SOCIEDAD LATINOAMERICANA EN PERCEPCIÓN REMOTA Y SISTEMAS DE INFORMACIÓN ESPACIAL
XXI SIMPÓSIO INTERNACIONAL SELPER
4-8 de novembro 2024 - Belém, Brasil

THE OBSERVATORY OF MINING ATIVITIES IN FRENCH GUIANA : 20 YEARS OF REMOTE SENSING APPLIED TO MINING DEFORESTATION

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RESUMEN. Desde a década de 2000, a mineração de ouro experimentou um grande ressurgimento na floresta amazônica, inclusive na Guiana Francesa. Juntamente com as minas de ouro legais, a mineração ilegal de ouro expandiu-se, resultando em impactos socioeconómicos e ambientais significativos. Para resolver esta questão crítica, o governo francês criou o Observatório de Atividades Mineiras (OAM), que utiliza a deteção remota por satélite há mais de 20 anos para monitorizar o fenómeno, orientar ações de fiscalização e avaliar os impactos. Utilizando o conjunto de dados OAM, este artigo examina os métodos utilizados para monitorar as atividades de mineração de ouro, os dados coletados e potencial para melhorar o processo de monitoramento. Ao longo do tempo, os métodos de processamento de imagens foram adaptados para incorporar várias fontes de imagens disponíveis, incluindo Landsat, SPOT e agora Sentinel-2, garantindo a continuidade dos esforços de monitorização. As áreas processadas pela fotointerpretação flutuam de acordo com as restrições impostas pela acessibilidade da imagem e pela nebulosidade. No entanto, a utilização dos dois satélites Sentinel-2, em conjunto com o download e processamento automatizado de inúmeras imagens, permitiu a organização semanal do fluxo de trabalho de fotointerpretação. Além disso, a operação Harpie, em curso desde 2008, contribuiu para abrandar a taxa de desflorestação ilegal em menos de 40 % desde essa altura. Para melhorar os métodos de deteção, propomos a automatização da caraterização dos objectos detectados e a utilização de inteligência artificial baseada na aprendizagem profunda.

Palabras-clave: Mineração ilegal; Sensoriamento remoto; Guiana Francesa; Desmatamento; Observatório.

RESUMO. Desde la década de 2000, la minería de oro ha experimentado un importante resurgimiento en la selva amazónica, incluida la Guayana Francesa. Además de las minas de oro legales, la minería de oro ilegal se ha expandido, lo que ha tenido importantes impactos socioeconómicos y ambientales. Para abordar esta cuestión crítica, el gobierno francés ha creado el Observatorio de Actividades Mineras (OAM), que ha estado utilizando sensores remotos por satélite durante más de 20 años para monitorear el fenómeno, guiar las acciones de aplicación de la ley y evaluar los impactos. Utilizando el conjunto de datos OAM, este documento examina los métodos utilizados para monitorear las actividades de minería de oro, los datos recopilados y las posibles mejoras para mejorar el proceso de monitoreo. Con el tiempo, los métodos de procesamiento de imágenes se han adaptado para incorporar varias fuentes de imágenes disponibles, incluidas Landsat, SPOT y ahora Sentinel-2, lo que garantiza la continuidad de los esfuerzos de seguimiento. Las áreas procesadas por fotointerpretación fluctúan de acuerdo con las limitaciones impuestas por la accesibilidad de las imágenes y la nubosidad. Sin embargo, la utilización de los dos satélites Sentinel-2, junto con la descarga y el procesamiento automatizados de numerosas imágenes, ha permitido organizar el flujo de trabajo de fotointerpretación semanalmente. Además, la operación Harpie, que ha estado en marcha desde 2008, ha ayudado a reducir la tasa de deforestación ilegal en menos del 40% desde entonces. Para mejorar los métodos de detección, proponemos la automatización de la caracterización de los objetos detectados y el uso de inteligencia artificial basada en aprendizaje profundo.

Palavras-chave: Minería ilegal; Teledetección; Guayana Francesa; Deforestación; Observatorio

ABSTRACT. Since the 2000s, gold mining has experienced a major resurgence in the Amazon rainforest, including in French Guiana. Alongside legal gold mines, illegal gold mining has expanded, resulting in significant socio-economic and environmental impacts. To address this critical issue, the French government has set up the Observatory of Mining Activities (OAM), which has been utilizing satellite remote sensing for over 20 years to monitor the phenomenon, guide enforcement actions and assess impacts. Using the OAM dataset, this paper examines the methods used to monitor gold mining activites, the data collected, and potential improvements to enhance the monitoring process. Over time, image processing methods have been adapted to incorporate various available imagery sources, including Landsat, SPOT and now Sentinel-2, ensuring continuity in monitoring efforts. The areas processed by photointerpretation fluctuate in accordance with the constraints imposed by image accessibility and cloud cover. However, the utilisation of the two Sentinel-2 satellites, in conjunction with the automated downloading and processing of numerous images, has enabled the organization of the photointerpretation workflow on a weekly basis. Furthermore, operation Harpie, which has been ongoing since 2008, has helped to slow the rate of illegal deforestation less than 40% since that time. To improve the detection methods, we propose the automation of the characterization of detected objects and utilizing artificial intelligence based on deep learning.

Keywords : Illegal Mining; Remote sensing; French Guiana; Deforestation; Observatory.

1. INTRODUCTION

For over 30 years, the Amazon has been under pressure from gold mining, a corollary of the continuous increase in the price of gold. Gold mining is responsible for numerous socio-environmental damages, particularly deforestation (Laperche *et al,* 2008). This phenomenon also affects French Guiana, where it is the primary cause of deforestation (Rahm *et al,* 2021). The financial crisis of 2008 significantly contributed to the increase in deforestation due to illegal gold mining in South American countries (Asner *et al.,* 2013). Concurrently, in French Guiana, 2008 was marked by the launch of operation Harpie, a large-scale police operation aimed at combating illegal gold mining conducted with the support of the armed forces, Additionally, the mining permit regime was reformed. These measures have successfully limited deforestation caused by gold mining despite a socio-economic context highly favorable to its development.

In the context of the Amazon rainforest, a vast and uniform area with limited access, the use of satellite remote sensing makes particular sense for monitoring and assessing the development of mining activity. This technology enables the identification of new mining sites, the monitoring of their progress and the measurement of their impact. Optical imagery also provides an objective description of environmental degradation and facilitates communication through clear visual representations (Polidori, 2000, Le Tourneau, 2005).

One of the first operational applications of this technology was developed in French Guiana with the support of the French Agricultural Research Centre for International Development (CIRAD). This initiative was based on a method of exploiting Landsat and SPOT images for the benefit of the National Forests Office (ONF) (Gond, 2005). The ONF adopted this solution to set up regular monitoring of deforestation and mines in French Guiana. In 2008, the ONF initiated the creation of the Mining Activity Observatory (OAM) to sustain this system and coordinate the efforts of the various institutions involved in monitoring mines and combatting illegal gold mining (Joubert, 2008). The remains operational and has adapted to the evolution of satellite supply, now incorporating high-resolution optical imagery accessible through the Sentinel missions of the European Union's Copernicus space programme. A substantial data heritage has thus been built up and capitalized on, comprising a 30-year time series of remote sensing data (Linarès, 2019).

The aim of this article is to identify and analyze the main methodological challenges encountered in monitoring mining activity using optical satellite remote sensing in French Guiana. It seeks to assess the impact of technological and analytical innovations on the accuracy, reliability and completeness of the data produced. Finally, it proposes recommendations to overcome these challenges and improve future practices. To achieve this, we will present a detailed chronology of the implementation of the satellite monitoring system, highlighting the historical factors influencing its development. We will carry out a descriptive analysis of the OAM dataset and suggest areas for improving the system based on this analysis, integrating the latest technological innovations.

2. MATERIAL AND METHODS

French Guiana, a French territory with an area of 84,000 km², is located on the North Atlantic coast of South America and bordering Brazil and Suriname. Mining activity is mainly concentrated in an area of approximately 30,000 km² known as the “gold crescent”, which corresponds to the geological formation of the volcanic-dominated and sedimentary-dominated greenstone belts (Laperche *et al.*, 2008).

The use of remote sensing products for monitoring activities makes particular sense in a territory as large as French Guiana. Optical satellite images are suitable for detecting objects such as gold mining sites. These sites can be distinguished from tropical rainforest by a strong contrast between the bare soil and the surrounding vegetation (Gond, 2005). Moreover the risk of confusion with other activities causing deforestation, such as agriculture and logging, is low because these activities are located in relatively distinct areas with minimal overlap.

Guianese mining activity is mainly represented by small-scale sites. Legal mining is mainly carried out by small and medium enterprises, with operating permits of 1 km² for a period of 4 years. Illegal gold mining, on the other hand, is characterized by a constellation of smaller sites. They correspond to the concept of “artisanal and small-scale mining” (ASM), which is based on an informal and little mechanized operating mode but widely practiced in the Amazon region (Noucher, 2021).

The alluvial deposits in the valley floor are the most exploited. Illegal gold minning also targets primary deposits located in bedrocks of the reliefs. Table 1 details the characteristic objects of mining activity that can be found on satellite imagery in the context of French Guiana.

Type of activity	Type of mining objets	Physical description	Size and géometry	Aspect of the impact on the image
Legal	Alluvial placer	Mechanized flat mining, with complete deforestation and opening of vast water basins	one autorisation can concern 2 km along a creek and less than 500 m wide	homogenous area of bare soil with some area of water
	Tracks	forest tracks on bare soil allowing the passage of excavator and engins	hundred meters to kilometers of long, less than ten metres wide	The linear impacted is visible by parts
Illegal	Base camp	Grouping of small rough buildings mainly under forest cover	a camp usually has less than 10 buildings an area of a few hundred square metres	when visible : degraded forest
	Primary and elluvial open pit	Open pit drug in the relief	tens of meters wide	little area of bare soil
	Primary underground	Digging of small shafts and roadways in relief, with disposal of sterile materials on the ground	little area area of a few hundred square metres	when visible : degraded forest. The most important site have bare soil
	Alluvial placer	Manual flat mining with partial deforestation and opening of small water basins	from small forest gap to continuous linear lines over several kilometers	Mixt of degraded forest, bare soil and water

Table 1. Typology of objects characteristic of mining activity identifiable by satellite remote sensing.

One of the first operational applications of this technology was developed in French Guiana with support from CIRAD. Based on the supervised classification of Landsat and SPOT images (Gond, 2005), the method enabled a comprehensive assessment of the progression of mining activity from 1990 to 2006. A transfer of skills was initiated for the benefit of the ONF. The detections produced feed the spatial data layer of the extension of areas exploited by mining activity in the ONF GIS.

In 2005, a direct image reception station, SEAS Guyane (Satellite Assisted Monitoring of the Amazon Environment), was established in Cayenne. This station provides institutional users with a continuous flow of SPOT images free of charge, enabling them to cover the entire territory several times a year (Faure *et al.,* 2006). In line with CIRAD's work, an evaluation demonstrated the value of this resource and highlighted the contribution of the new SPOT 5 satellite for the continuous monitoring of mining activity by remote sensing (Linarès, 2008). However, the large number of images acquired leads to varying levels of cloudiness. Supervised classification then produced numerous confusions between gold panning objects and clouds due to similar spectral signatures. A manual photo-interpretation method became necessary (Joubert, 2008).

With the operation Harpie in 2008, illegal activity is developing as much as possible under forest cover. It is therefore necessary to also monitor forest degradation. This new impact is made visible by the higher resolution of SPOT 5 images while the limits of Landsat 5 are reached. In addition, with SPOT 5, the more discreet secondary impacts linked to camps, mining tracks or other more discreet modes of exploitation (underground exploitation) are also identifiable.

From 2013, Landsat 8 images were also utilized, in order to anticipate the end of SPOT 5 operations in 2015 and the gradual commissioning of Sentinel-2 satellites at the end of the same year. Sentinel-2 images serve as a continuation of SPOT 5 images, featuring a spatial resolution of 10 meters and equivalent spectral bands. Significantly, the revisit time for the two Sentinel-2 satellites is 3 to 5 days over the whole of French Guiana, with systematic acquisitions. The use of Landsat 8 images was therefore quickly abandoned in favor of Sentinel-2.

<table>
<tr><th>Satellite image</th><th>Spatial resolution (m)</th><th>Channels Used</th><th>Surface (km²)</th><th>Revisit (day)</th><th>Mission period</th><th>Images processed</th></tr>
<tr><td>Landsat 5</td><td rowspan="2">30 (multispectral)</td><td>RGB, NIR, MIR</td><td>185x185</td><td rowspan="2">variable</td><td>1984-2013</td><td>20</td></tr>
<tr><td>Landsat 8</td><td>RGB</td><td></td><td>2013-…</td><td>88</td></tr>
<tr><td>SPOT 2</td><td rowspan="2">20 (multispectral)</td><td>RGB</td><td>60x60</td><td>Variable</td><td>1990-2009</td><td>20</td></tr>
<tr><td>SPOT 4</td><td>RGB, NIR, MIR</td><td rowspan="3">100x100</td><td rowspan="2">4 min.</td><td>1998-2013</td><td>461</td></tr>
<tr><td>SPOT 5</td><td rowspan="2">10 (multispectral)</td><td rowspan="2">RGB</td><td>2002-2015</td><td>1061</td></tr>
<tr><td>Sentinel-2</td><td>3 to 5</td><td>2015-…</td><td>2843</td></tr>
</table>

Table 2. Summary of satellite images used and their specifications.
Images used by CIRAD until 2006 are not included.

Since 2019, image downloading and post-processing has been carried out by an automated chain based on the Sen2Chain Python package (Révillion *et al.,* 2024). As soon as new Sentinel-2 images at L1C level (without atmospheric correction) become available over the gold crescent, they are downloaded and stored on dedicated servers. Each week, the operator visualizes these products in the free GIS software QGIS (Figure 1). A true-color composition is employed with an enhanced contrast to highlight bare soil, pollution, degraded forest, and healthy forest. This facilitates the detection of objects to be interpreted. Turbidity anomalies in watercourses are particularly visible and help guide the search for potential illegal sites located upstream. A 10x10 km grid is used to systematize the area of interest. The photo-interpretation, conducted at a scale of 1:5000, excludes objects smaller than 600 m² (6 pixels) in order to limit false positives, such as large flowering tree crowns.

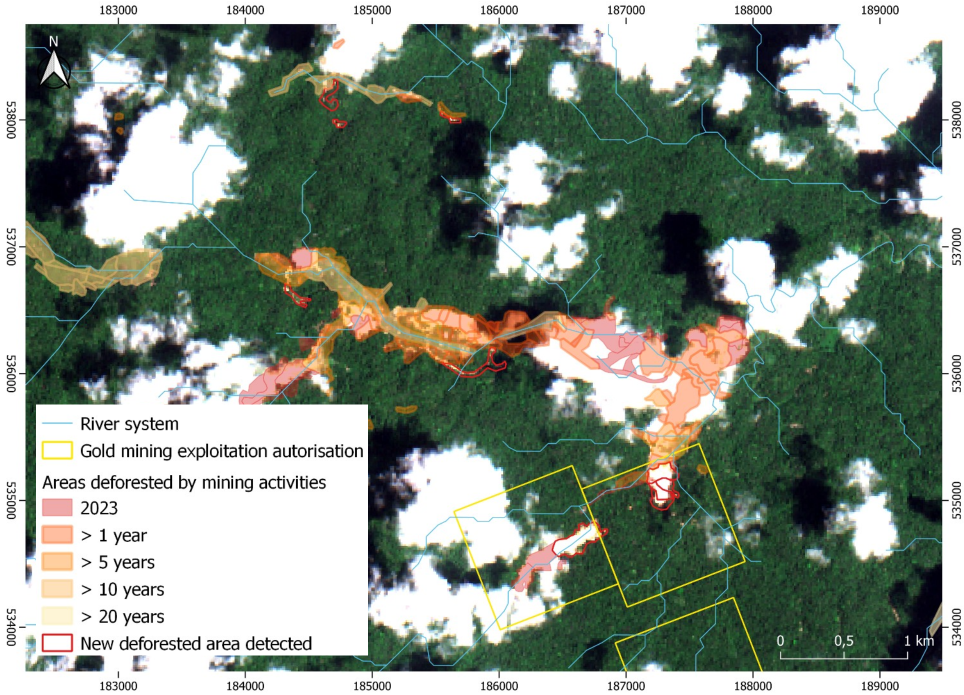

Figure 1. Illustration of detection of deforestation with a satellite image Sentinel-2 of 01/10/2023 (RGB with contrast stretching).

The data series produced capitalizes on the areas exploited by mining activity, based on observed deforestation or forest degradation. The data comprises impacted areas that are added to those that were previously detected. The extension of these areas over time is therefore observed. Each new area identified by remote sensing is uniquely referenced. Field checks or expert opinions then make it possible to characterize these areas, in particular the nature of the site (primary or alluvial) and the type of associated infrastructure (camp, track). Legality is determined by cross-referencing various contextual data, including the legal mining cadastre and surveys of existing illegal sites. Metadata includes the date and source of the observation, as well as the date of integration. Every week, new observations are made available to partners involved in the fight against illegal gold mining and to the mining inspectorate, assisting inguiding surveillance and law enforcement missions in the field. Within three months, these detections must be validated and then integrated into the reference data set. This data series is centralized within the OAM. Since 2024, an annual publication has also been made available on the regional *GéoGuyane* platform as open data, in accordance with current standards including the European INSPIRE directive relating to access to public environmental data. This initiative adresses the expectations of civil society that had not been met until now (Noucher, 2021).

3. RESULTS AND DISCUSSION

Over nearly 25 years, the OAM has collected 20,000 detections covering 34,000 ha of mining-related deforestation in French Guiana. Although the earliest polygons were digitized in 1950, it was not until the 1990s that the dataset was really filled in, based on archived satellite data or field surveys. Various optical sensors were used, each with its own specifications. Figure 2 shows the annual cumulative area of satellite imagery processed by the ONF between 2006 and 2023.

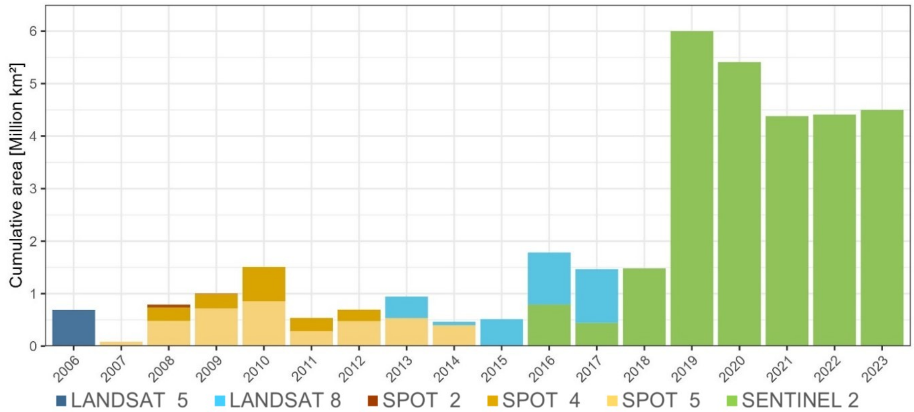

Figure 2. Annual cumulative area of satellite imagery used between 2006 and 2023.

The use of optical satellite remote sensing to monitor mining activities began with Landsat 5 in 2006 (0.68 Mkm²). Between 2007 and 2014, the cumulative area of satellite images processed highlights the nearly exclusive use of the SPOT series and mainly SPOT 5. The area processed during this period remains very similar to the 2006 values (between 0.5 and 1 Mkm² on average) despite an increase to 1.5 Mkm² in 2010. With the launch of Landsat 8 in 2013, we anticipated the end of SPOT in 2014 and maintained the processing in 2015. Subsequently, the cumulative area processed increased significantly (around 1.5 Mkm² as in 2010) following the switch to Sentinel-2 from 2016. This level remains stable until 2018, before increasing fourfold in 2019 to 6 Mkm².

The cumulative area processed over the years depends on products access and cloud cover limitations. This shift reflects a transition from a processing method based on a small number of minimally clouded images to a method based on the continuous acquisition of imagery with variable cloud cover. The SEAS program in French Guiana has made this possible over the period 2008-2014. Although the images were not collected systematically, this accumulation of images provided global coverage of the territory with periodic updates, allowing any point in the territory to be observed multiple times a year. In 2016, our working method was adapted to the limited human resources available. Despite the potential of Landsat 8 and Sentinel-2, we had to revert to a one-off manual selection of images based on cloud cover. However, from 2019, with the implementation of the automated imagery acquisition and pre-processing system, the full potential of the two Sentinel-2 satellites could be used. The number of available images increased sharply, leading to a weekly photointerpretation workflow. Consequently, the high number of images processed remains stable over the following years. From 2021, the cumulative area processed decreases slightly to 4.4 Mkm² as a result of a strong phase of climate phenomenon La Niña over the two consecutive years (2021, 2022) and independent human factors.

Figure 2 can be compared with Figure 3, which shows the annual change of illegal gold mining polygons area and their cumulative deforestation area.

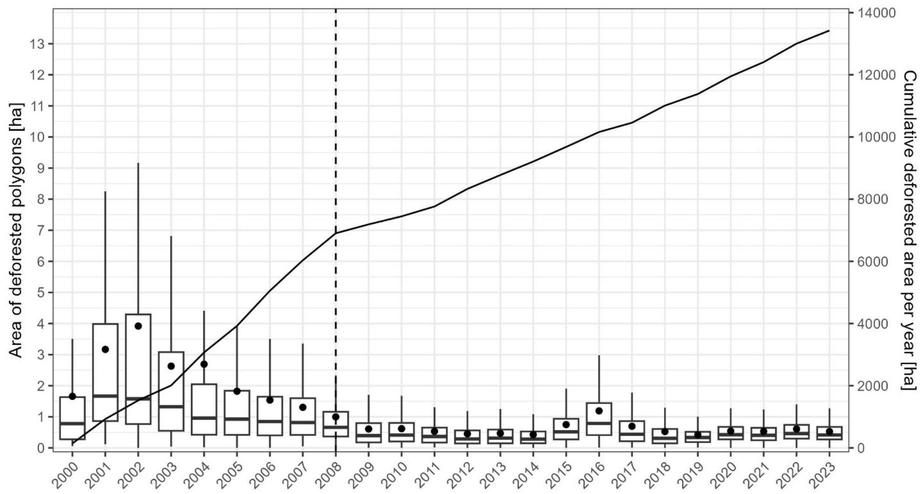

Figure 3. Detections mean area by year for illegal mining sites (outliers are not shown to make the figure easier to read) and cumulative illegal deforestation area since 2000. The dashed vertical line marks the start of Harpie.

The mean polygon area decreased steadily between 2002 and 2014, from 3.92 ±6.72 ha to 0.43 ±0.47 ha. It increased again from 2015 to 2016 (1.19 ±1.41 ha) and then stabilised at around 0.45 ha. The sensor type, the availability of the processed images, and the various limitations described above all influence the variations in object size. Indeed, when the ONF experienced better availability of products and human resources, it was able to detect deforested areas more quickly and monitor their extension more closely. The size of objects and their variability decreases with the frequency of revisits to the area.

Between 2000 and 2023, a total of 13,425 ha were deforested due to illegal gold mining activity. Nearly half of this deforestation (44.9 %, or 6,903 ha) occured in the 8 years preceding the Harpie operation, with an average annual deforestation rate of 754.3 ±151.5 ha.year^{-1}. Since the intensification of military operations in 2008, the average annual deforestation decreased by 38.76 % to 461.9 ±151.51 ha.year^{-1}. The Harpie operation and the subsequent change in illegal gold miners' practices forced them to adopt more discreet extraction methods, resulting in smaller areas being impacted.

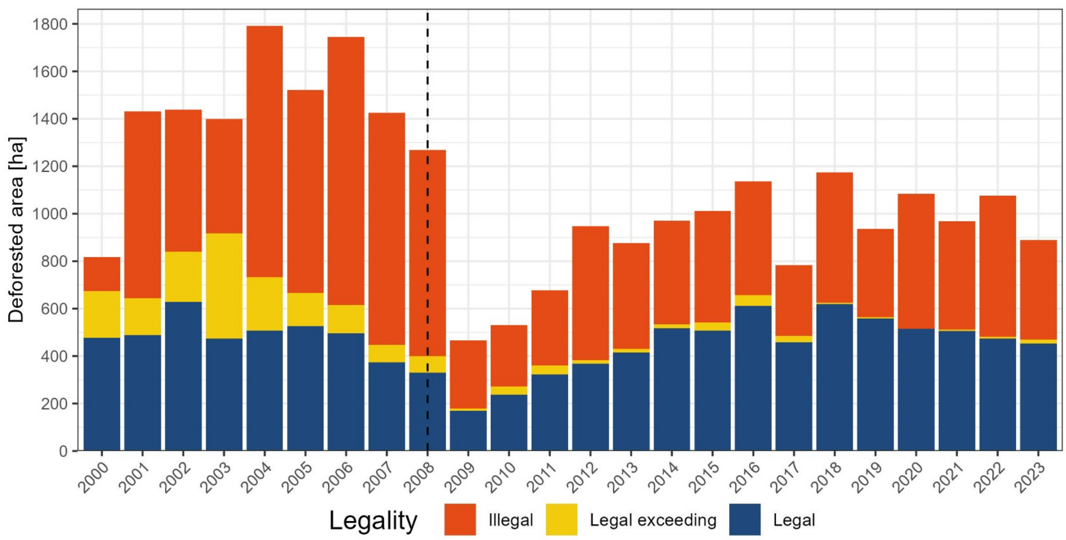

Figure 4. Extension of mining deforestation by year. Data for 2023 are currently being consolidated. The vertical line marks the start of Harpie.

Figure 4 illustrates the annual extension of gold mining areas by legality category : illegal, legal exceeding, and legal. Between 2000 and 2023, 26,366 ha were deforested with over half attributable to illegal mining (50.9 % or 13,425 ha), excluding the overruns by legal mines. This translates to an average deforestation rate of 1.099 ±348.99 ha.year^{-1} over the period. Comparatively, 42,130 ha were deforested in neighboring Suriname between 1997 and 2019, with 85 % due to illegal gold mining (Quash *et al.,*2024). The Harpie operation and the mining licence reform had a noticeable impact in 2009, leading to a significant decline in illegal activity and a decrease of legal mines, especially those exceeding their limits. Thereafter, exploitation increased again between 2012 and 2023, gradually stabilizing at an average of 988.23 ±114.54 ha.year^{-1}. Throughout this period and continuing today, deforestation caused by illegal gold mining averages 471.69 ±87.44 ha.year^{-1}. The deforestation caused by legal gold mining is slightly higher on average, at 499.97 ±73.91 ha.year^{-1}.

Considering the extended period covered by the dataset, the reexploitation of former sites, wether legal or illegal, seems unavoidable. However, this phenomenon is not quantified, and we focus only on the extension of the areas deforested each year. There is a significant value in further developing the dataset to account for and quantify this activity.

The high spatial resolution of the sensors is adequate for monitoring the dynamics of illegal work sites, as the primary objective is to detect changes. The use of very high spatial resolution (VHSR) optical satellite imagery is also possible, as demonstrated by the Brasil MAIS program in Brazil. However, in French Guiana, these VHSR images provide excessive detail, complicating interpretation. Furthermore, images from the Copernicus series are free and come with a guaranteed right of access, unlike VHSR images which area mainly produced from commercial sources. Nevertheless, VHSR images can still be used on an occasional basis for specific analyses, particularly through the PlanetScope offer available online for the tropical region.

Several developments could be implemented to improve the monitoring method of gold mining impacts in French Guiana. Currently, polygon validations and characterizations are performed by OAM partners through ground checking and data cross-checking with contextual information. Given the time involved and the number of detections requiring validation each year, time-saving measures would be highly valuable. The process could be improved by using an advanced system and automatic spatial queries to cross-reference existing information with new detections.

Artificial intelligence through deep learning using spectral information from Sentinel-2 is another potential automation method. This approach has already been applied in similar contexts in Africa (Ngom *et al.*, 2020, Gallwey *et al.*, 2020). The situation in French Guiana is particularly suitable for such developments, as the environment is relatively uniform, with few competing activities in the same area. Moreover, the OAM provides a substantial training dataset comprising 6,625 objects identified from SPOT 5 and 8,646 from Sentinel-2. As with supervised classification methods, the main challenge remains the cloud cover, which is a major consideration when setting up a continuous and automatic processing flow.

Radar imagery also offers promising possibilities for monitoring gold mining activities using Sentinel-1 (Ballère *et al.*, 2021). It cannot be used to detect forest degradation. However, radar sensors enable continuous acquisition independent of cloud cover and would thus complement current processing based on optical imagery.

Implementing these improvements will optimize the time required for the process and ensure the sustainability of the monitoring method. It will also help to assess other aspects such as the reactivation or revegetation of sites.

4. CONCLUSION

Twenty years after CIRAD's intial developments in satellite remote sensing to monitor mining activity in French Guiana, our solution is now fully operational, supported by a dedicated observatory that provides significant institutional foundation. The French Guiana solution has been maintained and consolidated while adapting to sensor changes, facilitated by a constantly expanding satellite service offering. The system, based on optical sensors, has successfully been implemented, overcoming the challenges posed by tropical cloud cover to ensure continuous monitoring. Today, the OAM relies on the Copernicus' freely-available imagery and processing can be done using open-source softwares and tools. It is a significant advantage when public resources are often very limited.

A dataset spanning the 30 years of the current gold cycle in French Guiana has been developed, providing insights into trends in legal and illegal gold mining trends and assessing the effectiveness of public measures over this period. This dataset also supports the development of publics policies of spatial planning. Furthermore, the system's responsiveness enables quick action to monitor legal gold mines and repress illegal gold mining activities. The OAM's data are now available in open access offering opportunities for the French and international scientific community working on this area.

These results underscore the importance of Sentinel-2 in OAM activities and emphasize the necessity of maintaining and enhancing satellite mission capabilities to meet the growing needs of land monitoring and management. They also point out the challenges associated with managing large volumes of data. While the potential of optical imagery is well established but it will be enhanced by artificial intelligence for automatic processing and complemented by radar imagery. This represents the challenges of the OAM's modernisation project that has just begun.

Gold mining remains a threat to the Amazonian environment. It is crucial to keep developing operational solutions for monitoring this phenomenon with the same vigilance and to support public policies to control mining activity to limit its impact on the environment and local populations.

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