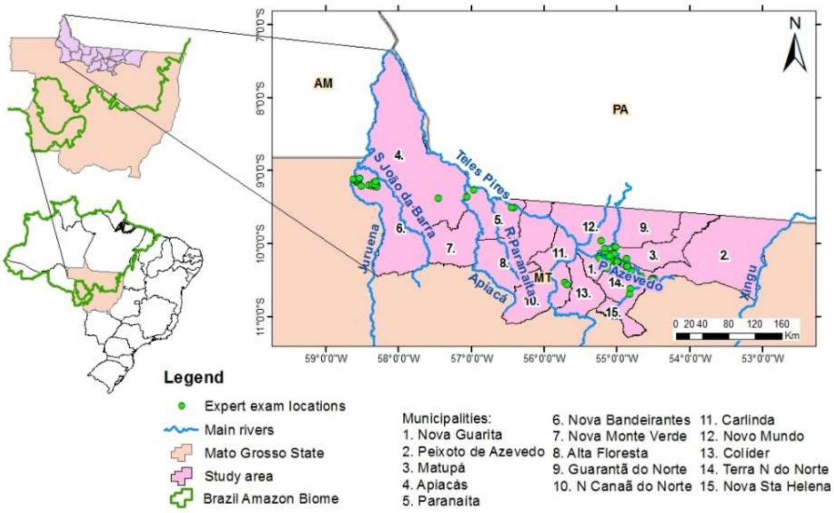

Figure 1. Map of the state of Mato Grosso highlighting the study area established from gold mining sites found in expert examinations by the Federal Police in its northern region, Southern Amazon Biome, Brazil, consisting of 15 municipalities located in the Juruena, Teles Pires and Xingu river basins.
Figura 1. Mapa do estado de Mato Grosso destacando a área de estudo estabelecida a partir de sítios de mineração de ouro encontrados em exames periciais realizados pela Polícia Federal em sua região norte, Bioma Amazônia Meridional, Brasil, composta por 15 municípios localizados nas bacias dos rios Juruena, Teles Pires e Xingu.

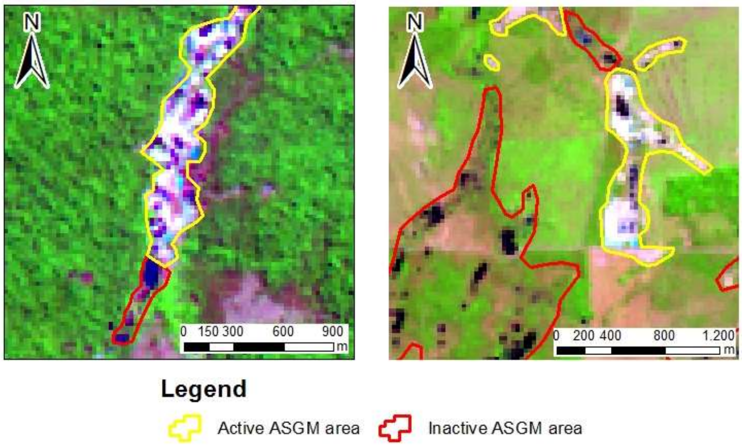

Figure 2. Images from the LANDSAT 8 OLI satellite show active and inactive artisanal and small-scale gold mining (ASGM). In inactive ones, water bodies tend to have cleaner water (dark blue or black), and the soil is pinkish or reddish (red outline polygons). In the active ones, the bodies of water tend to have greater turbidity due to the suspended sediments, presenting a light blue color, and the soil is shiny white due to the high reflectance of the quartz sand materials recently exposed by the excavations and by the deposition of tailings (yellow outline polygons).
Figura 2. Imagens do satélite LANDSAT 8 OLI mostrando mineração de ouro artesanal e de pequena escala (ASGM) ativa e inativa. Nas inativas, os corpos d'água tendem a ter água mais limpa (azul escuro ou preto) e o solo é de coloração rosada ou avermelhada (polígonos de contorno vermelho). Nas ativas, os corpos d'água tendem a ter maior turbidez devido aos sedimentos em suspensão, apresentando coloração azul claro, e o solo é branco brilhante devido à alta refletância dos materiais de areia de quartzo recentemente expostos pelas escavações e pela deposição de rejeitos (polígonos de contorno amarelo).

2.3 Identification and demarcation of ASGM areas

Satellite images from 2009 to 2019 with a spatial resolution of 23 to 30 m from LANDSAT and IRS systems obtained from the National Institute for Spatial Research (INPE) website and the United States Geological Service (USGS) were used as a basis. Images were acquired from the LANDSAT 5 TM (Thematic Mapper) satellites of the LANDSAT system, which operated until 2011, and from LANDSAT 8 OLI (Operational Land Imager), whose images started to be made available in 2013. Images from the RESOURSESAT 1 LISS3 (Linear Imaging Self Scanner) satellite of IRS were acquired for 2012, covering the gap in the LANDSAT system that year.

Images were preferably selected in July for each year due to lower coverage by clouds and smoke from fires. The spectral bands of the medium infrared (1.55 µm to 1.75 µm), near-infrared (0.76 µm to 0.90 µm) and red (0.63 µm to 0.69 µm) were used. Composition in false color is given in the sequence R5-G4-B3 (RESOURCESAT-1 and LANDSAT-5) and R6-G5-B4 (LANDSAT 8) through the program TerraView® 5.3.3. RESOURCESAT images were georeferenced based on images from the same location in the previous year (2011) using ESRI/ArcMap 10.1®.

Support maps were acquired in ESRI/shapefile format with the themes: hydrography and hydrographic basins at a 1:100,000 scale and political division of municipalities at a 1:250,000 scale from the Planning Secretary of Mato Grosso State (SEPLAN MT, 2012); biomes, national conservation units, vegetation and climate at a 1:5,000,000 scale from the MMA; and soils at a 1:5,000,000 scale from EMBRAPA (2001).

Active ASGM areas were identified and demarcated by direct visual inspection of the composed satellite images and using a manual edition of features. The search for these areas started with images captured in 2009 and involved identifying the occurrence of groupings of events compatible with mineral extraction. Doubtful cases were resolved by comparing high-resolution images from Google Earth Pro® and the Bing maps® website. This feature is useful even in cases where these images are from a date later than the images used in mapping since changes due to mineral extraction remain evident after abandonment (Lobo et al. 2016). Areas in regions of high concentration were demarcated, and a review was carried out throughout the study area to identify ASGM areas in regions of low concentration. This procedure was repeated for all images of the subsequent years, with a mapping file in ESRI/shapefile format of the active ASGM areas being produced for each year.

2.4. Validation of the mapping of ASGM areas

Validation of maps of active ASGM was done by comparing the points obtained from expert reports and technical documents of the Federal Police, which were, in this way, considered control points, with ASGM maps for the year in which each examination was performed. The control points were plotted on ASGM maps for the same year, and their corresponding locations were examined. When the control points fell within a polygon of ASGM area carried out in the same year, we had a match, and that area was considered reliable. Points without a corresponding polygon were considered Type 2 errors (false negative for the occurrence of ASGM). Although not evaluated, type one errors (false positives for the occurrence of ASGM) were reduced by identifying mining zones and confronting questionable areas with high-resolution images. This error occurs mainly in urban zones and their surroundings, where it is common to excavate land to execute industrial, housing and infrastructure works.

2.5. Identification of mining zones and dimensioning of ASGM areas

The identification of mining zones was carried out in three steps, as shown in Figure 3's diagram. First, a map of accumulated ASGM areas from the 11 years of the analyzed period was produced through the union of the active ASGM shapefiles of each year in a single file with the elimination of overlaps. Second, a 10 km-wide proximity strip (buffer) was calculated around the accumulated ASGM areas according to the buffer zone concept of environmental conservation units proposed by Alvarez-Berríos et al. (2015) and studies on pollution potential and distance from mining activity carried out by Durán et al. (2013). Third, zones were identified following the criterion of continuous areas obtained in the previous step limited by the perimeter of the pre-established study area. Areas of great extension were subdivided using dividing lines, rivers over 30 m-wide or an imaginary average line relative to land strips without the occurrence of ASGM separating regions of distinct concentration of ASGM areas. In the end, active ASGM areas were dimensioned by year, and mining zones and analyses were made based on the values obtained.

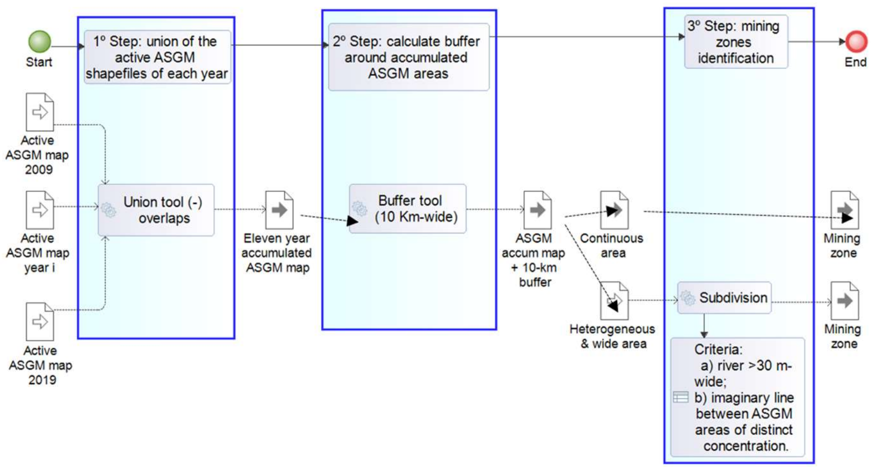

Figure 3. Flowchart representing the process of identifying mining zones: the input data are the shapefile maps of the active ASGM areas of each year, opened in layers in the GIS; in step 1, the shapefile layers are joined to form a single accumulated ASGM map; in step 2, the 10 km width proximity buffer is calculated around the accumulated ASGM areas; in step 3, the well-defined continuous areas are directly identified as mining zone, the large areas with a great diversity of ASGM concentration areas are subdivided.

Figura 3. Fluxograma representando o processo de identificação de zonas de mineração: os dados de entrada são os mapas shapefile das áreas ativas de ASGM de cada ano, abertos em camadas no GIS; na etapa 1, as camadas shapefile são unidas para formar um único mapa ASGM acumulado; na etapa 2, o buffer de proximidade de 10 km de largura é calculado em torno das áreas ASGM acumuladas; na etapa 3, as áreas contínuas bem definidas são diretamente identificadas como zona de mineração, as grandes áreas com grande diversidade de áreas de concentração de ASGM são subdivididas.

2.6. Survey of the price of gold on the national market

To investigate the relationship between the dynamics of active ASGM areas during the study period and movements in the price of gold on the national market, the average annual metal price was calculated from historical daily quotes provided by the Bullion Rates website. The calculated prices were subsequently adjusted for July 2019 by the General Price Index – Internal Availability (GPI-IA) of Getúlio Vargas Foundation (FGV) according to the formula:

$$\text{Ajusted gold price}_{\text{year i}} = \text{nominal price}_{year\ i} \times \text{GPIIA}_{\text{accumulated year i}}$$

where,

$$\text{GPIIA}_{accum\ year\ i} = \left(1 + \text{GPIIA}_{\text{12 year i}}\right) \times \left(1 + \text{GPIIA}_{\text{12 year i+1}}\right) \times \ldots \times \left(1 + \text{GPIIA}_{\text{12 year 2018}}\right);$$

$\text{GPI-IA}_{\text{12 year i}}$ = 12-month IA rate (August of year i to July of year i + 1).

Two alternative hypothetical scenarios were considered for the relationship: the first, in which the market and gold extraction via ASGM moved in a synchronized way, that is, production and the area explored in a given year reflect the price of gold in that same year (relationship *without delay*); and the second, with a delay of one year in the response of the sector about the gold market (relationship *with delay*). These hypotheses are based on the differentiation of the miner profile as proposed by Coelho et al. (2017): if more entrepreneurial, then attentive to the future market and aiming at medium- and long-term results; if more artisanal, then based on an immediate view and aiming at survival, eventually counting on luck and the chance of getting rich quick.

2.7. Data analysis

The relationship between the dynamics of ASGM activity and the evolution of the gold market was analyzed using the generalized linear mixed model (GLMM) function glmmPQL in the Mass package (Venables et al. 2002). This methodology was chosen due to the argument in the function that corrects data with a possible autocorrelation effect. We evaluated the relationship between active ASGM areas and the gold market in the study area as a whole and by mining zone to determine the explanatory power of gold price over the ASGM area in general and the occurrence of sub-regional specificities that influence this relationship considering the two previously-mentioned scenarios as follows: in the *without delay* scenario, the prices from 2009 to 2019 were used with the one-year ASGM area being related to the gold price of the same year; and in the *with delay* scenario, the prices from 2008 to 2018 were used, with the ASGM area of one year being related to the gold price of the previous year. We initially built a first set of general models with 'all zones' included as a covariate, in which case we spatially control autocorrelation. A second set of models was built separately for each zone; in this case, we temporally controlled autocorrelation with the variable 'year of collection' as a covariate in the model. Thus, the model used' plots' as a random variable to control spatial autocorrelation. The statistical significance test was calculated by analyzing Type II square deviations using the Anova function of the car package (Fox et al. 2019). All analyses were performed in the R environment (R Core Team, 2019). The graphs in Figures 11 and 12 were built with the ggplot2 package (WICKHAM, 2016).

3. RESULTS

The Validation of the ASGM maps found 83 of the 90 control points to fall within demarcated polygons for the year referred to for the point; three fell into polygons of subsequent years, and four fell into non-demarcated areas. Thus, a 92% accuracy was achieved in the mapping of active ASGM considering the strict year and 95% considering some delay between the occurrence of the activity and its perception through orbital images. The locations for the 5% undetected control points (Type two error) with the images of corresponding years indicate that this error is due to the limited spatial resolution of the orbital sensors used.

The ASGM areas exploited from 2009 to 2019 were mapped by year according to the image chart shown in Figure 4. Eight mining zones were identified, as shown in Figure 5 and described in Table 1.

Table 1. Description of the gold mining areas mapped as shown in Figure 5.
Tabela 1. Descrição das áreas de mineração de ouro mapeadas conforme Figura 5.

Zone	Description	Hydrographic basin
1	Rural area in the north of the Nova Bandeirantes municipality is far from the urban perimeter along the southern boundary of the Juruena National Park.	Juruena river and São João da Barra river
2	South of the municipality of Apiacás and northwest of Paranaíta along the southern boundary of the Kaiabi Indigenous Land covering the urban area of Apiacás.	Apiacá river, Ximari river, Teles Pires river and São João da Barra river
3	In the northern portion of the municipality of Paranaíta, north of the municipal headquarters.	Teles Pires river
4	They were surrounding the headquarters of Alta Floresta, center and north of the municipality of Carlinda and south of Novo Mundo, bordering the south of the Cristalino State Park.	Teles Pires river and Peixoto de Azevedo river
5	Region of influence of the urban areas of Guarantã do Norte, Matupá and Peixoto de Azevedo, northern portion of the municipality of Terra Nova do Norte and most of Nova Guarita.	Peixoto de Azevedo river
6	Region of the União do Norte district takes the Peixoto de Azevedo municipalities, Matupá, Terra Nova do Norte and Nova Santa Helena.	Peixoto de Azevedo river
7	Surrounding the headquarters of the municipalities of Colíder and Nova Canaã do Norte.	Teles Pires river
8	União da Serra district in the south of Alta Floresta municipality.	Paranaíta river

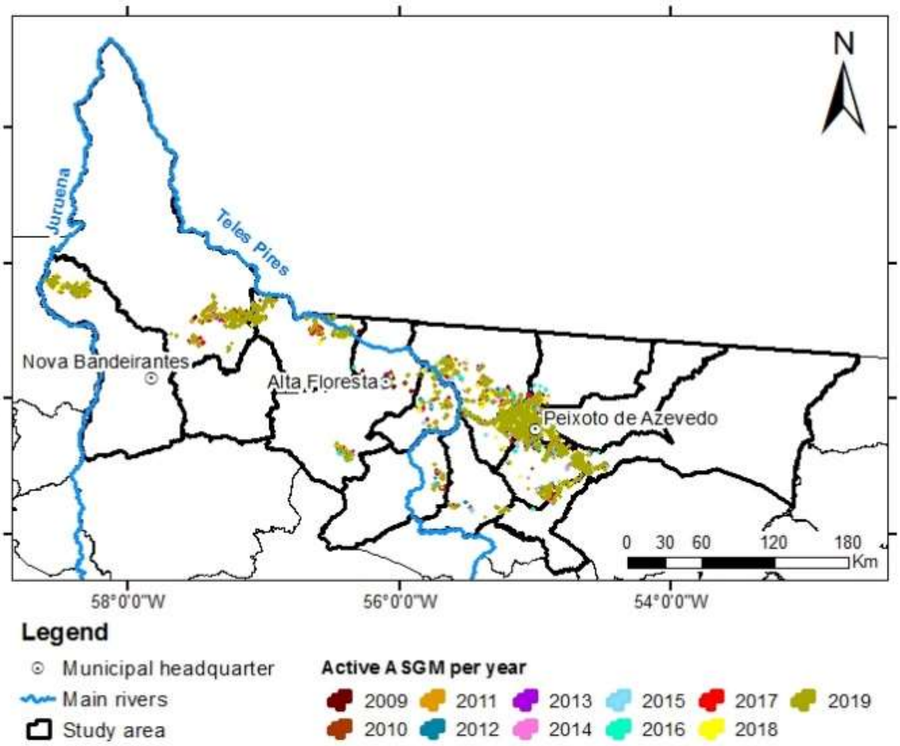

Figure 4. The study area chart shows active ASGM areas between 2009 and 2019.
Figura 4. Área de estudo mostrando áreas ativas de ASGM no período entre 2009 e 2019.

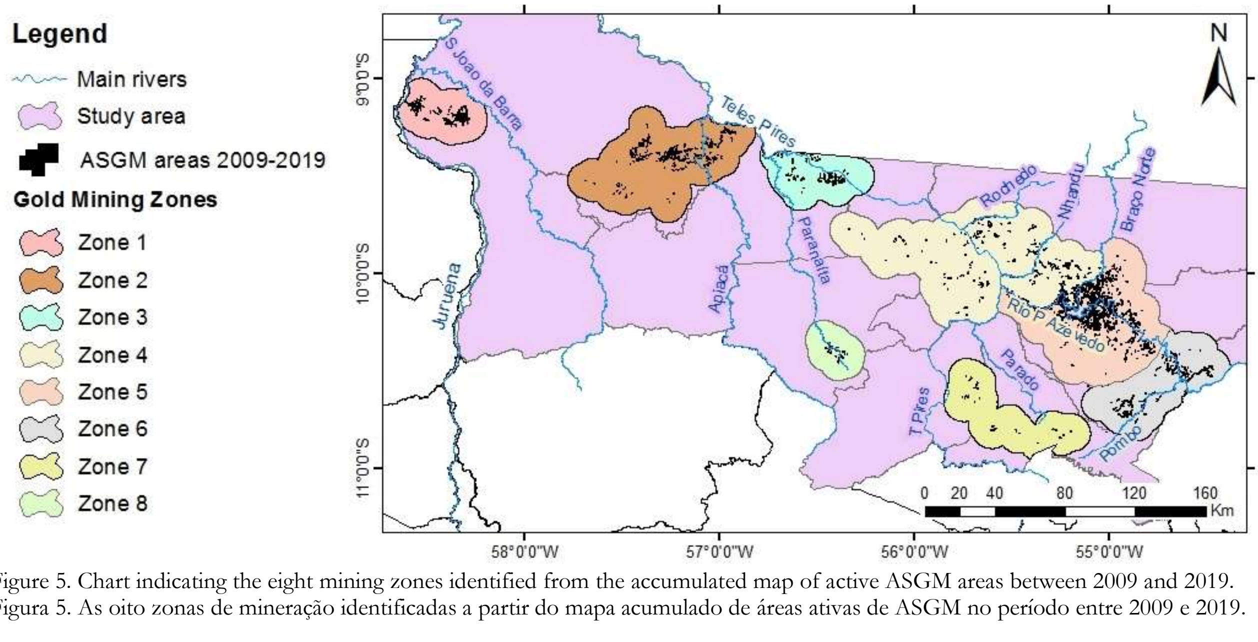

Figure 5. Chart indicating the eight mining zones identified from the accumulated map of active ASGM areas between 2009 and 2019.
Figura 5. As oito zonas de mineração identificadas a partir do mapa acumulado de áreas ativas de ASGM no período entre 2009 e 2019.

Analysis of the maps of mining zones allowed the immediate identification of threats and real impacts of ASGM on protected areas. In Zone 1, the mining fronts encroached on the limits of Juruena National Park between 2016 and 2019, exploiting a total area of 227 ha (see demonstration in Figure 6).

Figure 7 shows the mining fronts advancing downstream of a tributary of the Ximari River in Zone 2 in the northern direction, approaching the southern boundary of Kaiabi Indigenous Land (TI KAIABI). In Zona 4, Cristalino State Park, to the north of the municipality of Novo Mundo (see Figure 8), is threatened. Mining fronts advance north upstream of Rochedo Brook and its tributaries, approaching the southern limit of that conservation unit.

ASGM areas were calculated by year and mining zone; the results are shown in Figure 9. There was a growth of 195% in the area exploited between the first and the last year of the studied period, from 4,016 ha in 2009 to 11,890 ha in 2019, with an average annual growth rate of 13.83%. In the analysis by mining zone, growth was also noted in all but Zone 8. But this growth was heterogeneous. In zones 4, 5, 6 and 7, the growth from 2009 to 2019 was 294%, 212%, 324% and 517%, respectively, while in zones 1, 2 and 3, it was 129%, 119% and 16%; Zone 8 experienced a drop of 9%. During the period, there were downward fluctuations in the area in 2017 and 2019, but they did not occur homogeneously across zones. For example, there were drops in zones 1, 2, 3, 4 and 8 in 2010; in zones 2, 5 and 8 in 2017; in zones 1, 2, 3 and 7 in 2018; and all except zones 2 and 7 in 2019. There was also heterogeneity in spatial distribution. Zones 4, 5 and 6 together concentrated an average of 78.04% of the whole exploited area (7,153 ha), with 54.57% located in Zone 5 (5,000 ha), while zones 3, 7 and 8 only contributed 5.35% (490 ha).

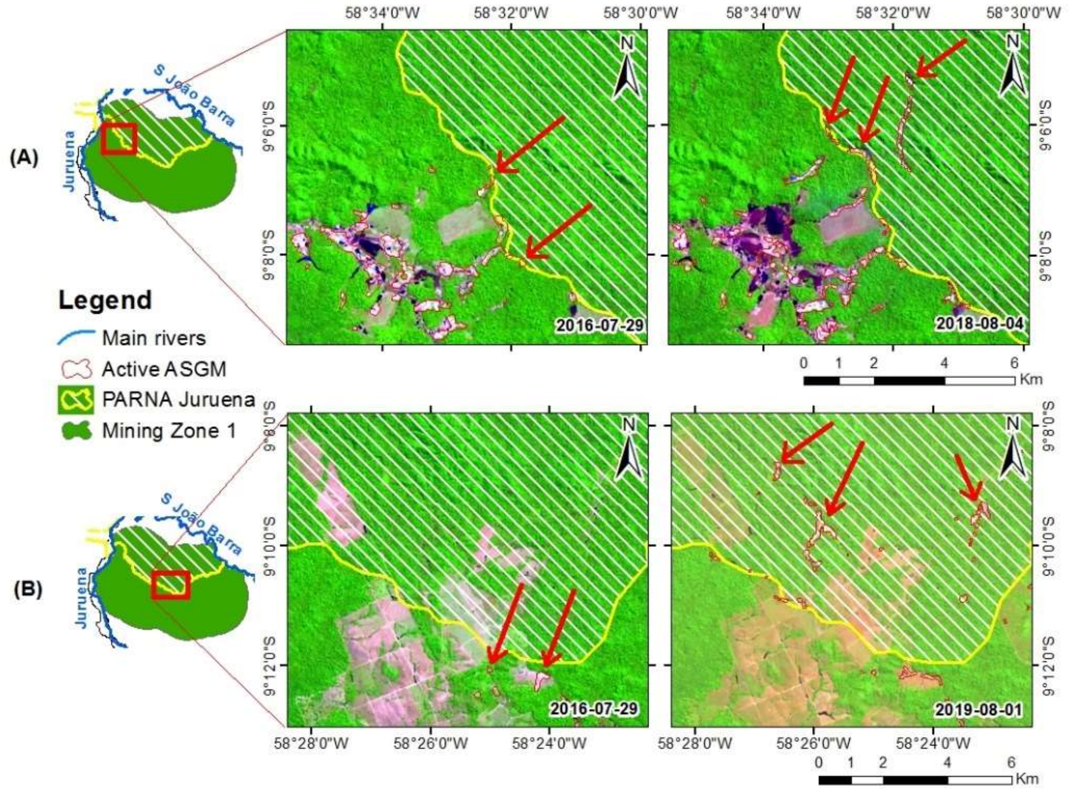

Figure 6. Multitemporal analysis of satellite images of two fragments in Mining Zone 1 (A and B) shows a moment before and another after mining prospectors' encroachment of the southern portion of the Juruena National Park. In fragment (A), the encroachment occurs between July 2016 and August 2018 (see red arrows), and in fragment (B), between July 2016 and August 2019 (red arrows).
Figura 6. Análise multitemporal de imagens de satélite de dois fragmentos na Zona de Mineração 1 (A e B) mostrando um momento antes e outro depois da invasão da porção sul do Parque Nacional do Juruena por garimpeiros. No fragmento (A) a invasão ocorre entre julho de 2016 e agosto de 2018 (ver setas vermelhas) e no fragmento (B), entre julho de 2016 e agosto de 2019 (setas vermelhas).

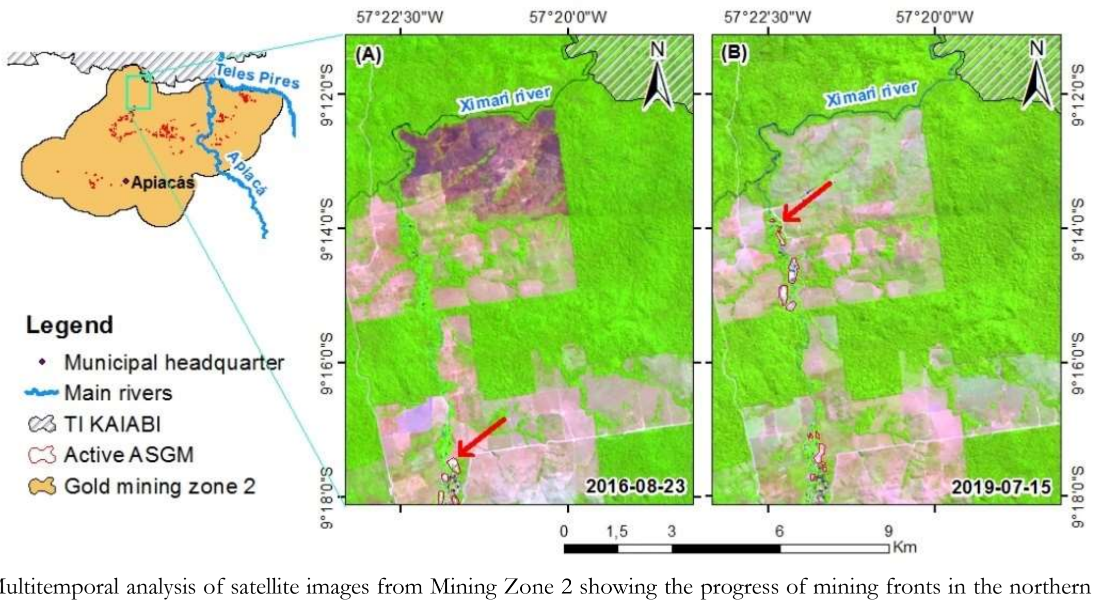

Figure 7. Multitemporal analysis of satellite images from Mining Zone 2 showing the progress of mining fronts in the northern direction approaching TI KAIABI between August 2016 (A) and July 2019 (B), indicated by red arrows.
Figura 7. Análise multitemporal de imagens de satélite da zona de mineração 2 mostrando o progresso das frentes de mineração na direção norte se aproximando de TI KAIABI entre agosto de 2016 (A) e julho de 2019 (B), indicado por setas vermelhas.

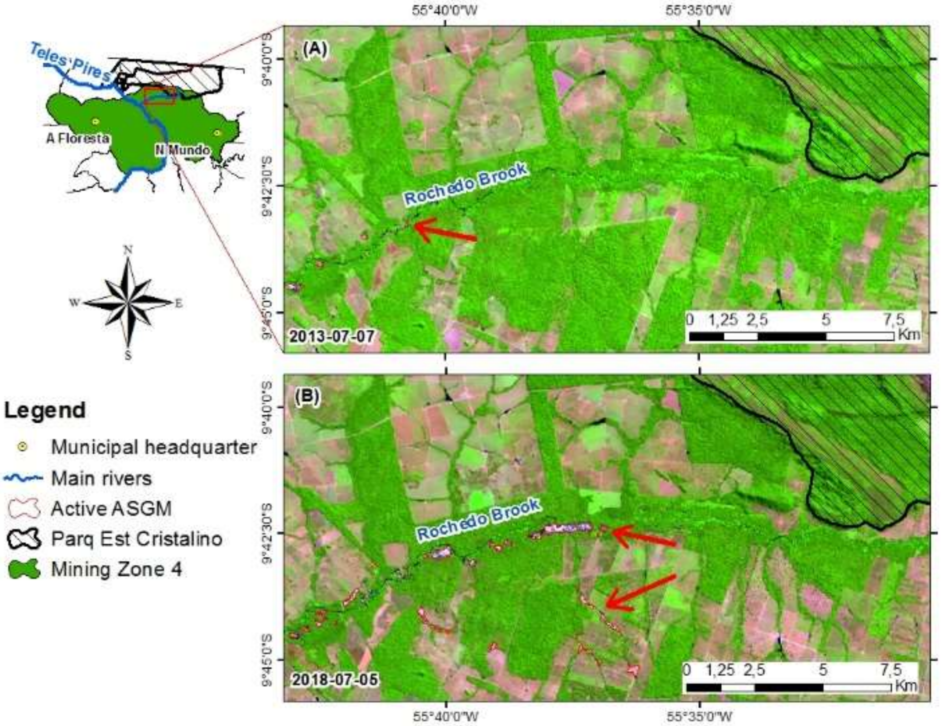

Figure 8. Multitemporal analysis of satellite images of Mining Zone 4 showing the progress of mining fronts (red arrows) along the Rochedo Brook upstream between the years 2013 (A) and 2018 (B), approaching the southern limit of the Cristalino State Park in the municipality of Novo Mundo.

Figura 8. Análise multitemporal de imagens de satélite da Zona de Mineração 4 mostrando o avanço das frentes de mineração (setas vermelhas) ao longo do Córrego Rochedo a montante entre os anos de 2013 (A) e 2018 (B), aproximando-se do limite sul do Parque Estadual do Cristalino no município de Novo Mundo.

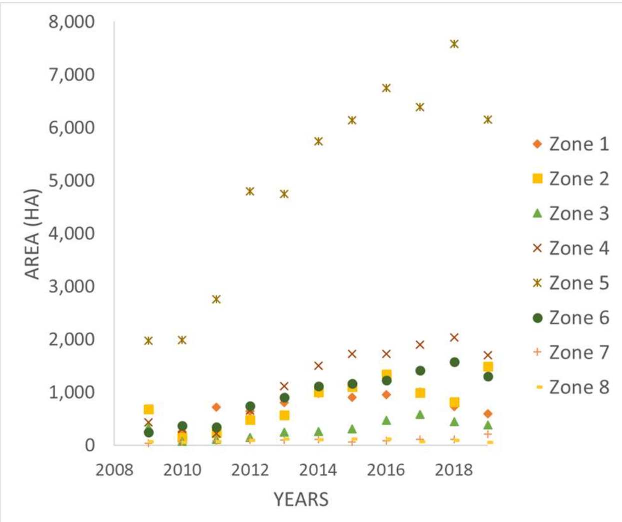

Figure 9. Evolution of active ASGM areas between 2009 and 2019 by zone (ha). They all grew, especially zones 2, 4, 5 and 6. In 2019, all fell except zones 2 and 7. Zone 8 was the most stagnant.

Figura 9. Evolução das áreas ativas de ASGM entre 2009 e 2019 por zona (ha). Em geral, todas apresentaram crescimento, especialmente as zonas 2, 4, 5 e 6. Em 2019, todas caíram, exceto as zonas 2 e 7. A zona 8 foi a mais estagnada.

Table 2 shows the average annual gold prices from the national market surveys from 2008 to 2019.

Figure 10 shows the evolution of the whole ASGM area and the price variation for the studied period. There was, in general, a predominance of upward movement in the price of gold, going from R$ 92.19/g in 2008 to R$ 157.01/g in 2018 (scenario *with delay*), an increase of 70.32% and from R$113.19/g in 2009 to R$ 177.28/g in 2019 (scenario *without delay*), an increase of 56.62%. However, fluctuations in the adjusted gold price were not always accompanied by variation in the whole active ASGM area in the same direction. For example, the price fell in 2013, and 2014 did not imply a drop in the exploited area in the same period. Despite a price increase in 2019, there was a decline in exploited areas.

Table 2. Average monthly nominal gold prices and prices adjusted for July 2019 in the national market in R$/g.

Tabela 2. Preços nominais médios mensais do ouro e preços ajustados para julho de 2019 no mercado nacional em R$/g.

Year	Gold price (R$/g)[a]	GPIIA/ year[b]	GPIIA accum July/2019[c]	Adjusted price for July/2019 (R$/g) [d]
2008	51,10		1,8040	92,19
2009	62,11	-1,0095	1,8224	113,19
2010	69,82	5,9832	1,7195	120,06
2011	83,47	8,3581	1,5869	132,46
2012	104,79	7,3242	1,4786	154,94
2013	97,36	4,8439	1,4103	137,31
2014	95,68	5,0580	1,3424	128,44
2015	123,70	7,4100	1,2498	154,60
2016	139,43	10,6300	1,1297	157,51
2017	129,14	-1,4300	1,1461	148,01
2018	148,75	8,5800	1,0555	157,01
2019	177,28	5,5524	1	177,28

[a] Annual average of nominal gold prices in Brazil retrieved from Bullion Rates

[b]IA rate was retrieved from FGV for 12 months, referring to August of a year to July of the following year.

[c]$\mathrm{GPIIA_{acum\ year\ i}} = \left(1 + \mathrm{IGPDI_{12\ year\ i}}\right) \times \left(1 + \mathrm{IGPDI_{12\ year\ i+1}}\right) \times \ldots \times (1 + \mathrm{IGPDI_{12\ year\ 2019}})$

[d] $\text{Gold price ajusted} = \text{Nominal price}_{\text{year i}} \times \mathrm{GPIIA_{acum\ year\ i}}$

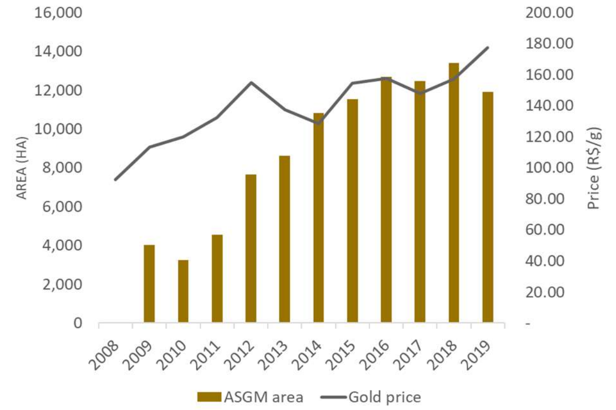

Figure 10. Evolution of the active ASGM area from 2009 to 2019 and variation of the average annual gold price in the national market from 2008 to 2019 adjusted for July / 2019. Overall, the exploited area grew by 195%, while the gold price grew by 57%, considering the scenario *without delay* and 70% *with delay*. The annual price fluctuation was not always accompanied by a variation in the explored area in the same sense or proportion as in cases from 2010, 2013, 2014, 2017, and 2019.
Figura 10. Evolução da área ativa de ASGM de 2009 a 2019 e variação do preço médio anual do ouro no mercado nacional de 2008 a 2019 ajustado para julho/2019. No geral, a área explorada cresceu 195%, enquanto o preço do ouro cresceu 57% considerando o cenário sem atraso e 70% com atraso. A flutuação anual do preço nem sempre foi acompanhada de variação da área explorada no mesmo sentido ou na mesma proporção, casos dos anos de 2010, 2013, 2014, 2017 e 2019.

To analyze the relationship between the gold price and ASGM area under the without delay scenario, the relationship between the price of gold and active ASGM areas, controlling the variable 'mining zone', was insignificant in the whole area. In the analysis by zone, the relationship was significant and positive in all zones except two, zones three and eight (Figure 11).

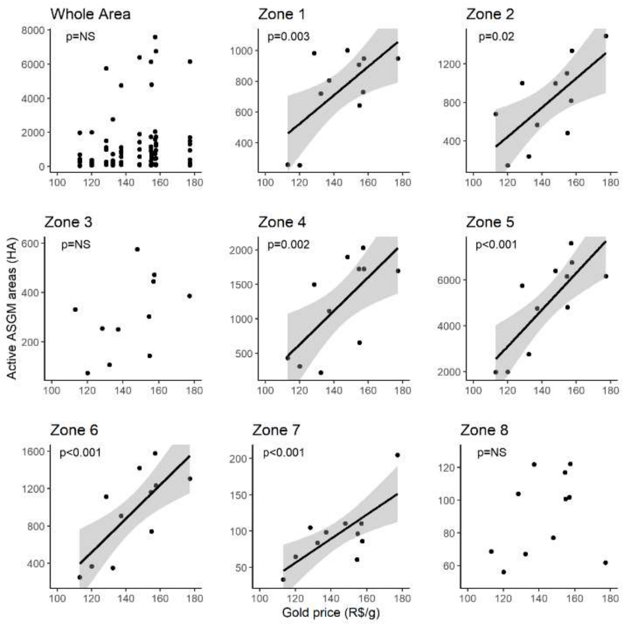

Figure 11. Relationship between the area exploited by the ASGM activity and the value of the gram of gold in the national market *without delay*: in the whole area of the GLMM analysis, controlling the spatial variable (mining zone), the relationship was not significant considering α = 0.05; in the relations by zone it was significant in all except zones 3 and 8.
Figura 11. Relação entre a área explorada pela atividade ASGM e o valor do grama de ouro no mercado nacional sem atraso: em toda a área da análise GLMM, controlando a variável espacial (zona de mineração), a relação não foi significativa considerando α = 0,05; nas relações por zona foi significativa em todas, exceto nas zonas 3 e 8.

In the *delay* scenario, the relationship between the gold price and active ASGM areas, controlling the variable "mining zone," was also insignificant in the whole area. In the analysis by zone, the relationship was significant and positive in all zones (see Figure 12).

Thus, the increase in the price of gold on the national market unequivocally influenced the progress of ASGM developments in the northern region of Mato Grosso from 2009 to 2019, but this relationship depends on regional factors. In most mining zones, the relationship between the analysis and delay has as much explanatory power as the analysis without delay. Thus, it is impossible to distinguish whether the mineral entrepreneur will continue the business and invest in improvements according to the present price or the market forecast for the following year.

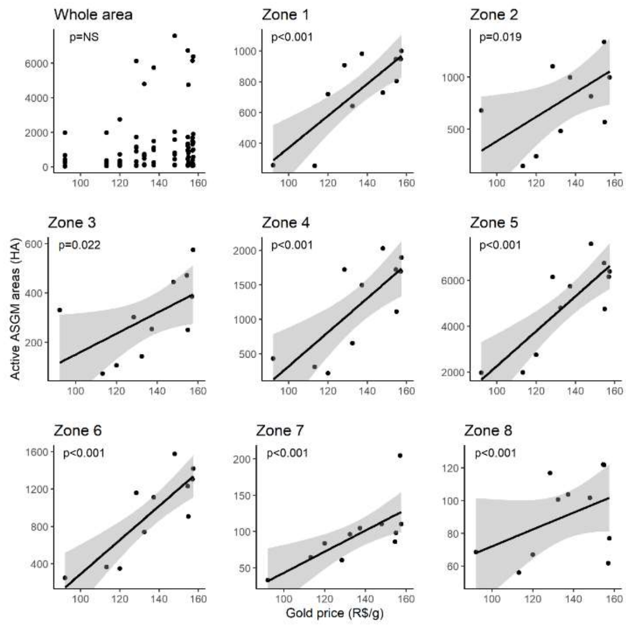

Figure 12. Relationship between the area exploited by the ASGM activity and the value of the gram of gold in the national market with delay: In the whole area, the GLMM analysis, controlling the spatial parameter (mining zone), showed no significant relationship. However, the correlations by zone were all significant, considering α = 0.05.
Figura 12. Relação entre a área explorada pela atividade ASGM e o valor do grama de ouro no mercado nacional com atraso: Em toda a área, a análise GLMM, controlando o parâmetro espacial (zona de mineração), não mostrou relação significativa. No entanto, as correlações por zona foram todas significativas considerando α = 0,05.

4. DISCUSSION

The present study found a marked increase in the area exploited by ASGM enterprises from 2009 to 2019. Variations unequivocally influenced this increase in the price of gold on the Brazilian national market. This relationship is evidenced mainly when sub-regions called mining zones segment the study. Based on the gold price with a delay of one year, the relationship was significant and positive in all areas, indicating a trend towards short-term artisanal management according to management profiles of small-scale mining (COELHO et al., 2017). It was impossible to distinguish the predominance of undertakings with a business or artisanal profile since six of the eight zones also had a significant and positive relationship when taking the price *without delay*. This is an important issue to be addressed in future studies that will further characterize ASGM projects in the region.

The fact that the relationship between the whole exploited area and variation in the price of gold was not significant, unlike the relationship by zone, implies the search for sub-regional factors that explain the dynamics of the activity in conjunction with this variable. Alvarez-Berríos et al. (2015) point out that the dramatic rise in the international price of gold in the first decade of the 2000s made it possible to exploit deposits in the Amazon region that were previously considered unfeasible due to their low ore content or their remote location, often within important environmental conservation units. Informal enterprises predominate in these marginal areas, which are precarious from both legal and technological standpoints and, therefore, vulnerable to movements of the gold market as they depend on short-term results (VERBRUGGE et al., 2019). On the other hand, these authors emphasize that informality allows ASGM enterprises greater versatility in dealing with socio-political instability and the precarious work relationships frequent in developing countries, favoring greater adaptability of medium and large industrial mining companies.

The general growth of ASGM areas observed in the study area was concurrent with the expansion of activity in South America and Brazil. During the first decade of the 2000s, more than 100 ore processing plants in Ecuador were built in the Portovelo-Zaruma region, leading to an influx of 20,000 workers (MISERENDINO et al., 2013). In Brazil, the official bulletins of Ministério das Minas e Energia (MME) report a 120% growth in gold production through ASGM during the period from 2009 to 2018, with an increase in its participation in the country's whole gold production from 13% to 21% (Departamento Nacional de Produção Mineral 2009; Agência Nacional de Mineração 2020). Lobo et al. (2016) documented a 50% growth in the area exploited by ASGM from 2000 to 2012 in the upper course of Rio Tapajós. They attributed this growth to the increased adoption of mechanization through hydraulic excavators, powerful motor pump sets, and the high market price of gold. Similarly, Massaro et al. (2018) considered as a landmark of change in the activity dynamics an aggregation of heavy machinery facilitated by paving access roads to the Peixoto de Azevedo region, implying an acceleration of exploratory capacity. When looking for the causes of a 40% growth in the area exploited by ASGM during the period from 2012 to 2016 in Peru, Asner et al. (2016) also mentioned the issue of improved access, adding factors such as a labor force migrating from other regions and the proliferation of cooperatives and associated entities of miners. Also, small-scale mining was identified in other countries as an activity receiving the workforce affected by unemployment in agriculture and other sectors generated by cyclical economic crises in developing countries (VERBRUGGE, 2015).

The encroachment or threat of mining fronts into protected areas and indigenous lands reported here has also occurred in other countries that comprise the Amazon biome. Using remote sensing, Alvarez-Berríos et al. (2015) identified an overall growth of deforested area due to ASGM of 1,680 km² in countries of the Amazon (Colombia, Venezuela, Guyana, Ecuador, Bolivia, Brazil, Peru, Suriname and French Guiana) from 2001 to 2013, with 15 km² within the strict perimeter and 172 km² in surrounding areas (10 km buffer) of protected areas. These authors point out that 77% of this deforestation occurred after the 2008 global economic crisis. In Peru, 64 thousand hectares of forest were lost due to gold mining from 2010 to 2017, coinciding with the construction and paving of the Interoceanic Highway (ESPEJO et al., 2018).

In Guyana, 91% of deforested primary forest areas in 2010 were attributed to the uncontrolled advance of ASGM. However, annual rates have been falling due to reforms in mining policy promoted by the government (HOOK, 2018). The vulnerability of primary forests and protected areas to ASGM may also be a result not only of the uncontrolled advance of mining fronts but also of the low degree of implementation of conservation units, where their implementation was not accompanied by programs for the allocation and education of labor displaced from the area or prevented from using its mineral resources (BAIA JÚNIOR et al., 2014). Hook (2019), on the other hand, argues that among the factors that lead to the fragility of Indigenous lands in the face of the advance of small-scale mining is the hybridism of the very way of life of the Indigenous communities, which often stimulates its execution on their lands or even their direct operation of it. The lack of policies and resources mainly drives this to support maintaining their culture and traditional way of life. The weakening of Brazilian legislation and drastic cuts in the budget of environmental agencies in the last decade have the potential to relax the licensing processes for mining activity within protected areas, further aggravating threats to their function of environmental conservation (SALVADOR et al., 2020).

Swenson et al. (2011) highlighted the lack of monitoring of the accelerated advance of ASGM areas in recent years by adequate technologies, regulations and time studies. As a result, mining activity continues without environmental control, with unrestricted importation of mercury and damage to the environment and health. The present study breaks the cycle of disinformation about the dynamics, organization and processes of ASGM activity, ceasing to feed unsuccessful policies that generate poverty and environmental degradation, as Saldarriaga-Isaza et al. (2013) warned.

It is necessary to continue the mapping presented here in subsequent years since the expansion of the activity is expected to continue in 2020, with the price of gold closing on the rise in 2019 and the worsening of the socio-economic crisis caused by the COVID-19 pandemic, which is expected to release more surplus labor hungry for alternative sources of income such as those offered by ASGM. On the other hand, it should be noted that the effectiveness of such mapping also depends on the exchange of information with the real world of the artisanal miners. Its construction must include a process of consultation and active participation of all stakeholders, such as miners, communities of affected locations, geologists and service technicians, mining and environmental regulation and inspection bodies and public prosecutors.

5. CONCLUSIONS

The production of a continuous time series of geospatial data on land occupation by gold mining activities is an innovation in the northern region of Mato Grosso, south of the Brazilian Amazon. Identifying eight subregions represented by the gold mining zones facilitates understanding the activity's specificities and allows visualizing interaction hotspots with the environment.

The mapping of active artisanal and small-scale gold mining (ASGM) areas from 2009 to 2019 showed, with a 92% accuracy rate, that this activity remains a carrier of great regional relevance. It has grown in importance in recent years. It can maintain its upward trend depending on regional and subregional factors that favor or inhibit activity coupled with the mineral commodities market.

The areas explored by ASGM grew by 195% in general, which implies greater pressure on the environment, as shown in this study related to some protected areas. The accelerated increase in the gold mining area tended to positively correlate with the price of gold in the domestic market, mainly considering a one-year delay in reflecting the price raised in the exploited area.

The strength of this correlation varies between the mining areas identified, and this may be associated with regional factors such as ease of access to mining sites, mineral content of deposits and technological profile of the undertakings, factors that should be the subject of future studies. Therefore, the present study has the potential to be a starting point for integrating research from different areas of knowledge.

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