Geospatial indicator of illegal mining[1] fronts from the Mining Alert System (LOGAR) of CENSIPAM

Indicador geoespacial de frentes de garimpo a partir do Sistema de Alertas de Garimpo (LOGAR) do CENSIPAM

Indicador geoespacial de frentes de minería ilegal a partir del Sistema de Alertas de Minería (LOGAR) del CENSIPAM

Indicateur géospatial des fronts de l’orpaillage à partir du Système d’Alerte de l’Orpaillage (LOGAR) du CENSIPAM

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Abstract

This study presents a geospatial tool for identifying active illegal mining fronts in the Brazilian Legal Amazon, based on historical alerts from the LOGAR system (CENSIPAM). The Mining Front Index combines the spatial density and temporal persistence of alerts linked to illegal gold mining to detect areas with ongoing activity. The goal is to improve territorial monitoring and prioritize enforcement efforts, particularly in Indigenous Lands. Results demonstrate the index’s effectiveness in capturing distinct patterns. In the Kayapó Indigenous Land, from 2023 to 2025, active fronts persisted despite a reduction in the number of alerts, including spatial shifts in activity. In the Yanomami Indigenous Land, the index recorded a peak in February 2023, followed by a sharp and sustained decline, likely reflecting the impact of government-led

[1] **Translator’s note:**
For the purposes of this article, the term illegal mining is used as a translation of the Brazilian concept of *garimpo,* acknowledging that, in the Brazilian legal framework, gar*impo* may refer to both legal and illegal small-scale mining activities. The use of illegal mining reflects the predominant empirical context addressed in the analysis.

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removal operations. The methodology, based on satellite imagery and GIS, is practical and replicable. It supports public policy, enhances interagency coordination, and guides strategic acquisition of high-resolution imagery. The index enables smarter, more targeted surveillance, and is capable of tracking illegal mining trends across vulnerable regions of the Amazon.

Keywords: Legal Amazon; illegal activities; remote sensing; deforestation; PlanetScope.

Resumo

Este trabalho apresenta uma ferramenta geoespacial para identificar frentes ativas de garimpo na Amazônia Legal, com base em alertas históricos do sistema LOGAR (CENSIPAM). O Índice de Frente de Garimpo (IFG) combina a concentração espacial e a persistência temporal de alertas associados à mineração irregular, permitindo detectar áreas com atividade contínua. A proposta visa otimizar o monitoramento territorial e priorizar ações de fiscalização, especialmente em Terras Indígenas. Os resultados mostram que o IFG é eficaz para captar dinâmicas distintas. Na TI Kayapó, entre 2023 e 2025, mesmo com redução no número de alertas, foram identificadas frentes persistentes e realocação espacial da atividade. Na TI Yanomami, observou-se um pico em fevereiro de 2023, seguido por queda acentuada nas frentes. A metodologia, baseada em sensoriamento remoto e SIG, é prática, replicável e útil para apoiar políticas públicas, coordenar ações interagências e priorizar aquisição de imagens. O IFG contribui para uma vigilância mais inteligente e estratégica, capaz de acompanhar a evolução do garimpo irregular em contextos de alta vulnerabilidade.

Palavras-chave: Amazônia Legal; Ilícitos; sensoriamento remoto; desmatamento; PlanetScope.

Resumen

Este trabajo presenta una herramienta geoespacial para identificar frentes activos de minería ilegal en la Amazonía Legal, basada en alertas históricas del sistema LOGAR (CENSIPAM). El Índice de Frente de Minería (IFM) combina la concentración espacial y la persistencia temporal de alertas asociadas a la minería irregular, lo que permite detectar áreas con actividad continua. La propuesta busca optimizar el monitoreo territorial y priorizar acciones de fiscalización, especialmente en Tierras Indígenas. Los resultados muestran que el IFM es eficaz para captar dinámicas distintas. En la TI Kayapó, entre 2023 y 2025, aun con la reducción en el número de alertas, se identificaron frentes persistentes y reubicación espacial de la actividad. En la TI Yanomami, se observó un pico en febrero de 2023, seguido de una fuerte disminución de los frentes, reflejando el probable efecto de las operaciones de desintrusión. La metodología, basada en teledetección y SIG, es práctica, replicable y útil para apoyar políticas públicas, coordinar acciones interinstitucionales y priorizar la adquisición de imágenes. El IFM contribuye a una vigilancia más inteligente y estratégica, capaz de acompañar la evolución de la minería ilegal en contextos de alta vulnerabilidad.

Palabras clave: minería ilegal; Amazonía; geointeligencia; teledetección; SIG.

Résumé

Ce travail présente un outil géospatial destiné à identifier les fronts actifs d’extraction minière illégale dans l’Amazonie légale, à partir d’alertes historiques du système LOGAR

(CENSIPAM). L'Indice de Front de Garimpo (IFG) combine la concentration spatiale et la persistance temporelle des alertes liées à l'exploitation minière irrégulière, permettant ainsi de détecter les zones d'activité continue. La proposition vise à optimiser le suivi territorial et à prioriser les actions de contrôle, en particulier dans les Terres Indigènes. Les résultats montrent que l'IFG est efficace pour capter des dynamiques distinctes. Dans la Terre Indigène Kayapó, entre 2023 et 2025, malgré une diminution du nombre d'alertes, des fronts persistants et une relocalisation spatiale de l'activité ont été identifiés. Dans la Terre Indigène Yanomami, un pic a été observé en février 2023, suivi d'une baisse marquée des fronts. La méthodologie, fondée sur la télédétection et les SIG, se révèle pratique, réplicable et utile pour soutenir les politiques publiques, coordonner les actions interinstitutionnelles et prioriser l'acquisition d'images. L'IFG contribue à une surveillance plus intelligente et stratégique, capable de suivre l'évolution du garimpo illégal dans des contextes de forte vulnérabilité.

Mots-clés : Amazonie légale ; activités illicites ; télédétection ; déforestation ; PlanetScope.

1 INTRODUCTION

Mining in Brazil dates back to the colonial period, with the expedition of Martim Afonso de Sousa sent by Portugal to search for gold, silver, and precious stones. In 1549, Governor-General Tomé de Sousa began the exploitation of seashells in the Bay of All Saints, used in the production of lime for construction. In the 17th and 18th centuries, with the discovery of gold in Minas Gerais, Brazil stood out globally, producing about 50% of the world's gold and diamonds in the so-called Gold Cycle. In 1728, with the depletion of deposits in Mato Grosso, exploration advanced to the Upper Amazon and the Northern region. During World War II, the country became a supplier of strategic minerals such as mica, quartz, tungsten, tantalum, zircon, beryl, manganese, and iron. During this period, the Vale do Rio Doce Company was created to meet the demand of the USA and the United Kingdom. Today, Brazil is the sixth largest producer of non-fuel minerals in the world (Machado; Figueirôa, 2001).

In parallel with large-scale mineral extraction, artisanal and small-scale mining (ASM) and *garimpo* activities also exist, which can be irregular or regular, when carried out under the Artisanal Mining Permit (PLG), according to Law No. 7805/1989. Illegal mining has grown by 1200% in Brazil over the last four decades, especially in the Amazon, where approximately 91% of Brazil's illegal mining activity occurs (Siqueira-Gay; Sánchez, 2021; Mataveli *et al.*, 2022; Cortinhas Ferreira Neto *et al.*, 2024). From a legality perspective, Cortinhas Ferreira Neto *et al.* (2024) show that almost 80% of the mining that occurred in 2022 showed signs of illegality. Illegal mining promotes irreversible social and environmental impacts. According to Lobo *et al.* (2018), the Amazon accounts for about 80% of South American mercury (Hg) pollution in the environment, with Hg being ubiquitous and dynamic throughout the region.

Due to the persistence of Hg in the food chain, exposure, especially human exposure, to the toxic form of this element does not depend on proximity to the polluting source. The consumption of Methylmercury levels are two to six times higher than safe doses in some Amazonian regions.

The Legal Amazon region has the lowest Human Development Index in Brazil (PNUD, 2013). The socioeconomic vulnerability of the populations in this region is aggravated by the growing, and recent, presence of illegal mining. It is estimated that about 40% of illegal mining operations are five years old or less. This percentage rises to 62% when mining areas within indigenous territories are analyzed (Cortinhas Ferreira Neto *et al.*, 2024). With the rapid increase in the irregular extraction of minerals, mainly gold, social conflicts in the Amazon have also increased. Haslam and Tanimoune (2016) found a relationship between the intensity of conflicts arising from illegal mining and social vulnerability, where the greater the poverty and precariousness of the local infrastructure, the more intense the effects of mining. Formed by a mosaic of different social contexts such as riverside communities, extractivists, fishermen, family farmers, *quilombola* communities, and indigenous peoples, the Amazon is a priority area for combating and controlling illegal mining.

Mineral exploitation in Indigenous Lands (ILs) by invaders constitutes a serious socio-environmental problem affecting a significant portion of these territories in Brazil. In 2021, illegal mining activities occurred in 17 ILs, representing the direct conversion of an area of approximately 200 km², which corresponds to about 5% of the 332 officially recognized Indigenous lands. Although the direct conversion is relatively small, the indirect impacts can reach more than a third of the area of some Indigenous Lands, such as 33.4% in the Kayapó IL, 31.4% in the Munduruku IL, and 34.4% in the Yanomami IL (Da Silva *et al.*, 2023).

Remote sensing is a set of techniques for obtaining information about the Earth's surface without direct contact. Sensors can be optical, operating in the visible and infrared spectrum and are passive because they depend on solar radiation, or microwave, which are active because they emit their own radiation and allow data acquisition even without sunlight or in the presence of clouds (Liu, 2015). In the context of environmental monitoring, these technologies play a fundamental role, especially in regions of high biodiversity and vast territorial extent, such as the Legal Amazon. The integrated use of active and passive sensors allows the detection, analysis, and monitoring of various environmental and anthropogenic processes, such as deforestation, fires, floods, construction of clandestine airstrips, presence of vessels, and illegal mining activity. These technologies enable the generation of large-scale data, with high temporal frequency and access to hard-to-reach areas, contributing significantly to the formulation of public policies, enforcement actions, and environmental conservation strategies.

Monitoring areas of illegal mining presents several challenges, especially due to the small scale at which these activities occur, often covering areas smaller than one hectare. These limited dimensions require the use of medium to high spatial resolution images (equal to or less than 20 meters) for adequate detection. Another complicating factor lies in the complexity of the Amazonian hydrographic networks, where mining activity can occur in both clean and turbid water environments, as well as developing on riverbanks. This variability contributes to the generation of spectral signatures similar to those of exposed soils, making it difficult to accurately differentiate between natural areas and areas impacted by mining, especially when using conventional optical remote sensing (Lobo *et al.*, 2018).

LOGAR (Location of Mining Sites) was created by CENSIPAM to detect, analyze, and monitor illegal mining activities in the Legal Amazon, evolving from *ProAE-Inteligência* (Special Areas Monitoring Program – Intelligence), initiated in 2008. Reformulated in 2014 and updated in 2018, it began operating as a Geographic Information System for Intelligence, integrating data from *DETER/INPE* and PlanetScope of the Brazil MAIS Program, with a centralized database to identify typical patterns of illegal mining. The LOGAR database, composed of polygons of illegal mining activities since 2005, represents a valuable historical basis for understanding the spatial and temporal evolution of illegal mining in the Legal Amazon. However, the distinction between historical illegal mining sites and active fronts, that is, areas with illegal mining activity or emerging in the present, is essential to guide environmental control, public security, and territorial management actions in a strategic and efficient manner.

From an enforcement perspective, identifying illegal mining fronts allows for the optimization of human and logistical resources, prioritizing action in areas where environmental and social impact is ongoing or about to intensify. This capability is crucial for planning land clearing operations, especially in Indigenous Lands and Conservation Units, where the presence of illegal miners compromises the integrity of traditional populations and sensitive ecosystems. Furthermore, up-to-date information on active fronts supports decisions regarding the use of ultra-high-resolution commercial imagery and SAR (Synthetic Aperture Radar) sensors, allowing for prioritization of coverage of the most critical regions and reducing costs associated with redundant or unnecessary imaging.

Another relevant aspect is the generation of geospatial intelligence for interagency actions, such as those coordinated by the Ministry of Justice, IBAMA (Brazilian Institute of Environment and Renewable Natural Resources), ICMBio (Chico Mendes Institute for Biodiversity Conservation), and the Armed Forces. By anticipating the movement of illegal mining activities, it is possible to act preventively, avoiding the consolidation of illegal infrastructure (barges, airstrips, camps) and the formation of logistical support chains. There are also gains for monitoring socio-environmental risks, such as mercury contamination, river siltation, and the expansion of deforestation associated with mining. In strategic terms, the ability to detect active mining fronts reinforces the role of LOGAR as a territorial intelligence tool aimed at protecting the Amazon and governing its natural resources. Therefore, this work aims to present a simplified and accessible methodology for identifying illegal mining fronts, called the IFG (Mining Front Index), based on the database of deforestation alerts associated with mining activity. The Kayapó and Yanomami Indigenous Lands were used as pilot areas.

2 MATERIAL AND METHODS

2.1 STUDY AREA

The study was conducted within the boundaries of the Legal Amazon (AL), a region encompassing nine Brazilian states and occupying approximately 5,015,068.18 km², equivalent to 59% of the national territory. In terms of biomes, the AL is predominantly composed of Amazon rainforest (approximately 80%), followed by the Cerrado with 15% and the Pantanal with 1% (IBGE, 2003). From a climatic point of view, the region is distributed across three Köppen classifications: Af (humid equatorial climate), predominant in the northwest, with average temperatures between 25 °C and 28 °C and average annual rainfall (AWF) above 2,000 mm, possibly exceeding 3,000 mm, without a well-defined dry season; Am (monsoon climate), which extends from the western to the northeastern portions of the AL, has a short dry season (June to August), but maintains a high AWF, between 1,600 mm and 3,000 mm; and Aw (tropical savanna climate), with strong seasonality, a dry winter (from May to September), and average rainfall varying between 1,000 mm and 1,500 mm (Dubreuil et al., 2018). These variations reflect the environmental diversity that characterizes the region.

From a socio-environmental perspective, the Legal Amazon (LA) holds one of the greatest biodiversities on the planet and a wide socio-cultural diversity. LA is home to more than half of the country's indigenous population, approximately 51.2% (IBGE, 2023). There are

424 Indigenous Lands in the Amazon where 46% of the indigenous people of LA live, and which together account for approximately 22% of the LA's area (1,153,444 km²) (IBGE, 2023). Regarding *quilombola* populations, the 2022 Demographic Census of IBGE counted 426,449 *quilombola* people in the municipalities of LA – almost a third (32.11%) of the total of this population in the country, of which 80,899 live in officially demarcated *Quilombola* Lands, representing 48.38% of the national total of this group. The 2022 Demographic Census also provided robust data on indigenous peoples and extractive communities, highlighting their significant relevance to the sustainable management of natural resources. Currently, there are 41 federal Extractive Reserves in the Legal Amazon, inhabited by traditional populations such as rubber tappers, Brazil nut gatherers, and other groups linked to extractive lifestyles.

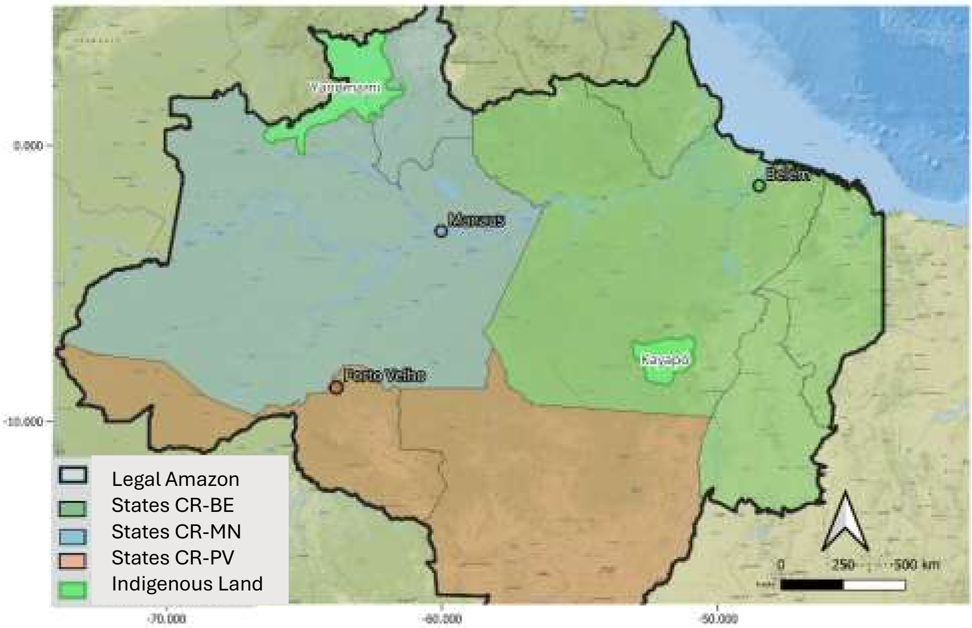
The survey also identified that 11.8 million people live in Conservation Units in Brazil, corresponding to 5.8% of the total population. Of this universe, traditional peoples and communities represent significant portions: *quilombola* communities total 282,258 people (2.39% of the population residing in Conservation Units) and indigenous people total 132,804 people (1.12%). Almost all (98.73%) of the people living in Conservation Units are in sustainable use areas, such as Environmental Protection Areas and Extractive Reserves. The 2022 Census data also reveal social challenges in these areas: the illiteracy rate among residents of Conservation Units is 8.84%, above the national rate of 7.00%. Among the 9,245,172 residents aged 15 or older in these areas, 817,383 are illiterate (IBGE, 2023). Similarly, riverside populations stand out, maintaining a strong link with the dynamics and "health" of the rivers, and are officially recognized as traditional communities by Decree No. 6,040/2007, which establishes the National Policy for the Sustainable Development of Traditional Peoples and Communities (PNPCT).

2.2 DESCRIPTION OF THE ALERT DATABASE AND LOGAR METHODOLOGY

The *sig_alertas* is an internal relational database of CENSIPAM, based on PostgreSQL and designed to store and manage geospatial data used by the operational area of the institution's different Centers. Deployed on a server on an internal network, the system allows both local and external access via VPN, guaranteeing the confidentiality and authenticity of the data for authorized users. The database is structured to support analytical and operational operations related to territorial monitoring of the Legal Amazon, making use of geographic extensions such as PostGIS for advanced manipulation of spatial information. The *sig_alertas* is accessed directly by Geographic Information System (GIS) tools, specifically QGIS, allowing the visualization, analysis, and editing of spatial data in real time by authorized analysts and technicians.

The methodology applied in LOGAR is based on the integration of remote sensing technologies, geoprocessing, and an analytical routine structured in two main phases: validation and review. The LOGAR area of coverage corresponds to the Brazilian Legal Amazon, subdivided for operational purposes among the Regional Centers of Belém (CR-BE), Manaus (CR-MN), and Porto Velho (CR-PV), each responsible for monitoring the states under its jurisdiction (Figure 1). Each analyst is assigned to a fixed set of satellite scenes, ensuring that the entire Legal Amazon is analyzed at least once a year.

Figure 1 – Subdivision of the jurisdiction of the states of the Legal Amazon of each Regional Center (CR): Manaus (MN), Belém (BE) and Porto Velho (PV) of the Management and Operational Center of the Amazon Protection System (CENSIPAM/MD). The two Indigenous Lands analyzed in this study (Kayapó and Yanomami) are highlighted



Source: Designed by the authors.

The main input data used for detecting illegal mining targets are deforestation alerts associated with mining activity, originating from two main systems: DETER (Real-Time Deforestation Detection), from the National Institute for Space Research (INPE), and the alert system based on the PlanetScope satellite constellation, linked to the Brazil MAIS program of the Ministry of Justice and Public Security. In Brazil MAIS, automatic processing uses PlanetScope images (3 m) to detect changes in land cover. The workflow involves radiometric and geometric corrections, cloud removal, and application of the change detection algorithm.

Spectral indices such as NDVI, NBR, and NDWI are calculated, comparing time series to identify abrupt drops in vegetation and the presence of turbid water typical of illegal mining. The method is pixel-oriented, with predominant use of unsupervised classification to highlight areas of change and then spectral rules to refine the polygons. The detected areas are transformed into vectors and automatically classified, serving as alerts. INPE's DETER system operates with medium-resolution sensors (250 m – MODIS/Terra and Aqua; 64 m – WFI/CBERS-4; 60 m – WFI/Amazonia-1), prioritizing rapid large-scale detection. The processing applies multi-temporal change detection algorithms, supported by indices such as NDVI, EVI, and NBR, associated with supervised classification techniques and object-oriented segmentation. This object-oriented approach allows for the differentiation of geometric patterns of deforestation (e.g., regular agricultural polygons versus irregular clearings), generating alerts with greater spatial coverage and near-daily periodicity. Despite its lower resolution, DETER ensures systematic and broad coverage, serving as an agile and complementary monitoring tool to Brasil MAIS, which focuses on detecting smaller-scale changes. In addition to these two sources, CENSIPAM supplements its coverage with data from other Earth observation sensors, such as CBERS, LANDSAT, SENTINEL, and SAR sensors, allowing flexibility in image selection according to cloud conditions, spatial resolution, and orbital revisit.

The analytical process follows a daily routine, beginning with analysts connecting to the geospatial database via the QGIS platform. Newly generated alerts are then loaded and displayed as vector layers, which are cross-referenced with the cartographic database of Indigenous Lands, Conservation Units, and mining titles from the National Mining Agency (ANM). Polygons identified with evidence of illegal mining activity are then classified according to their legality based on spatial overlap with these reference layers.

Initial validation is performed based on visual interpretation of high-resolution images (Planet), considering typical characteristics of mining sites, such as clearings with irregular outlines, the presence of structures like ramps and barges, and evidence of turbidimetry in water bodies. Confirmed targets proceed to the review phase, which consists of cross-checking by a second analyst. After this double check, the records are consolidated into the final database.

LOGAR also has proactive capabilities: in regions without continuous coverage or outside the reach of automatic alerts, CENSIPAM conducts independent searches through systematic image analysis, ensuring comprehensive geospatial coverage. In this way, LOGAR represents a robust model for territorial surveillance and the production of geospatial intelligence aimed at combating illegal mining.

2.3 DEFINITION OF MINING FRONT AND DESCRIPTION OF THE MINING FRONT INDEX (IFG)

Based on the information available in LOGAR, it was possible to propose a simple and accessible way to identify mining fronts, calculated from the estimate of the Mining Front Index (Equation 1).

$$\text{Mining Front Index (IFG)} = \frac{Area/Time}{T - T_{today}} \quad (1)$$

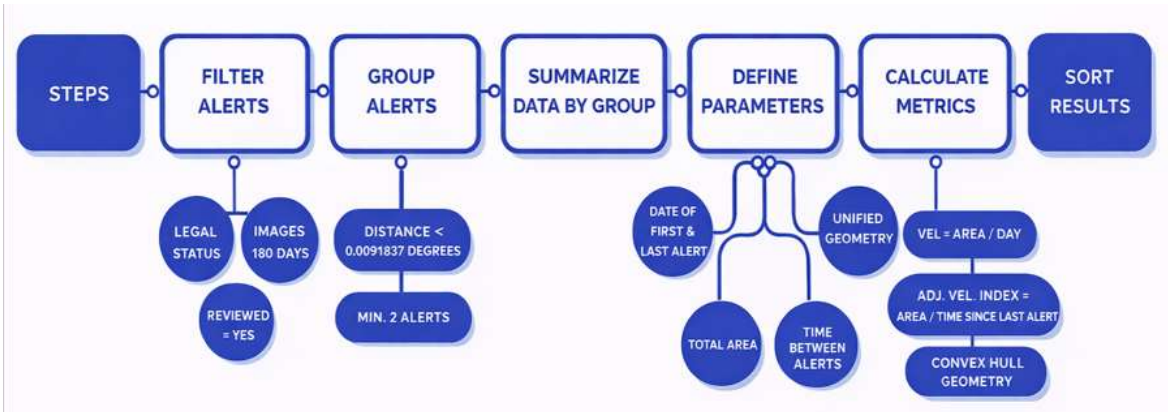
Where "Area" is the sum of the areas of the alerts, "Time" is the time interval between the date of the first alert and the last, while "T" represents the date of the last alert and "Today" is today's date.

The code creates a materialized view that groups alerts of illegal mining registered in the last 180 days and calculates an index of the expansion rate of these areas. Spatial clustering is used to identify groups of nearby alerts and, for each group, it calculates the total area, the time interval between alerts, the time since the last alert until today, and generates a representative geometry. The view highlights the groups with the highest growth rate, allowing for the prioritization of critical regions for inspection.

Main steps (Figure 2):

1. Filter recent and illegal alerts (pol): Selects only illegal mining alerts with "ILLEGAL" status, reviewed (reviewed = 'S'), with images within the last 180 days. Includes information such as alert date, status name, geometry, and area;
2. Spatially groups alerts (groups): Uses the st_clusterdbscan function to group alerts that are close to each other (distance < 0.00181237 degrees or 200 meters), forming alert groups with at least 2 occurrences.
3. Summarize the data by group (data): For each group;
4. Calculate: The date of the first and last alert; Total area (sum of the areas of the alerts); Time between alerts; Time since the last alert until today; Unified geometry of the group;
5. Calculate metrics: For each valid group (time_diff > 0 and group IS NOT NULL), calculate: vel: rate of increase of deforestation associated with illegal mining (area per day). ind_vel: rate index adjusted for time since the last alert. Convex hull geometry to represent the total area. Results are ordered by rate index in descending order.

Figure 2 – Flowchart of the steps used to define mining fronts and calculate the Mining Front Index (IFG)



Source: Designed by the authors.

3 DEVELOPMENT

3.1 RESULTS

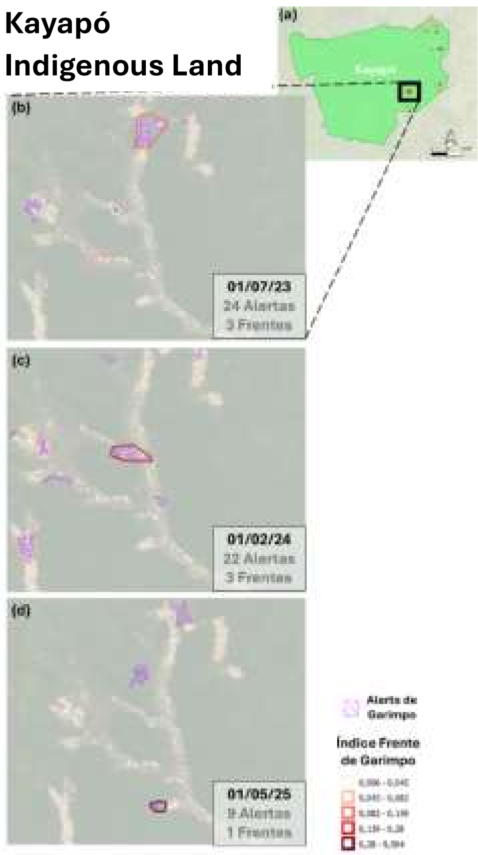
The Mining Front Index (IFG) was developed as an analytical tool to identify areas with persistent and concentrated recent alerts of illegal mining, going beyond simply counting occurrences. By combining the spatial density and temporal continuity of alerts, the indicator allowed the detection of mining fronts that remain active over time (last 180 days), even if the raw number of alerts varies. This approach offers a more qualified understanding of illegal mining dynamics, allowing for targeted monitoring and prioritization of critical areas for enforcement actions.

The sequence of images (Figure 3) shows the dynamics of mining activity within the Kayapó Indigenous Land (Figure 3a) over three distinct periods, highlighting both the number of alerts and the presence and intensity of mining fronts. On July 1, 2023 (Figure 3b), 24 alerts and three active fronts were recorded, with areas demarcated in different intensities of red according to the IFG, a tool that synthesizes the degree of spatial concentration and persistence of alerts. The most active fronts showed high IFG values (up to 9.564), evidencing growing illegal mining areas.

In the second period, on February 1, 2024 (Figure 3c), the number of alerts decreased slightly to 22, with three fronts still identified. However, there was a spatial reorganization of these fronts, with a more prominent concentration in the central portion of the image, associated with a polygon with an intermediate-high IFG (between 0.139 and 0.28). This displacement, captured by the IFG, reveals the usefulness of the tool to identify not only the number of alerts, but also mobility patterns and possible expansion or contraction of mining fronts over time.

The last image (Figure 3d), from May 1, 2025, shows a sharp drop in the number of alerts (nine) and a significant reduction in the number of active fire fronts, leaving only one. The marked areas indicate low intensity, with values in the lower ranges of the IFG. The functionality of the IFG becomes evident in this scenario: even with few alerts, it allows differentiation between sporadic activities and those that, although punctual, concentrate continuous efforts. This differentiation is crucial for guiding territorial monitoring and response strategies.

Figure 3 – Evolution of illegal mining alerts and identification of mining fronts in the Kayapó Indigenous Land (a) in three periods: (b) 01/07/2023, (c) 01/02/2024 and (d) 01/05/2025. The areas shaded in purple indicate the alerts detected, while the solid outlines represent the mining fronts identified based on the Mining Front Index (IFG). The intensity of the polygon coloring varies according to the IFG value. The intensity of the polygon coloring varies according to the IFG value. The intensity of the polygon coloring varies according to the IFG value. A progressive reduction is observed in both the number of alerts and active fronts throughout the analyzed period

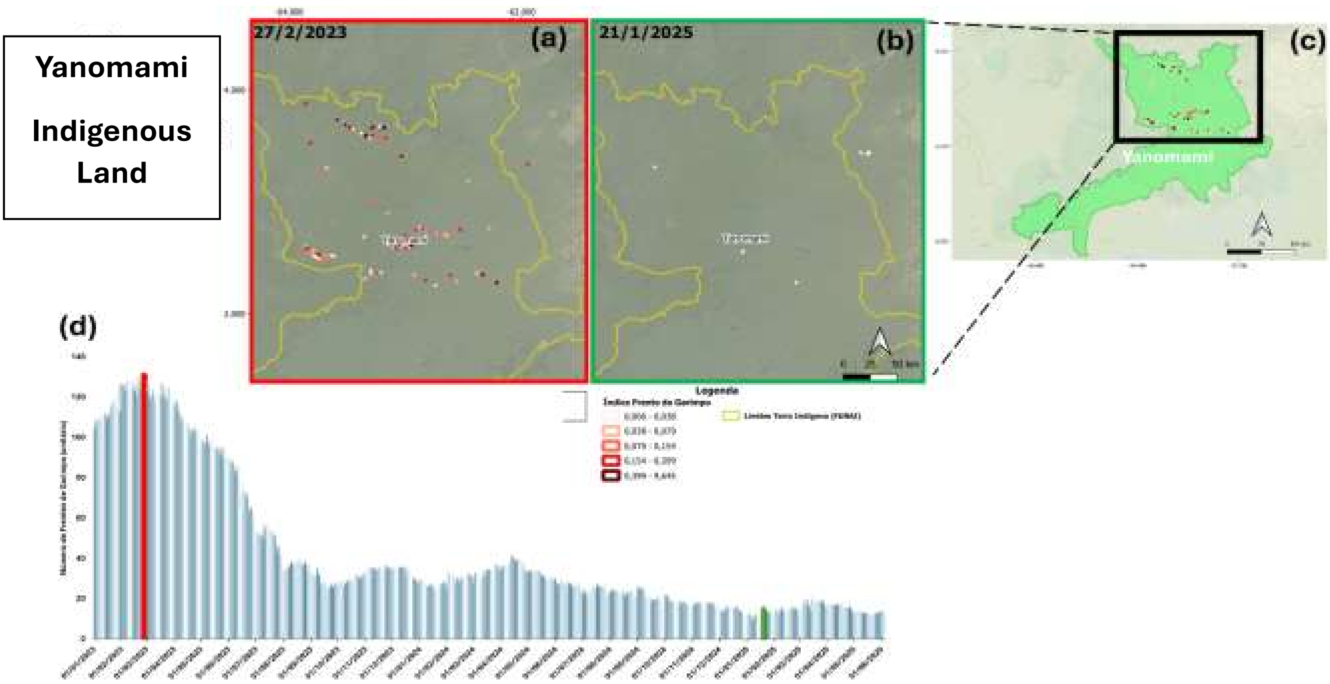


Source: Designed by the authors.

Additionally, a historical case study was conducted during the period from 2023 to 2025 in the Yanomami Indigenous Land (Figure 4), known for being under strong pressure from illegal mining and subsequent intense repression of this illicit activity. In the Yanomami Indigenous Land, the temporal data reveal a particular scenario, with a peak in mining activity in February 2023, followed by a sharp and continuous decline. The rapid reduction of mining fronts after the peak indicates an immediate and probably coordinated response to government intervention, such as operations to remove invaders widely publicized in the media during this period. The stability observed in the low levels of activity from the second half of 2023 suggests the effectiveness of the actions taken, at least within the analyzed time frame.

The maps (figure 4a-b) corroborate this trend: on February 27, 2023, mining fronts are concentrated mainly in the central portion of the Indigenous Land, with some areas of high intensity. In contrast, on the map of January 21, 2025, there is practically no record of active fronts. The almost complete elimination of mining activity detectable by remote sensing may represent a significant result of territorial control.

Figure 4 – Comparative maps of the spatial distribution of mining fronts referring to the maximum (a) and minimum (b) of mining activity in the Yanomami Indigenous Land (c). The polygons are classified according to the mining front index (IFG). In (d) the time series of the number of mining fronts detected in the Yanomami TI between January 2020 and June 2025 is presented. The red line indicates the peak date of mining activity, and the green line the date of lowest recorded activity



Source: Designed by the authors.

3.2 DISCUSSION

Remote sensing has been a strategic ally in detecting land-use change, whether deforestation for timber or associated with illegal mining. In a review by Kozinska and Górniak-Zimroz (2021), the authors evaluate methods for detecting illegal open-pit mining, highlighting techniques based on remote sensing. The most common techniques were image classification: supervised, unsupervised, and hybrid. The most used data sources were free satellite images (Landsat, Sentinel). However, the low resolution hindered the detection of small sites, characteristic of illegal mining and prospecting, requiring higher-resolution images, sometimes paid images. Finally, the authors conclude that the choice of the ideal method depends on data availability, terrain characteristics, and technological resources, but the two most accurate were the CLASlite system (94%) and image fusion with spectral indices (91.1%). CLASlite relies on image quality and performs best in tropical regions, while spectral index fusion requires careful band selection and can be sensitive to seasonality and spectral noise.

Regarding the transnational Amazonian biome, recent studies seek to propose and improve methods for alerting illegal mining. The study by Becerra *et al.* (2024) presents a near real-time alert system to detect deforestation due to illegal mining in the Peruvian Amazon using Sentinel-1 SAR data. In this study, 185,460-pixel alerts were detected between February and December 2022, totaling 1,864 ha of mining, with an accuracy of 99.98%. Finally, the authors concluded that the RAMI platform is effective for continuous monitoring, even under cloud cover, supporting rapid enforcement actions. In Brazilian territory, Mataveli *et al.* (2022) associate collection 6 of the MapBiomas project, which uses Landsat satellite images classified by the Random Forest algorithm, with the Mann–Kendall test to detect the growth of illegal mining within Indigenous Lands. The authors found an increase of approximately 1200% between 1985 and 2020, with a growing trend. Finally, the study highlights the challenge of enforcement and the urgent need for investment in effective public policies, pointing out that demarcated Indigenous Lands are vulnerable. Considering this increase in illegal mining in Indigenous Lands, especially in the Kayapó, Munduruku, and Yanomami Indigenous Lands, Da Silva *et al.* (2023) identified areas of high mining interest, roads, and clandestine airstrips as the main vectors associated with illegal mining.

In terms of challenges and opportunities in the remote and continuous detection of illegal mining in the Legal Amazon, a robust database is fundamental. Specifically, a database of illegal mining alerts with an extensive time series, systematic validation, and multiple information sources is crucial for the development of reliable and operational metrics, such as an index of illegal mining growth. The integration of alerts generated by different image classification methods with visual inspections carried out by analysts allows for greater consistency in the records and greater control over data quality. The diversity of sources reduces dependence on a single detection method, minimizing biases and increasing the robustness of the analyses. Without a database with these characteristics, derived indicators tend to present limitations in terms of temporal precision, comparability, and applicability.

Due to the atmospheric and climatic conditions of tropical forests, especially in much of Latin America, multisensor remote sensing approaches are growing, particularly the use of active sensors such as radar. In the study by Forkuor, Ullmann, and Griesbeck (2020), time series data obtained by the Sentinel-1 sensor were used to monitor small areas of artisanal mining located in Southwest Ghana. The dataset consisted of 155 images, collected between July 2015 and April 2019. However, the analysis was partially limited by the presence of atmospheric interference, resulting in the exclusion of low-quality scenes. Although Synthetic Aperture Radar (SAR) data offer advantages for monitoring in regions with high cloud cover, the results of Forkuor, Ullmann, and Griesbeck (2020) demonstrated a sensitivity of the Sentinel-1 C-band to intense cloudiness events.

Cloud cover in the Amazon varies according to the climate of the sub-regions (Af, Am, and Aw according to Köppen), directly affecting visibility for optical sensors. Wetter Af and Am regions have greater cloud cover, while drier Aw areas offer better observation conditions, especially during the dry season. In this context, the results indicate that the effectiveness of optical detection systems, such as those used by DETER and the Brasil MAIS program, is directly limited by climatic conditions, especially the high cloud cover associated with regions classified as Af and Am, where alert detection is slower or fails (Silva *et al.*, 2020; Albuquerque *et al.,* 2025). The performance of Brasil MAIS alerts improves during the dry months (May to September), when there is less convective activity, and worsens between November and March, a period of intense rainfall, when cloud cover reduces the number of useful images, even with the high revisit frequency of Planet satellites (Albuquerque *et al.*, 2025). The DETER system presents similar limitations, facing persistent cloud cover during the rainy months, coinciding with increased illegal logging activity, which ends up not being detected (Silva *et al.*, 2020). As an alternative, sensors with SAR (Synthetic Aperture Radar) technology suffer less atmospheric interference and can operate in a wider variety of weather conditions.

The illegal mining front identification tool represents a strategic advancement for monitoring and combating illegal mining in the Legal Amazon. By integrating geospatial alerts and growth indices, it allows for more precise location, analysis, and monitoring of active or expanding areas. Its uses extend beyond enforcement, offering support for tactical actions, interagency planning, academic studies, and public policy formulation. Identifying illegal mining fronts allows for targeted acquisition of high-resolution commercial images, optimizing resources and avoiding redundant imaging. Regions with high growth rates of mining activity can be prioritized for more frequent coverage or with specific sensors, such as SAR radars, expanding detection and response capabilities in near real-time. Another application of the tool is in the planning and logistics of field enforcement operations. With updated data on illegal mining fronts, agencies such as IBAMA, ICMBio, the Federal Police, and the Armed Forces can coordinate joint actions more efficiently, reducing risks and maximizing the impact of interventions. The data extracted from the tool also serve as a basis for studies on the spatial and temporal dynamics of illegal mining in the Amazon. It is possible to identify patterns of expansion, relationships with infrastructure (roads, rivers, clandestine airstrips), activity cycles, and specific territorial profiles, contributing to more in-depth socio-environmental and regional analyses.

The Mining Front Index (IFG) has as its main limitation its direct dependence on the quality and robustness of the database used. The reliability of the results is conditioned both by the confirmation and improvement of the alert itself, and by possible data cross-referencing, as in the case of categorizing the legality of mining. The latter depends on information provided by the National Mining Agency (ANM), whose data crossing has already shown inconsistencies and is in the process of improvement, reinforcing the need for constant validation and updating of reference sources.

Finally, among the upcoming challenges are improving the tool by calibrating the time window and distance radius to better represent the growth dynamics of illegal mining, as well as evaluating which Index value best represents the priority mining fronts for monitoring. In the medium and long term, improvement can occur through the use of predictive algorithms and greater integration of socioeconomic, climatic, and geological data. Key questions include: What vectors are driving new fronts? What is the relationship between active fronts and protected territories? How to predict areas under imminent risk of illegal occupation?

4 FINAL CONSIDERATIONS

The Mining Front Index (IFG) has proven to be an efficient and accessible tool for spatial and temporal monitoring of illegal mining activity in the Legal Amazon. By combining density and permanence of alerts, the index allows the identification of fronts of continuous activity, even in scenarios with low alert frequency, making it especially valuable for strategic enforcement actions. Case studies in the Kayapó and Yanomami Indigenous Lands demonstrated the method's sensitivity in detecting both the persistence and retraction of illegal activities in response to control policies. Furthermore, the tool can support inter-institutional decisions, optimize the use of commercial images, and inform resource allocation. Although the IFG is limited by its dependence on the quality of databases, both in confirming alerts and in cross-referencing for categorizing legality, its application can be expanded to other regions of the Amazon, contributing to the strengthening of environmental governance and the protection of traditional territories against the increasing pressure of illegal mining.

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