Analysis of Sentinel-2A orbital imagery for the detection of deforested areas caused by artisanal mining activities in the Tapajós Environmental Protection Area, northern Jacareacanga municipality, Pará State, Brazil.

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Abstract

This study analyzed the advance of deforestation associated with artisanal mining in the Tapajós Environmental Protection Area (APA), north of Jacareacanga, Pará State, Brazil, for 2017 and 2024. The National Institute for Space Research (INPE) monitors deforestation in the Amazon using remote sensing, and the Tapajós APA stands out among protected areas for high rates of mining-related deforestation. Sentinel-2A images were used to generate the Normalized Difference Vegetation Index (NDVI) and RGB composites, assigning the 2017 NDVI to the red channel and the 2024 NDVI to the green and blue channels. Auxiliary data, including active mining processes in 2024 and the hydrographic network, were integrated for analysis. This approach enabled the identification of two distinct spectral responses: (i) cyan areas corresponding to regions that were non-vegetated in 2017 but exhibited regenerated vegetation in 2024; and (ii) red areas corresponding to regions that were non-vegetated in 2024. The results enabled visualization of the spatial progression of deforestation, particularly along drainage networks and in relation to active mining areas, revealing a pronounced expansion associated with artisanal mining across multiple waterways, with an upstream progression consistent with alluvial gold and cassiterite deposits. The data corroborate deforestation alerts issued by the Real-Time Deforestation Detection System (DETER) and the Deforestation Alert System (SAD)/Imazon, indicating the continuity of artisanal mining pressure in the Tapajós APA. The methodology demonstrated efficiency in detecting environmental changes and can be replicated in other areas under mining pressure, contributing to territorial monitoring and environmental management.

1. Introduction

The artisanal mining activity is one of the main causes of deforestation in the state of Pará, Brazil (Veiga et al., 2002). Between 1991 and 2000, gold production from artisanal mining in the Tapajós River region represented approximately 70% of the artisanal mining production in Pará and around 52.5% of the production in the Amazon. According to data from the Deforestation Alert System (SAD) of the Institute of Man and Environment of the Amazon (Imazon), the state of Pará had the largest deforested area among the nine states of the Legal Amazon between August 2021 and July 2022, including areas located in Indigenous Lands and Conservation Units (Amorim et al., 2024).

This mining dynamic has been historically associated with the Tapajós Mineral Province, an area where intense artisanal mining activity occurred mainly between the 1980s and 1990s. The region, recognized as one of the most important gold provinces in the country, was responsible for a large part of the gold extracted in Brazil between 1970 and 1980, with a cumulative production exceeding 225 tons from artisanal mines up to 1995 (Juliani et al., 2014).

Within this context, the Tapajós Environmental Protection Area (APA), created by Decree on February 13, 2006, is defined as a Sustainable Use Conservation Unit (BRASIL, 2006). It covers an area of 20,395.81 km², located in the municipalities of Itaituba, Jacareacanga, Novo Progresso, and Trairão, in the state of Pará, and is close to the border between the states of Amazonas and Mato Grosso. According to the Real Time Deforestation Detection System (DETER), data generated by the National Institute for Space Research (INPE) indicate that the Tapajós APA is one of the environmental protection areas with the highest rates of deforestation related to mining.

Remote sensing has become a fundamental tool for environmental monitoring, allowing the identification and tracking of changes in land cover over time. Thus, using orbital images, such as Sentinel-2, and digital processing techniques, it is possible to detect vegetation removal and observe the expansion of activities such as artisanal mining.

Several studies confirm the efficiency of remote sensing in detecting and analyzing land cover changes in detail, being widely used to monitor deforestation. Aguiar (2023) conducted a bitemporal analysis between 2018 and 2022 using Sentinel-2 images in the municipalities of Senador José Porfírio and Anapu, in Pará State, Brazil, quantifying the conversion of forested areas into deforested areas. Similarly, Torres et al. (2021) used Sentinel-2 and Landsat-8 images to map deforested areas in the Amazon forest, reinforcing the relevance of remote sensing in monitoring forest loss.

The objective of this study is to analyze the progression of deforestation caused by artisanal mining in the Tapajós APA, located north of the municipality of Jacareacanga, Pará State, Brazil, using Sentinel-2A satellite images from 2017 and 2024, and correlating it with the active mining processes in the region.

The study area is located northwest of the Tapajós APA in the municipality of Jacareacanga (Figure 1) and corresponds to 2,050.757 km² (13.84%) of the total area of the APA. The APA is entirely contained within the Tapajós Hydrographic Basin and the sub-basins of the Jamanxim and Crepori Rivers, and the study area, specifically, is completely within the Crepori River sub-basin.

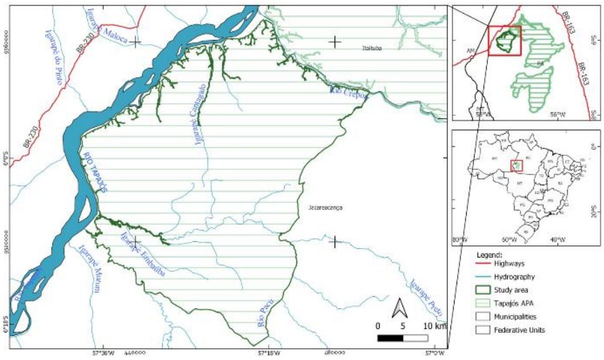


Figure 1. Location map of the study area.

2. Gold and Cassiterite in the Tapajós Mineral Province

The Tapajós region is one of the main gold-producing areas in Brazil, with a focus on primary gold deposits associated with silver and base metals (Juliani et al., 2014). However, most of the gold production is derived from artisanal mining of secondary deposits, classified as: (i) auriferous alluvium; (ii) alluvial or colluvial placers; and (iii) residual and/or lateritic types (Klein et al., 2001). In addition to secondary gold mineralization, the occurrence of active alluvial cassiterite mines has been reported in the Tapajós region (Santos et al., 1975; Pessoa et al., 1977; Almeida et al., 2000a; Almeida et al., 2000b).

2.1 Artisanal Mining Activity in the Tapajós Environmental Protection Area

Since the beginning of DETER surveys in 2015, the Tapajós APA and the Jamanxim National Forest have been among the most critical areas in terms of deforestation detected by the system. In the Tapajós APA, most alerts correspond to deforestation with bare soil, without direct association to specific activities. However, INPE data indicate that approximately 28% of the deforestation recorded between January 2022 and March 2023 is related to mining (Figueiredo, 2023).

According to Geiser (2020), gold artisanal mining in the Amazon occurs through three main methods: i) river dredges, which churn up the riverbed; ii) pit mining, characterized by manual excavation in search of gold veins; and iii) “baixão” artisanal mining, of alluvial nature, carried out near stream and floodplain areas.

In “baixão” mining, the removal of vegetation cover and surface soil exposes the layer with auriferous potential. This layer is then dismantled with water jets, and the resulting pulp is pumped to gravimetric tables, where the gold particles are deposited. The remaining mud and water are discarded on site. Afterwards, the carpets that retain the gold particles are washed, and the gold is separated from the impurities with mercury, forming an amalgam that is easily detached from the other particles. This amalgam is burned with a blowtorch to evaporate the mercury, leaving only the raw gold (Geiser, 2020). This practice results in deforestation, contamination, and silting of the stream, highlighting the negative environmental impacts of gold extraction in the region (Basso, 2021) (Figure 2).

Figure 2. Gold artisanal mining in the Alto Tapajós region (Basso, 2021).

3. Materials and Methods

For the development of the study on areas deforested by artisanal mining in the Tapajós APA, Sentinel-2 satellite images and auxiliary data were used, including the cartographic base and mining rights, for data integration, analysis, and interpretation (Figure 3).

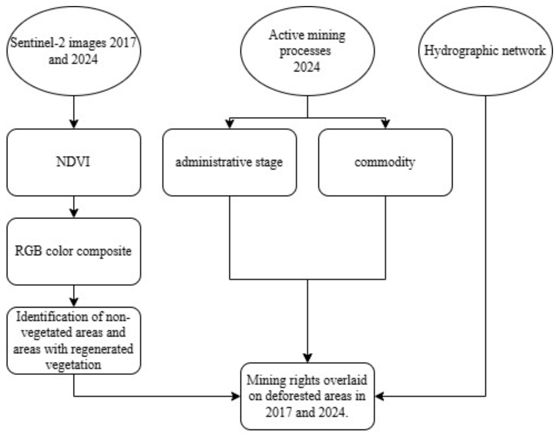


Figure 3. Simplified flowchart of the methodology used in the study area.

3.1 Data Acquisition

The boundaries of the Tapajós APA were obtained on the database provided by the Chico Mendes Institute for Biodiversity Conservation (ICMBio, 2023). The selected study area corresponds to 2,050.76 km² located north of the municipality of Jacareacanga, in the state of Pará, Brazil. The hydrographic network, at a scale of 1:250,000 (IBGE, 2025).

On the website of the Mining Geographic Information System (SIGMINE) developed by the National Mining Agency (ANM), mining rights data for the state of Pará were obtained in shapefile format, dated October 29, 2024 (ANM, 2024).

The satellite images used were Sentinel-2 Level-2A from July 19, 2017 and July 22, 2024, obtained from the ESA Copernicus Browser platform. In this study, only Band 04 (red) and Band 08 (near-infrared — NIR) were used, both with a spatial resolution of 10 m. The images were processed in the free software QGIS, for the generation of NDVI products and RGB color composite image to highlight the non-vegetated areas.

3.2 Normalized Difference Vegetation Index (NDVI)

The NIR and RED bands were applied in the normalized difference vegetation index equation:

$$\text{NDVI} = (\text{NIR-RED})/(\text{NIR} + \text{RED}), \quad (1)$$

Where, NIR corresponds to near infrared and RED, to the red range in the visible spectrum.

The values obtained by the equation range from –1 to 1, with values close to 1 indicating areas with dense vegetation, values close to 0 corresponding to bare soils, and negative values representing surfaces without vegetation or with the presence of water (Meneses and Almeida, 2012).

3.3 RGB color composite

The RGB color composite image was generated so that the 2017 NDVI image corresponds to the red channel, and the 2024 NDVI image to the green and blue channels (Figure 4). The methodology was adapted from techniques originally applied to radar images, which use records from different dates to compose a multitemporal image, assigning each date to one of the three color bands. This procedure allows highlighting changes that occurred over time (ESA, 2025).

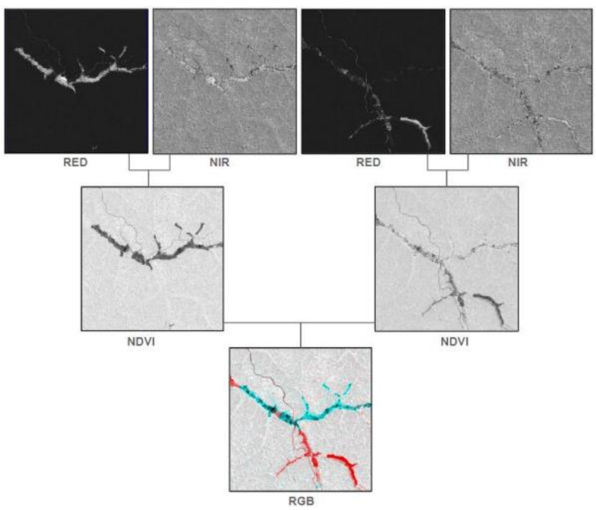


Figure 4. Subset of NDVI images from 2017 and 2024 and RGB color composite highlighting vegetated areas in light gray, non-vegetated area in red and regenerated vegetation areas in cyan.

Areas that were non-vegetated in 2017 exhibit low NDVI values, indicating minimal or no vegetation. By 2024, vegetation regeneration in these areas increases NDVI values, enhancing the intensities in the green (G) and blue (B) channels. In the RGB color composite, the combination of low red values with high green and blue values produces cyan, highlighting regenerated vegetation. Conversely, areas that were vegetated in 2017 show high NDVI values, but with vegetation loss by 2024, these values decrease. In this case, the combination of high NDVI values in the red channel and low values in the green and blue channels, indicating regions without vegetation in red.

To compare and validate the vegetation changes observed in the NDVI-based RGB composition, true-color (RGB 4-3-2) composites were generated for 2017 and 2024, allowing the visualization of non-vegetated areas with bare soil characterized by high albedo (Figures 5A and 5B). A comparison between these images enabled the identification of the expansion and progression of non-vegetated areas and regenerated vegetation areas (Figure 5C).

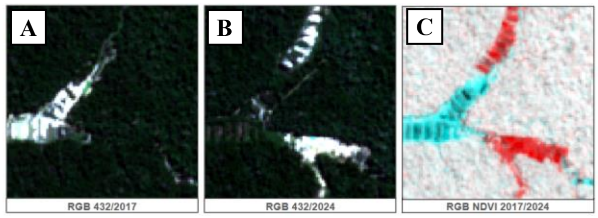


Figure 5. Subset image of RGB 432 (5A and 5B) and NDVI RGB color composites (5C).

3.4 Active mining processes

In Brazil, the availability of areas for mining is currently regulated by the Mining Code (Decree No. 9,406/2018) and administered by the National Mining Agency (ANM) (Law No. 13,575/2017) (BRASIL, 2018). In simplified terms, mining titles are polygonal areas that define the boundaries within which an individual or company holds priority and exclusive rights to explore and commercially exploit mineral substances of economic value (ANM, 2024).

According to ANM (2024) mineral rights data from October 2024, a total of 149 active mining processes are located within the study area, covering 2,027.406 km² and representing 98.86% of the total area (Figure 6A). Six administrative stages of mining processes are observed in the study area: Exploration Application, Exploration Authorization, Mining Concession Application, Artisanal Mining Permit Application, Artisanal Mining Permit and Availability.

The main commodities associated with active mining processes in the Tapajós APA are gold, cassiterite and diamond ore (Figure 6B). Gold ore is the most frequent commodity, with 114 active mining processes, followed by cassiterite with 34, and diamond with only one.

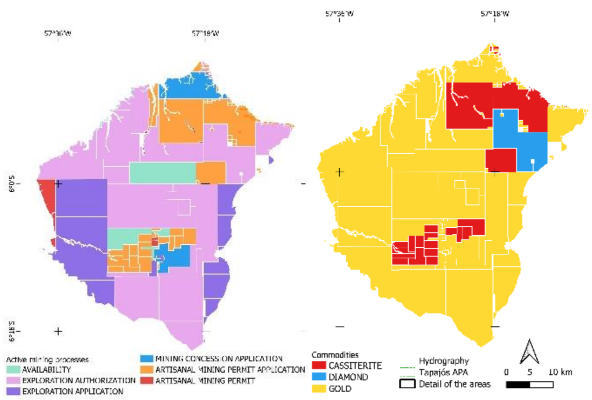


Figure 6. Distribution of mining rights by stage (6A) and commodity (6B) in the Tapajós APA (ANM, 2024).

4. Results and discussion

The RGB composite generated from the NDVI images for 2017 and 2024 revealed variations in vegetation cover (Figure 7). This composite was analyzed in conjunction with the spatial distribution of active mining processes within the study area, highlighting different administrative stages and types of commodities (Figures 8 and 9). The analysis enabled the observation of mining activity patterns, as well as the concentration and expansion of non-vegetated areas (deforestation) along the main rivers and their tributaries.

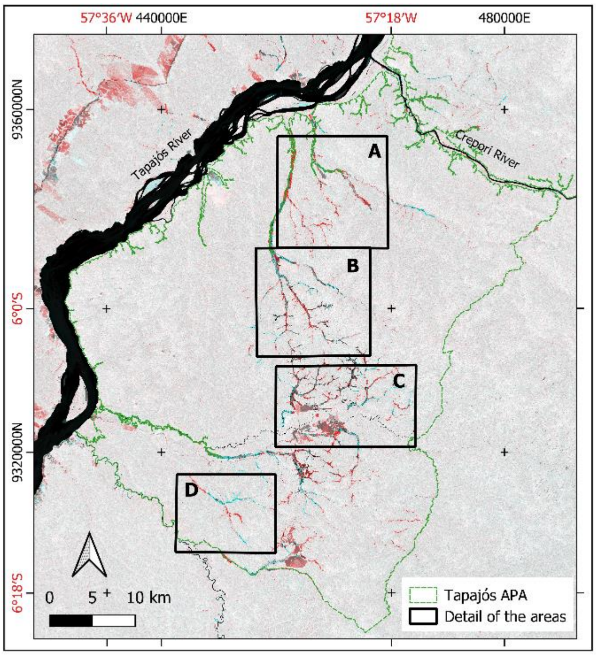
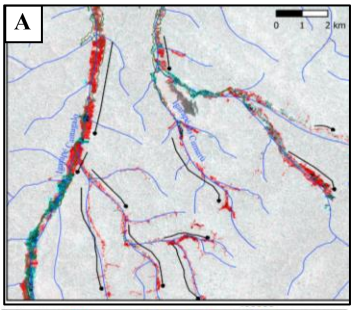
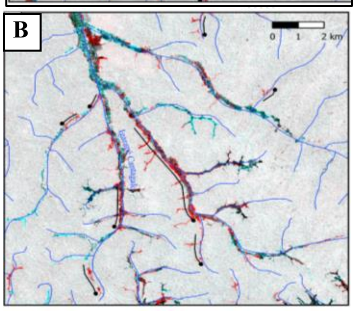
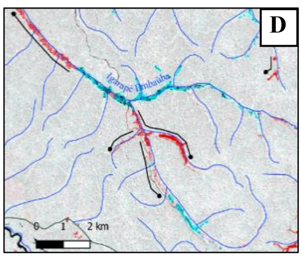


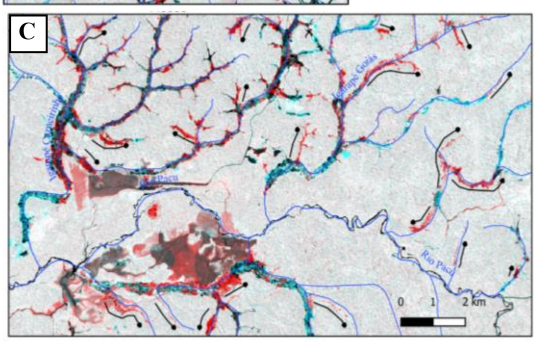
Figure 7. RGB color composite of Sentinel-2 NDVI images in the Tapajós APA, where vegetated areas appear in light gray, non-vegetated areas in red, and regenerated vegetation in cyan in 2024.



Figures 7A–D present detailed views of the NDVI RGB composite. The black line, with a circle at its end, suggests the direction of vegetation suppression advance.







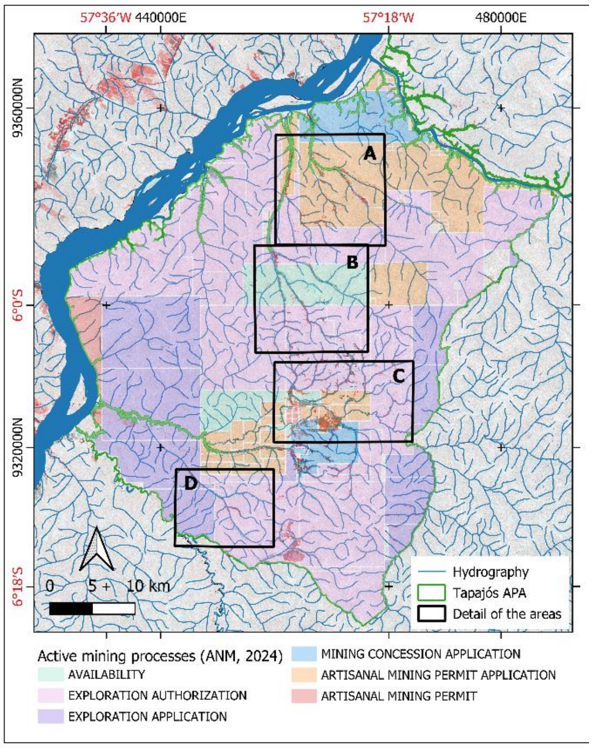


Figure 8. RGB color composite of NDVI images with active mining processes by stage in the Tapajós APA.

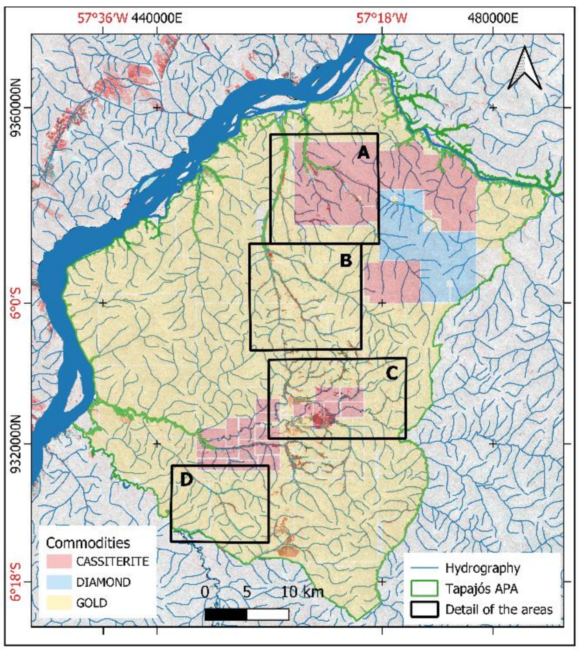


Figure 9. RGB color composite of NDVI images with active mining processes by commodity in the Tapajós APA.

Areas with active mining processes under the Artisanal Mining Permit stage are primarily dedicated to gold extraction. In the northern portion, mining activities in the Artisanal Mining Permit stage cover an area of 4.48 km² and extend along the Cumarú Stream, the Cantagalo Stream, and their tributaries (Figures 7, 8 and 9). In these areas, the cyan coloration in the RGB composite indicates deforestation that occurred in 2017, likely associated with artisanal mining activities, followed by vegetation regeneration by 2024 (Figures 7A and 7B). In contrast, the presence of red indicates deforestation or clear-cutting in 2024 upstream of the Cumaru Stream and Cantagalo Stream. Furthermore, an expansion of deforestation is observed in several tributaries of these streams, including in areas where mining processes do not legally authorize artisanal mining activities. In the southern portion, along the Tapajós River, the largest area under the Artisanal Mining Permit stage is concentrated covering an area of 27.94 km². However, the RGB composite reveals the presence of vegetation in both 2017 and 2024, suggesting the absence of deforestation in this region. In the central area, along the Pacu River up to the vicinity of the Carneirinho Stream, there is also no evidence of deforestation in areas under the Artisanal Mining Permit stage, which cover approximately 2.9 km² (Figure 7C). Nevertheless, many tributaries of the Pacu River show significant deforested areas in 2017, with vegetation regeneration by 2024, as well as evidence of ongoing deforestation expansion in the latter year.

Active mining processes under the Artisanal Mining Permit Application stage have cassiterite as their main substance and are concentrated in the northern portion, in the tributaries of the Crepori River, along the Cumarú Stream, and downstream of the Cantagalo Stream, near its confluence with the Tapajós River, covering an area of 241.59 km² (Figures 7A, 8 and 9). In the southern portion, it spans 93.78 km², including the Pacu River, Carneirinho Stream, Goiás Stream and Embaúba Stream (Figures 7, 8 and 9). Deforestation can be observed along the Carneirinho Stream and Goiás Stream in 2017, with its continuation and expansion in 2024 along their tributaries upstream (Figure 7C). It is observed that in the Pacu River and the tributaries of the Crepori River, the mentioned streams exhibit deforestation in both 2017 and 2024 (Figure 7C). Figure 7D shows the same pattern at Embaúba Stream, with substantial deforested areas in both 2017 and 2024, and deforestation progressing both upstream and downstream.

Active mining processes in the Mining Concession Application stage occupy an area of 63.96 km² in the northern portion of the Tapajós APA, with gold as the main substance (Figures 8 and 9). In the northern portion, deforestation was recorded in 2024 at the mouth of the Cumarú Stream (Figure 7A). In the southern portion, active mining processes occupy an area of 36.99 km², and deforestation is observed in the tributaries of the Pacu River and in the Ponte Segura Stream, in both 2017 and 2024 (Figure 7C).

The remaining administrative stages — Exploration Authorization, Availability, and Exploration Application — cover more extensive areas and occur both in regions without deforestation and in deforested areas along watercourses in 2017 and 2024 (Figures 7 and 8). The main substances of the active mining processes in these stages are gold and diamond (Figure 9).

4.1 Advance of Deforestation Caused by Artisanal Mining in Alluvial Deposits

The active mining processes in 2024 within the study area highlight the predominance of activities focused on the extraction of gold and cassiterite (Figure 6). The Mining Concession Application, Artisanal Mining Permit Application and Artisanal Mining Permit stages further confirm the presence of these mineral resources in the region (ANM, 2024). Integrated analysis of the active mining processes with Sentinel-2 NDVI RGB imagery revealed that deforestation advances extensively along multiple drainage systems in areas with gold and cassiterite occurrences (Figure 7). The deforested areas along rivers and their tributaries exhibit elongated shapes, primarily following the river channels, a pattern characteristic of alluvial deposit mining carried out near streams and floodplain areas using the artisanal method known as “baixão” (Geiser, 2020, Basso, 2021). Simionato et al. (2021) conducted a study to identify areas degraded by artisanal mining in the Amazon Rainforest, using a GEOBIA approach combined with data mining techniques applied to Sentinel-2 NDVI imagery, concluding that these degraded areas are characterized by elongated and highly asymmetric shapes.

4.2 Deforestation in the Tapajós Environmental Protection Area

According to Fonseca et al. (2017), the Tapajós APA was the second most affected Conservation Unit by deforestation in 2017, with 25.9 km² of deforested areas recorded by the Deforestation Alert System (SAD). In 2024, the Tapajós APA maintained the same position, recording a total of 6 km² of deforestation (Amorim et al., 2024).

Between 2017 and 2024, 3,251 deforestation alerts were recorded by the DETER (Real-Time Deforestation Detection System) program in the Tapajós APA, totaling 439.82 km² (INPE, 2024). Of this total, 218.33 km² are associated with the "mining" class, 218.24 km² with the "deforestation with exposed soil" class, and 3.25 km² with the "deforestation with vegetation" class. Thus, the area remains the second Conservation Unit with the largest deforested area.

Thus, in accordance with the results presented in this study, the Tapajós APA has a continuous history of deforestation, mainly related to gold and cassiterite artisanal mining in alluvial deposits. These activities occur along the main drainage channels of the Pacu River and Centrinho Stream, as well as in the Cumarú Stream and Cantagalo Stream.

5. Conclusions

This study analyzed the advance of deforestation associated with artisanal mining activity in the Tapajós Environmental Protection Area, in the northern sector of the municipality of Jacareacanga (PA). The results indicate that deforestation generally occurs along the drainage channels, with advancing vectors upstream, indicating a direct relationship between deforestation and alluvial deposits. This association is corroborated by active mining processes, such as Mining Concession Application, Artisanal Mining Permit Application and Artisanal Mining Permit, in which the extracted substances are gold and cassiterite.

Although legal instruments exist to control illegal practices, their application is still insufficient to mitigate anthropogenic pressure in the region. Despite the creation of the Tapajós APA representing a significant milestone for conservation, the absence of zoning and a management plan contributes to uncertainties regarding land use, compromising biodiversity protection and the sustainability of natural resources.

The methodology employed proved to be effective in identifying spatial patterns of deforestation and in analyzing their relationship with active mining processes. In the future, it could be applied throughout the Tapajós APA, also highlighting the importance of quantifying, through the classification method, the areas deforested by artisanal mining. The approach employed also has the potential to be applied in other areas with a similar socio-environmental context, including Conservation Units and Indigenous Lands, contributing to environmental monitoring and supporting decision-making in territorial management.

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