



Artisanal Exploitation of Mineral Resources: Remote Sensing Observations of Environmental Consequences, Social and Ethical Aspects

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Abstract

Since the rise of the gold price in 2000, artisanal and small-scale gold mining (ASGM) is a growing economic activity in developing countries. It represents a source of income for several millions of people in West Africa. Exploitation techniques have evolved from traditional gold panning to mechanization and use of chemical products that are harmful for the environment. Government strategies to control and regulate this activity are impeded by the difficulties to collect spatial information, due to the remote location and the mobile and informal nature of ASGM. Here we present and discuss the value of remote sensing techniques to complement the knowledge on artisanal mining impacts, including for detection of illegal sites, the evaluation of the degradation of soils and waters, the deforestation and the monitoring of expansion of ASGM with time. However, these techniques are blind regarding gender issues, labor relations, mobility, migration, and insecurity and need to be considered with knowledges from other disciplines. Remote sensing is also instilled with various powers accruing to those enabled to produce and interpret these data. Remote sensing should be therefore used in a reflexive manner that accounts for the social, ethical and political implications of ASGM governance informed by space observations.

Keywords Artisanal mining · Remote sensing · West Africa · Interdisciplinarity · Public policies

Article Highlights

- Artisanal and small-scale gold mining is an important economic activity in developing countries with gold resources
- Observations from space can be used to detect mining sites and evaluate their impact on the environments
- Remote sensing should be used in a reflexive and critical manner that accounts for the social, ethical and political implications of ASGM governance informed by space observations

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1 Introduction

Artisanal and small-scale gold mining (ASGM)—low-tech mineral, labor intensive extraction and processing—is a very important economic activity in developing countries with gold resources. In West Africa, for instance, thousands of artisanal gold mines provide employment for more than 2 millions of people, and livelihoods for at least three times more (IGF 2017). The number of gold miners and proportion of the population living from this sector vary from one country to another among the West African countries: Burkina (1,000,000 in 2017), Niger (450,000 in 2011), Côte d'Ivoire (503,100 in 2017), Ghana (1,100,000 in 2011), Guinea (300,000 in 2011), Mali (400,000 in 2016), Senegal (15,000 in 2014) and Sierra Leone (300,000 in 2011) (source: <https://delvedatabase.org/data>). These numbers are approximate, not recent, and most likely represent underestimation of present employment directly working in ASGM. These gold mines are frequented by men, women and children who rely on the income from artisanal mining and related activities to escape poverty or complement farming incomes, especially during the dry season (Cartier and Bürge 2011; Hilson and Garforth 2012). This activity is generally unlicensed and partakes in the predominantly informal economy that unfolds outside the legal domain of formal recognition by the State. In consequence, ASGM tends to be described as illegal or clandestine, by contrasts with the large-scale industrial mines (LSM). However, the distinction between industrial and artisanal mining should not be view as rigid or sharp, both because ASGM and LSM often interact throughout the mine cycle, and because ASGM is increasingly capitalized and mechanized. Recent studies indeed suggest that legal small-scale mining entrepreneurship is developing when the national framework promotes such activity (Hilson et al. 2018). Besides, formality and informality should not be equated to the presence or absence of rules. While artisanal mining occurs mainly outside the legal framework of the State, artisanal miners have developed complex and efficient modes of organization. In contrast, while industrial mining is regulated by the legal system of the State, such laws may sometimes be questioned for failing to retain a sufficient share of the mining rent, to protect the environment, or to downplay the rights of local populations in favor of those of foreign investors. Large-scale mining and artisanal mining are both responsible for environmental degradation in gold mining areas, but in different ways, as the development and exploitation techniques of artisanal mining sites are essentially uncontrolled. Together with rural and urban poverty (Hilson and Garforth 2012), the rise in the price of gold since 2000 is the main cause of the proliferation of these artisanal mines, with spikes subsequent to global crises, such as following 2009 global downturn and more recently the COVID pandemic. Technological factors, such as the development of metal detectors, have contributed to the proliferation of ASGM. Despite the fact that it represents a source of income for the local population, it also causes damage to the environment, potentially affecting directly the health of gold miners and people living in their vicinity.

Faced with the proliferation of these artisanal mines, governments have sometimes tried to ban artisanal mining, but more generally adopt various strategies to control or regulate this sector of activity, which can take different forms. When the strategy is to regulate the activity through formalization, gold miners are expected to access mining permits, which in practice is often hindered by important financial and social barriers and administrative obstacles (Hilson 2020; Tschakert 2009). However, this activity is mobile by nature, depending on new discoveries, as well as frequent expulsions from the mining sites. Some gold mining sites have been exploited for one or two centuries and are tolerated, and yet most remain in the realm of informality. The deployment of this activity in space and time,

and its regulation, is therefore a complex issue involving many actors: the state and its representatives at various levels, the local authorities (e.g., heads of districts, mayors), the customary authorities (administrative heads of villages), investors from the political–economical elite, the landowners, as well as the villagers and immigrants from neighboring areas and countries.

The regulation of ASGM is accompanied by missions on the ground by the authorities, involving controls, the seizure or destruction of equipment, and so-called clearing operations of illegal sites. Conflicts with artisanal gold miners also occur in the case of attribution of exploration or exploitation permits to large/international mining companies. This regulatory effort is also accompanied by training of artisanal gold miners (e.g., training camps in Côte d'Ivoire) aimed at developing environmentally more friendly practices and the development of an activity within a legal framework. However, these efforts are strongly undermined by the costs and difficulties to monitor activities, which usually take place at large distance of major urban centers or capitals. Field observations (including aerial and unmanned aerial vehicles—UAVs) may not be conducted on a regular basis, expulsions are sometimes followed by the re-settlement of clandestine mining sites, whereas the boundaries of allocated corridors may not be observed by gold miners, especially when they are, or become, unproductive.

Therefore, to fill gaps related to the lack of geographic, spatial and temporal information on artisanal mining sites, researchers and governments, in different regions of the world, have used satellite data to identify, monitor and map artisanal mining sites and analyze/assess their environmental impacts. The objective of this article is to present an overview of the contributions of remote sensing approaches to the monitoring of ASGM and their environmental impact in developing countries. The focus is placed on West Africa, where solutions based on Earth Observations are generally under-exploited. Whereas applied research and exploration of mineral resources in West African received considerable attention over the last decades, research on the impact of mining activities and on mining environments has drawn the attention of international donors only recently, as illustrated with the recent installation of several Center of Excellences in this domain in Côte d'Ivoire, Niger and Guinée, with funding from the World Bank. This article also discusses the social aspects of the use of remote sensing techniques, including the compilation and presentation of data and facts on maps to the different actors (objectivity), as well as the risks associated with these techniques. The recent and future deployment of satellites orbiting the Earth with sensors with enhanced spectral capabilities and resolutions also offers new avenues for both research and support to public policies in this sector. These prospective aspects are discussed in the last section of this article.

The use of remote sensing to study and monitor areas degraded by gold mining activity began in the early 2000s in Brazil. The first study carried out was by Almeida-Filho and Shimabukuro (2000) and Almeida-Filho (2002). It focused on soil degradation. Our bibliographic synthesis therefore covers the period 2000–2021. Since this first study, the theme of "remote sensing and artisanal mining" has become more diversified. Some studies focus on the identification of exploitation areas (legal/illegal) (Gond et al. 2004; Laperche et al. 2008; Elmes et al. 2014; Gallwey et al. 2020; Asner and Tupayachi 2016; Almeida-Filho and Shimabukuro 2000; Lobo et al. 2018; LaJeunesse Connette et al. 2016; Le Tourneau and Albert 2005; Telmer and Stapper 2007). Other applications include the evaluation of deforestation (Rahm et al. 2014; Schueler et al. 2011; Poudori et al. 2001; Caballero Espejo et al. 2018; Diringer et al. 2020; Asner and Tupayachi 2016; Asner et al. 2009; Swenson et al. 2011), the measure of water turbidity related to ASGM (Lobo 2015; Gallay et al. 2018; Linares 2019; Lobo et al. 2018), and the analysis of gold panning expansion over

time (Kusimi 2008; Manu et al. 2004; Obodai et al. 2019; Snapir et al. 2017; LaJeunesse Connette et al. 2016; Isidro et al. 2017). Following the work of Almeida-Filho (2002), the analysis of land degradation by ASGM has continued in many other regions of the world.

The basic motivation for these different studies is that human activity in the broad sense around mining sites (exploration, extraction, storage and processing of ore) and the natural degradation of abandoned mining sites, including the formation of acid mine drainage, have physical properties (usually optical) that are distinct from other types of land use. Once these properties are known, usually through field studies, the specific spectral signature of the gold mining sites is analyzed, in time and/or space. Analysis of the changes detected in these areas from space allows quantification of the environmental impacts (deforestation, increase in water sediment load, soil degradation), and the expansion of ASGM. Different approaches have been pursued depending on the objectives; they differ in the type of data used, the method of site identification, and/or the method of detecting changes over time. Concerning the data, Landsat images have been the most frequently used over the period 2000–2018, their main assets being their accessibility (free), a large global coverage, and long time series. More recently, authors of this type of work have used higher resolution optical data (SPOT, Sentinel-2, UK-DMC2, MODIS—moderate resolution imaging spectrometer—, Google Earth and UAVs), while others have chosen to work with radar data (Sentinel-1, JERS1, PALSAR, ENVISAT) to avoid constraints related to cloud cover, particularly in tropical areas. Sentinel-1 radar images have been efficiently used to monitor deforestation in the tropical forest of French Guiana (Ballère et al. 2021; Bouvet et al. 2018), and these methods identify the fraction of deforestation related to gold mining. The contribution of data from hyperspectral satellites (Hyperion) and data from airborne sensors (Hymap, AVIRIS) have also been explored to know the impact of mining discharges and abandoned mining sites on the environment. Studies have focused in particular on the impact of acid mine drainage (AMD), defined as acidification of surface water due to the weathering of minerals exposed to the air following mining operations (Choe et al. 2008; Buzzi et al. 2014; Riaza and Müller 2010; Riaza et al. 2015, 2012b; Swayze et al. 2000; Pfitzner et al. 2018; Percival et al. 2014; Kemper and Sommer 2002; Jeong et al. 2018; Jackisch et al. 2018; Davies and Calvin 2017). Some of these studies are very simple and qualitative: photo-interpretation, thresholding, and manual digitization of sites, while other more complex and powerful approaches are developing (use of artificial intelligence and statistical methods) and allow for more comprehensive, automated, and recurrent treatment of regions affected by this activity. In all cases, prior knowledge of the terrain, i.e., the characteristics of the gold washing sites and the techniques used to extract and process the ore, is necessary to conduct these studies. The characteristics of the gold mining sites vary according to the geology of the region (nature of the deposits), thus influencing the ore extraction techniques. These techniques vary widely from one site to another, ranging from shafts and tunnels up to a few tens of meters deep to reach vein deposit, or to open shafts or the panning of riverbeds for placer deposits. The morphology of the sites is also dependent on the type and geometry of the deposit (vein or placer type). The spatial organization of the extraction and processing sites also varies, in particular according to the presence or absence of nearby water sources (see paragraph describing the study sites). Our synthesis is structured around the following applications of remote sensing techniques focusing on capabilities and limitations for each of them: detection and identification of ASGM sites, soil degradation, deforestation and analysis of the temporal expansion of ASGM, and ASGM and water pollution as seen from space. This organization is justified by the fact that the first information is the occurrence of a mining site (detection), whereas use of remote sensing data has then focused on the consequences on different compartments

of the natural environment: soil, vegetation and waters. Naturally, these compartments are open systems and communicate with each other. This section also includes a subsection focusing on research and applied prospective, based on the new capabilities of future satellites equipped with enhanced spectral capabilities and/or higher imaging resolutions. These sections are followed by a discussion on societal and ethical aspects of the use of space-based information for the governance of the mining sector. The discussion also emphasizes the use of research findings by various actors in the artisanal mining sector, and in particular in the operational applications of gold mining regulations that have developed in some countries as a result of academic work.

2 Remote Sensing Observation of ASGM

2.1 Detection of ASGM Sites

The most ubiquitous application of remote sensing techniques to ASGM is to address the question of the mapping mining sites, which may develop clandestinely in remote places. In French Guiana, following the government's plan to regulate and control ASGM, a feasibility study of the detection of gold panning sites by satellite imagery was conducted. This study, carried out by Gond and Brognoly (2005), provided information on the spectral and optical properties of gold mining areas. A detection algorithm was developed using the visible and infrared bands of a SPOT 4 image (20 m resolution) and Landsat 5 and 7 images (30 m resolution). The detection method was based on the contrasts between the observed object and its environment (Gond et al. 2004). These studies concluded that Satellite imagery is reliable for detection of mining sites despite the frequently dense cloud cover typical of equatorial regions. In the case of gold mining site detection by satellite imagery in the tropics, the observed object (the mining site) is distinguished from its environment (the tropical rainforest) by a strong contrast between the exposed ground and the surrounding vegetation (Fig. 1). Figure 2 illustrates the ASGM seen at different scales (from ground to space) in tropical areas (with an example in Côte d'Ivoire). This strong contrast will be revealed in a variable way on the spectral bands of the satellite data used. The contrast is more or less marked depending on the observation wavelength or the filter used. The major difficulty highlighted in this study is the similarity, from a spectral point of view, between the different types of bare soil: gold mining, deforestation for timber exploitation, cultivated areas, inhabited areas, etc..

The authors of the study in French Guiana therefore attempted to amplify this contrast by using spectral indices, which made it possible to identify threshold values to distinguish surfaces exploited for gold from other types of surfaces. A field campaign was conducted to validate these results. Once the gold mining sites were geolocated using this method, the information was collected in a geospatial database. Based on this study, the Guyanese government initiated remote sensing monitoring of gold mining activities to determine the location of illegal operations and to assess the expansion of the activity (Laperche et al. 2008). The government also created the "*Observatoire de l'Activité Minière*" (OAM) in 2008. The OAM currently monitors gold mining with the development of several processing lines that are used to monitor water turbidity and deforestation (Linares 2019). In 2019 during the presentation of the OAM 10-year review, it was reported that more than 2000 images from different sensors (Landsat 5 and 7 in 2006, SPOT 2–4 and 5 between 2007 and 2014, Landsat 8 between 2013 and 2017, Sentinel-2 since 2016) have been processed,



Fig. 1 Aerial photograph of AGSM, Central Côte d'Ivoire

which has allowed the detection of 15,439 sites and the digitization of 12,288 ha. However, the monitoring of the evolution of mining sites by optical satellite imagery faced problems related to cloud cover, which is frequent in tropical areas, and the temporal repeatability of Landsat and SPOT data did not allow for a sufficient number of cloud-free images, unlike what is now possible with Sentinel-2 data (Landsat-8 has a 16-day cycles, to be compared with the 5-day revisit frequency of the Sentinel-2a and b constellation). In Myanmar, LaJeunesse Connette et al. (2016) identified and mapped the extent and current expansion of artisanal mining activities using Landsat 8 satellite imagery and Google Earth imagery, producing the first public database on artisanal mining in that country. An approach based on photo-interpretation and comparison of satellite images at different dates was used in this study. The authors point out the constraint related to the resolution of Landsat data to detect gold panning sites, which are very small, and the similarity at the spectral level, which leads to confusion, hence the choice of photo-interpretation, which is more qualitative and subjective, using Google Earth.

In Ghana, Gallwey et al. (2020) applied deep learning to gold panning site detection. This study applied a convolutional neural network model to Sentinel-2 data. Results validated with field observations (test sites) showed less than 8% error, justifying the effectiveness of their approach. The model was also used to quantify the extent of deforestation related to illegal mining in the protected forests of Ghana and to estimate the effect of governance. The ASM land-use category increased by 15,000 ha over the period 2015–2019. However, this study also shows the effectiveness of the Ghanaian government's efforts to regulate gold mining in 2017 with a decrease of 6000 ha of impacted land. The deep learning approach also quantified the extent of illegal mining-related deforestation within Ghana's protected forests, measured at over 3500 ha, with 2400 of these lost since 2015. The results obtained with deep learning are much more accurate compared to those obtained using other machine learning methods such as random forest or multilayer perceptron (MLP). However, additional training data are needed in different climatic zones and land-use types to extend its application.

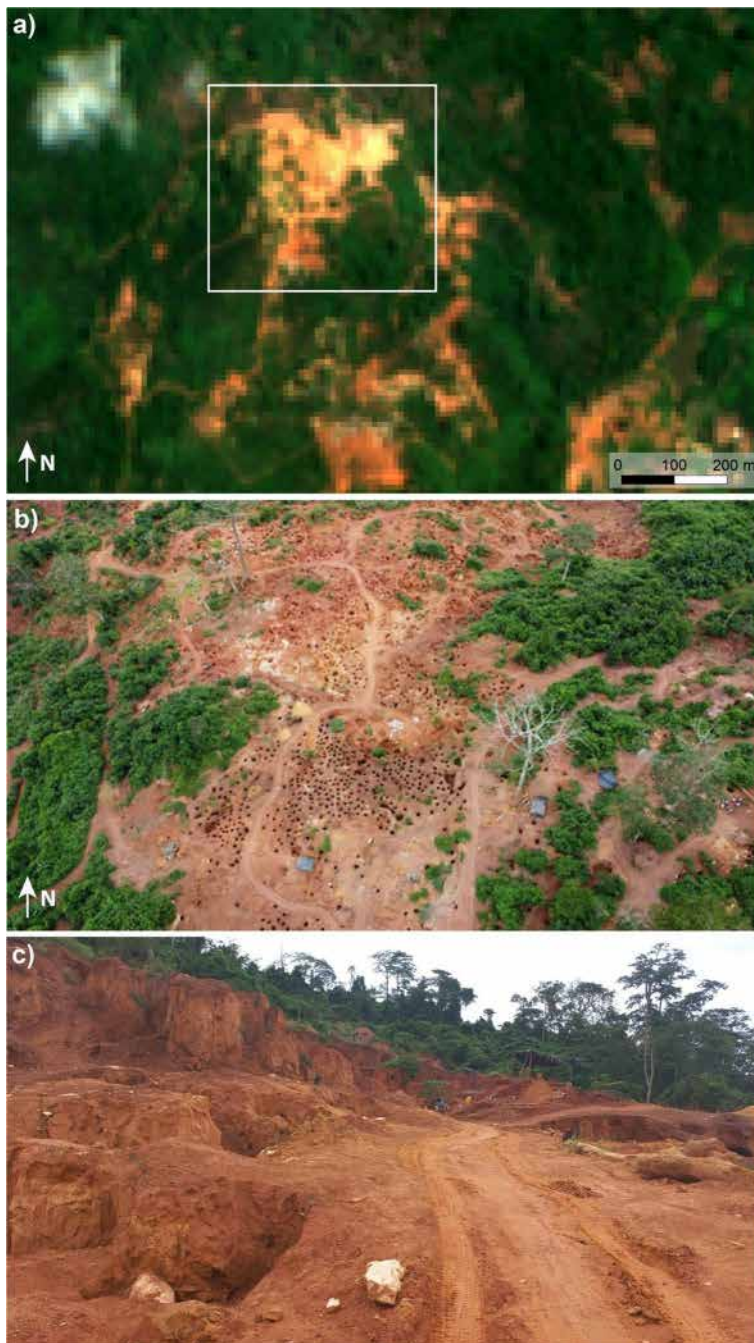


Fig. 2 Illustration of the detection of artisanal mining sites and appearance at different scales. **a** Extract of Sentinel-2 scene of 22 May 2020 (Central Côte d'Ivoire). RGB color composite approaching natural colors, R=band 4 (red, 664.6 nm), G=band 3 (green, 559.8 nm), and B=band 2 (blue, 492.4 nm). **b** Aerial image taken with a drone. The white square in a indicates the location of the aerial image. **c** Picture taken during a field campaign within the aerial image

Several other studies have demonstrated the capacity of satellite imagery in the identification and detection of ASGM sites (e.g., Simionato et al. 2021), but several difficulties arise. These difficulties are related to the optical spectral signature of the sites and their spatial footprints. Depending on the objectives and the study area, the approach to be adopted must take these difficulties into account. Regarding the spectral signature, ASGM sites are often confused with other types of bare soil. Spatially, the size of the sites makes their detectability with medium-resolution data difficult, if not impossible. In Senegal, Ngom et al. (2020) proposed a method for detecting and mapping ASGM sites with the minimal confusion possible using Sentinel-2 data and the Google Earth Engine. The method is based on the study of spectral properties over time of different landcover types such as bare soil, water, vegetation, settlement and area used for ASGM. These authors used principal component analysis (PCA) to determine the optimal period of the year for mapping ASGM area, separability and threshold (SEaTH) to determine the optimal bands or spectral indices to discriminate ASGM from other land use. The most relevant bands served as band sets for automatic classification and mapping of the scenes achieved with support vector machine (SVM) classifier. This proposed method has been validated with an accuracy of more than 80% showing the effectiveness of Sentinel-2 data for mapping gold panning sites. Beyond detection of mining sites, Earth Observation from space can also be used to quantify the consequences of ASGM as a function of time and in different compartment of our natural environment, including soil, vegetation and rivers. These topics are addressed in the next section.

2.2 Soil Degradation

This section focuses on studies whose objectives are of documenting from space, as a function of time, the state of soil degradation as a result of ASGM. Soil degradation is defined as a change in soil health that results in a decrease in the capacity of the ecosystem to provide goods and services for its beneficiaries. Soil degradation generally refers to its acidification, erosion or compaction, the modification or destruction of the humus in relation to changes in the vegetation, the decrease of the amount of organic matter, and the pollution by toxic metals (Fig. 3). A pioneering study in this domain (Almeida-Filho 2002) used a 12-year Landsat-Thematic Mapper (TM) image time series (1987–1999) at 30-m resolution to analyze areas degraded by gold miners. The approach, based on a principal component analysis of the images, highlights areas of bare soil in relation to the vegetation of the surrounding savannah. It is followed by a post-classification that consists of image segmentation and classification of the segmented regions. The results of this study showed that degraded areas increased from 94.4 ha in 1987 to 404.4 ha in 1994. Then, following the cessation of ASGM, a re-vegetation of the land was observed, decreasing the bare areas from 311.2 ha in 1995 to 246.2 ha in 1999. However, this study showed that the areas that were intensively exploited revegetated more slowly than in other cases of de-vegetation, thus demonstrating the particularly negative impacts of ASGM on soil fertility. Following this study, studies have been initiated in other regions of the world, such as Indonesia and Brazil (Telmer and Stapper 2007; Lobo et al. 2016), with improved approaches but also based on the detection of changes in optical signatures. In Niger, Abass Saley et al. (2021) were able to map the evolution of the mining site of Koma Bangou during four decades using Landsat data. This study relied on spectral indices designed to be sensitive to minerals present in mining waste (such as oxides and hydrated minerals) and took



Fig. 3 Artisanal gold mining site of Kharakhéna (Eastern Senegal) illustrating the degradation of soil

advantage of the scarcity of the vegetation in this region. The authors of this work were able to clearly distinguish the expansion of mining waste, as well as the introduction and expansion of cyanidation (hydrometallurgical technique for extracting gold by converting the metal to a water-soluble coordination complex using an aqueous solution of cyanide) during the last decade.

Several studies of land degradation caused by mining activities in general (not just ASGM) have also focused on acid mine drainage, which can, in addition to the acidification water, contribute to the release of toxic metals from mining waste in the soils. Hyperspectral and multispectral data have been able to detect and map this phenomenon in Pennsylvania (Williams et al. 2002), Iran (Seifi et al. 2019; Shahriari et al. 2013), California (Montero et al. 2005) and South Africa (Mielke et al. 2014). They are often combined with airborne data to understand contamination in acidic water basins in mining areas. Hyperspectral data can provide early indications of the status of soil contamination generated by waste from sulfide-rich mines, allowing authorities to activate mitigation procedures. Riaza et al. (2012a, b) used Hyperion data (30 m resolution, demonstrator) and Hymap airborne data (5 m resolution) to map mine waste from massive sulfide deposits in the Iberian area. This study showed that mine dams, mill tailings and mine dumps in a variable state of pyrite oxidation are recognizable on these types of data. Acidic water pools at mine sites are spectrally remarkable and can be mapped with simple image processing procedures, including Minimum Noise Fraction Transform, Pixel Purity Index, N-Dimensional Visualizer, or Spectral Angle Mapper. In addition, acidic waters of different chemical composition that are responsible for soil degradation can be mapped using hyperspectral data, whether at high or low spatial resolution (Quental et al. 2013; Riaza et al. 2015).

2.3 Deforestation

Deforestation is one of the best known and most documented impacts of gold mining. It has been measured from space by several authors in many different regions. It is generally defined (in the remote sensing and gold mining theme) by a conversion of forest into mining sites, the transformation being particularly visible on satellite images (Fig. 4). In this section, we include both destruction of natural forests and degradation of areas previously used for agroforestry (e.g., cocoa growing). Taking advantage of the availability of more than 30 years of satellite imagery, it has been possible to determine deforestation and expansion in areas where these activities were known for decades. In the Amazonian Park of French Guiana, the WWF (World Wildlife Fund) raised the alarm bells on the catastrophic situation caused by gold washing. Aerial overflights conducted three times a year to survey the sites showed record pressure from illegal gold mining in this protected area. Impacted areas had increased by 24% in 2016 and 139 active sites were identified (WWF 2016). One of the OAM processing chains mentioned in the previous paragraph is used to track areas impacted by ASGM in French Guiana and thus quantify deforestation. With this chain, monitoring is done on a weekly basis with Sentinel-2 data. The operating mode of the process is presented in Fig. 5. Thanks to this processing chain, several illegal operations have been detected and interrupted. One example is the destruction of the Grande Bagot creek detected by the “*Office National des Forêts (ONF)*” on the Sentinel-2 image of 15 May 2019. The gendarmerie intervened in 2019 on this site to put an end to illegal activities.

In the Peruvian Amazon in the department of Madre de Dios, a study by Swenson et al. (2011) used Landsat 5 data acquired between the period of 2003–2009 to quantify deforestation through an ISODATA unsupervised classification approach in the Guacamayo and Colorado-Piquiri mining areas. This study showed that, from 2003 to 2009, mining at both sites converted 6600 ha of primary rainforest and wetlands into large areas of ponds and tailings. This destruction of the Peruvian forest has been strongly correlated with the increase in the price of gold (~18% per year). It increased from 292 ha/year between



Fig. 4 Illustration of deforestation caused by gold mining in Central Côte d'Ivoire

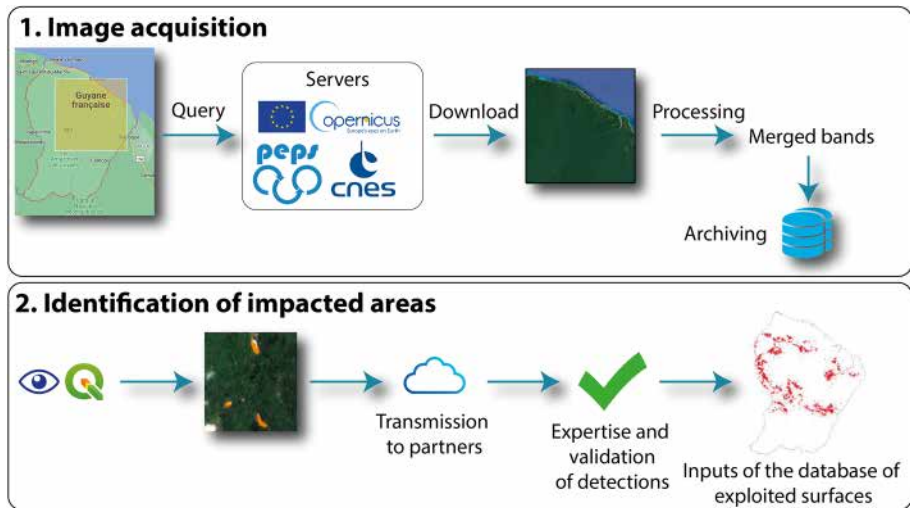


Fig. 5 Processing chain developed to monitor deforestation in French Guiana (translated and modified from Linares 2019)

2003 and 2006 to 1915 ha/year between 2006 and 2009, a sixfold increase. A further study by Caballero Espejo et al. (2018) using CLASlite (Asner et al. 2009) and Global Forest Change (Hansen et al. 2013) algorithms applied to Landsat data in the same area showed that ASGM caused deforestation quantified at 100,000 ha over a 34-year period (1984–2017) in the Peruvian forest.

In southern Ghana, Snapir et al. (2017) applied an unsupervised classification approach on UK—Disaster Monitoring Constellation-2 (UK-DMC2) satellite data at 22 m resolution to analyze the destruction of cocoa growing areas due to illegal gold mining between 2011 and 2015. This study showed that ASGM expanded very rapidly. The exploited areas tripled over the study period along the Offin, Ankobra, Birim, Anum, and Tano rivers. Despite the positive results of this study, the authors noted the difficulties of working with optical imagery due to cloud cover over the area, which poses a major challenge for mapping and monitoring illegal mining activities in southern Ghana. The study by Forkuor et al. (2020) therefore explores the contribution of Sentinel-1 radar imagery for change identification and detection. A change detection approach, based on three time-series characteristics—minimum, average, maximum—was used to calculate an appropriate back-scatter threshold for identifying/detecting mining-induced land-cover changes in the study area. This study showed a downward trend in the evolution of ASGM in southern Ghana from 2015 to 2019 illustrating the impacts of the efforts of the Ghanaian government in the fight against illegal gold panning. It should be noted that even radar data have limitations in tropical regions, as Forkuor et al. (2020) reported that 25% of the Sentinel-1 data were unusable due to atmospheric effects from high intensity rainfall events.

2.4 Water Turbidity

Remote sensing is used to analyze the impact of gold mining on rivers. Mining is most often carried out along streams, resulting in significant sediment discharge into rivers

(Fig. 6). In this case, the turbidity of the water is due to suspended matter following discharge of mining waste into the rivers.

In 2017, the French public organisation BRGM developed a telemetry system for water turbidity in French Guiana (Linares 2019). This system consisted in transforming the reflectance of turbid waters, measured from Sentinel-2 band 4 into a turbidity value expressed in nephelometric turbidity unit (NTU). It was first applied by the Amazonian Park of French Guiana for a turbidity observatory of the Maroni. The method was consolidated a few years later with approaches conducted by Gallay et al. (2018). In this study, the authors combined field data (water flow, precipitation, suspended sediment concentration, suspended sediment load estimates) and satellite data (MODIS) to monitor the evolution of suspended sediment fluxes in the Maroni and Oyapock rivers in French Guiana. The objective was to assess whether changes in sediment loads were associated with deforestation and removal of soil layers caused by the development of mining activities in the two rivers. Results showed that 15 years of intensive mining activities have altered the concentration of suspended sediment in the Maroni River, significantly increasing sediment loads and yields since 2009. This increase in sediment discharge is also correlated with deforestation along with the development of the mining activity (Gallay et al. 2018). This approach, also tested in Burkina Faso, has proven to be very effective for monitoring water turbidity (Robert et al. 2016). However, the resolution of MODIS data (250 m) does not allow detection of turbid waters of small areas. Recently, this processing chain has been adapted to Sentinel-2 data and the operability of this tool will allow monitoring of pollution of waterways related to mining activities. The work of Lobo et al. (2018) conducted on the Tapajós River in the Amazon quantified, particularly from Sentinel-2 data, the effects of suspended solids derived from mining activities on optical properties. In this study, the aim was to relate the reflectance of satellite data to the total amount of suspended solids in the water. The authors concluded that the inorganic nature of the mine tailings affected the underwater scalar irradiance in the Tapajós River basin. For tributaries with little or no influence of mine tailings, the waters are relatively more absorbent.

2.5 Future Capabilities, Persistent Limitations and Avenues for Interdisciplinary Research

With increasing temporal, spatial and spectral resolution, the future sensors and satellites imaging the surface of the Earth will offer new capabilities for monitoring the development of ASGM and assessing their consequences on the environment. In particular, hyperspectral imaging, which provides the capabilities to map the concentration of certain types of minerals, will be useful for mapping waste, cyanidation areas and acid mining drainage in detail. A resolution of a few meters to a few tens of meters per pixel will be required for such applications. For this purpose, it is possible to mention the PRISMA (PRecursore IperSpettrale della Missione Applicativa) and HySIS (HyperSpectral Imaging Satellite) satellites put into orbit in recent years and the future HSI (HyperSpectral Imager, Mücke et al. 2019) and HISUI (Hyperspectral Imager SUITE, Tachikawa et al. 2012) satellite missions. The spatial resolution of this new generation of satellite (30 m) will remain a possible limitation for mapping sparse and disseminated mining waste. Studies using hyperspectral satellite data will develop with these new generation of satellites, knowing that Hyperion was a demonstrator of this technology and that the spatial and temporal coverage of Hyperion data remain limited. For example, no Hyperion data are available for the Kharakhéna and Bantakokouta sites considered in the recent study of Ngom et al. (2020),

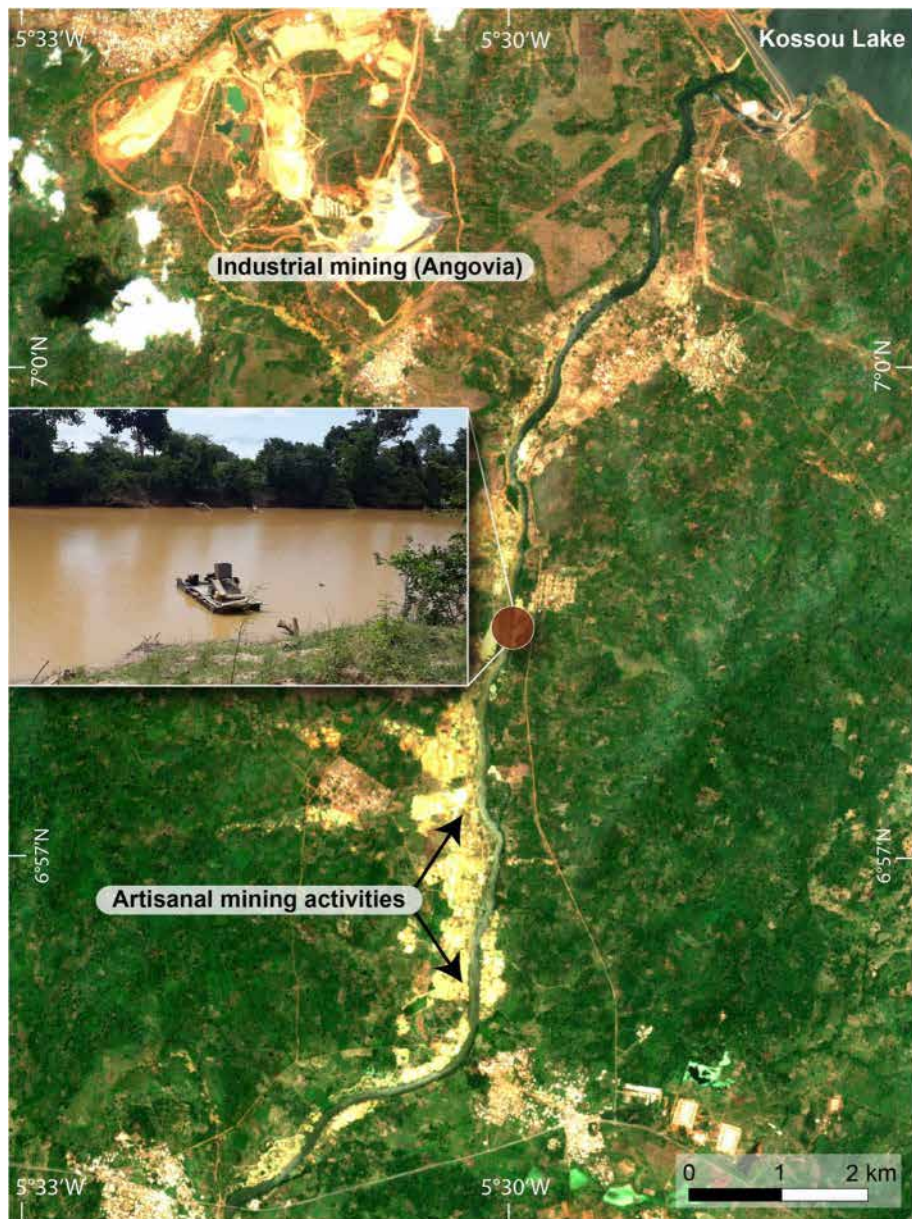


Fig. 6 Illustration of sediment discharge into rivers linked to artisanal mining activities. **a** Extract of Sentinel-2 scene of 23 May 2021 (along the Bandama river in the central Côte d'Ivoire). RGB color composite approaching natural colors, R=band 4 (red, 664.6 nm), G=band 3 (green, 559.8 nm), and B=band 2 (blue, 492.4 nm), **b** is a picture taken in the river illustrating the discharge of sediment potentially linked to mining activities

while only one scene has been acquired at the Kokumbo site in Côte d'Ivoire, but this one has a high cloud cover. This example illustrates the fact that cloud coverage will limit the capabilities of hyperspectral sensors as it does for satellite imagery. Only high revisit

frequency may overcome this obstacle in tropical regions, during the rainy season. The recent elaboration of new techniques to monitor deforestation (Reiche et al. 2021; Ballère et al. 2021; Bouvet et al. 2018) on the weekly basis from Sentinel imagery may provide additional relevant data with comparable or higher performance than optical imagery to detect artisanal mining sites in their early phases of development.

It should be finally noted here that all these techniques remain (and will likely remain) blind regarding gender issues, labor relations, insecurity on mining sites, and migrations related to gold panning, which all need to be considered in the governance of this sector. It is therefore clear that the governance of ASGM informed by space-based observations must include knowledge from other disciplines in an interdisciplinary approach. They are many possible connections between these issues and observations that can be inferred from space, which offers avenues for interdisciplinary research in geology, environment, social, political, economic and health sciences. The next section of this manuscript therefore addresses the social and ethical aspects of a governance of ASGM informed by remote sensing observations and lists some of these outstanding questions that may be addressed by interdisciplinary research.

3 Governance of ASGM Informed by Remote Sensing Observations: Social and Ethical Aspects

In many ways, remote sensing observations promise to complement the knowledge on artisanal mining impacts in the areas where it occurs, and which are often remote and hardly accessible for the agents of the concerned governments' branches. More broadly conceived, remote sensing observations complement the available tools (such as census, mapping, agents' delegation on site, episodic reporting, etc.) to a state to properly "see" the territory it is assumed to govern (Scott 2008) by objectifying and reducing it in legible formats. As any technology of the sight, remote sensing is also necessarily parceled in what it enables to see, and inevitably instilled with various powers accruing to those enabled to produce, make accessible (or not), and interpret through different frames and political agendas "objectified" representations of the landscape (Witjes and Olbrich 2017; Litfin 2002; Hall 2017; Davis et al. 2021). This final section is thus a call to the actors of this dynamic field to use remote sensing in a reflexive manner that accounts for the social and political implications of ASGM governance informed by space observations and that fosters access to information and enhance knowledge across levels beyond government. Taking stock of the prolific social science scholarship on artisanal and small-scale mining, we briefly point to some of the major issues that these considerations raise.

3.1 Earth Observation for an Inclusive Formalization Policy

As an instrument of governance, Earth Observation (EO) from space (or remote sensing) cannot be disentangled from current major regulatory trends. Spurred by major donors such as the World Bank and various UN agencies, the push toward the formalization of the artisanal mining sector has become a central piece of the development strategy of several countries in West Africa (Hilson 2017). Yet, after 15 years, dominant top-down formalization strategies (e.g., ASGM licenses, corridors, etc.) have overall had very limited results (Van Bockstael 2019; Hilson 2017; Geenen 2012) when not merely counterproductive (Marshall and Veiga 2017; Hilson and Maconachie 2017; Banchirigah 2006). The passage

from tolerance to formality (by dedicating specific sections to ASGM in the last round of mining codes' revision) has de facto placed most miners in the realm of illegality (Van Bockstael 2014; Hilson 2013), notwithstanding “vulnerabilizing” (Fisher 2007), “margin-alizing” (Tschakert and Singha 2007; Sauerwein 2020), or “criminalizing” (Crawford and Botchwey 2018) informal actors. Indeed, while ASGM relies on ephemeral and moving sites, constantly reconfigured by artisanal miners' mobility, formalization relies on the contrary on a fixation of the activity and the definition of specific spaces where it is legal (or not) to exploit. From the grounded perspective of the artisanal miners, the fraught equation between informality and illegality has then mainly translated in the multiplication of bans and (often violent) evictions (Bolay 2017; Dessertine 2019; Dessertine and Noûs 2021; Werthmann 2006; Hilson 2017; Wireko-Gyebi et al. 2020), putting at risk the livelihoods of thousands of miners and their dependents. It is therefore crucial that remote sensing instruments support a truly inclusive formalization policy (e.g., Hilson 2020), rather than merely implementing a surveillance apparatus of control and repression.

3.2 The Importance of an Open-Access EO Information and Products

Despite its mainly informal nature, artisanal mining is highly regulated by various forms of non-state “practical norms of real governance” (De Herdt and Olivier de Sardan 2015). Local actors such as “customary” village authorities or mine authorities (as the vigilante groups called *tombolomaw* in Mande populations, for example) enforce the everyday real governance of mining sites (collection of “informal” taxes, resolution of conflicts, allocation of plots, etc.) (Brottem and Ba 2019; Persaud et al. 2017; Grätz 2004, 2009; Sangaré et al. 2017), whose revenues tangibly contribute to local development (e.g., Teschner 2014; Bazillier and Girard 2018). The relative discrepancy between state and non-state actors and norms urgently raises the question of access to information generated by remotely sensed imagery. While remote sensing information can expectedly help governments in decision making and monitoring artisanal mining activities at a distance, i.e., identify new “rushes”, deforestation issues, or informal settlements, it is still vital that information flows extend beyond government offices and get accessed by local level actors who are often considered more legitimate both by miners and local populations. This is even more so regarding environmental deleterious impacts, whose “slow violence” (Nixon 2011)—i.e., its long-term consequences being often synchronically imperceptible—can be made more legible through longitudinal mapping.

Likewise, the increasingly open-access feature of EO makes it subject of political disputes along what term the measurement–commensuration–diffusion continuum (Noucher et al. 2021), that is the phases through which environmental governance quantifies, categorizes, and communicates environmental problems. At each of these stages, EO data may be embedded in and support different political agendas. In French Guiana, these authors show how the same reality of illegal artisanal gold mining is differently measured and interpreted by different actors within and outside the State. While the French State relied on its own EO data and was reluctant to make it available to the public, the WWF launched a competing mapping project through open access EO and participatory, crowd sourced, mapping. Not only did the quantification of the activity vary, but also its interpretation and the political measures that were communicated. Such discrepancies also manifested within state structures, with armed forces being more concerned by the legal status of operations and parks and conservation with the stage and intensity of the activity. WWF, instead, made no such difference at all as the NGO's aim was rather to challenge the State to increase

disclosure on environmental impacts, and alert the public on deforestation. All in all, beyond claims for objectivity, EO provides information that can serve contradictory goals such as support decision-making or legitimize decisions, establish forms of control or contest them. This calls for attention to the inherent political uses and to the discrepancies in accessing, interpreting, and diffusing information gathered from EO, for such information may both serve coercive aims as well as play a role in informing public debate in the context of a more concerted and inclusive regulation of artisanal mining.

The fact that the vast majority of countries facing ASGM do not produce satellite data themselves implies that these states may—temporarily—remain depend of open-access space data initiatives from countries with well-developed space programs. However, the more intensive use of earth observation products contributes to the development of a community of researchers and end-users, which will be ready to use their own satellite data in the future, mentioning, for instance, the recent launch of African satellites and the emergence of new space programs in several African countries (Pović et al. 2018).

3.3 Integration of Space-Based Results within Interdisciplinary Research Results into Governance Measure

Finally, as demonstrated in this review of remote sensing uses in mining and environmental governance, visualization from space can indeed inform on a series of environmental impacts such as pollution of rivers and water basins, deforestation, but also urbanization/new settlements (e.g., Gagnol et al. 2019). However, they are of little help to understand social questions that equally partake in sustainability issues, such as gender (Buss et al. 2019; Huggins et al. 2017; Hinton et al. 2017), labor relations (Lanzano and Arnaldi di Balme 2021; Bolay 2017; Hilson 2010), mobility and migration related to artisanal mining (Dessertine 2016; Werthmann 2010; Bolay 2014, 2016), or insecurity (Ros-Tonen et al. 2021; Lanzano et al. 2021), all while they underlie much of miners' practices and their potentially environmentally unsound consequences. As argued by Fisher et al. (2021), plural knowledges are necessary for addressing the complexity of sustainability in gold mining. As one among other forms of knowledge, remote sensing will probably need to be cross fertilized with other knowledges; scientific and formal certainly, but also more grounded forms of local (ecological) knowledge (e.g., Duff and Downs 2019; Hennessy 2015). This is both a conceptual challenge regarding how to actually do interdisciplinary research, and an operational one requiring grassroots approaches as traditionally devised in ethnographic methods or collaborative approaches potentially implicating crowd sourced data that have proven to be efficient, for instance in water governance (Buytaert et al. 2014).

Considering that the actual governance of mining sites, such as where, when, and by whom are gold deposit exploited, usually bypass government structures, information generated by remote sensing technologies can increase the local knowledge about mining and its impacts, provided that it is made accessible to the local actors of the “real governance” of artisanal mining. Yet, as argued by Poncian (2020) in a study on the role of Information and Communication Technologies (ICT) in the citizen engagement of extractive resources governance in Tanzania, while government bodies can indeed increase the flow of information through conventional and new media channels (in particular social medias), this does not necessarily translate into more citizen engagement. To actually increase engagement and the use of information by the local actors of governance, communication should, according to this author, not be limited to unidirectional, top-down, channels. This can be achieved through the usual

apparatus of onsite workshops and trainings, as well as through a more interactive use of media platforms throughout which qualitative information can flow up to governments. For instance, McFarlane and Rebecca (2019) study of artisanal mining in Myanmar uses USGS Landsat observations and Google Earth data to assess the growth of illegal suction pump mining over the last twenty years. To understand these changes, it builds upon human centered design workshops, field visits, household surveys and interviews to interpret the social, environmental and economic implications of this activity from the perspective of the workers and local population, upon which policy measures are proposed. Thus, as argued by Davis et al. (2021) more collaborative approaches to remote sensing that includes local stakeholders and researchers across data acquisition, analysis and dissemination in “active collaboration and knowledge exchange can help balance existing power structures” and ensure that local concerns and perceptions of sustainability are integrated in governance measures.

4 Conclusions

The article was conceived as an entry point in the already vast literature about remote sensing characterization of artisanal and small-scale gold mining sites. It is primarily intended either for students and researchers of the academic domain willing to develop further research in this domain. The present-day capabilities of satellites orbiting the Earth and their sensors offer various applications, including identification of ASGM site, mapping degradation of soil, deforestation, characterization of sediments discharge in rivers, and short- or long-term mapping of the expansion of artisanal gold mines and their waste. The development of a new generation of satellites with hyperspectral capabilities will open new avenues for research, as detailed characterization of minerals present in mining waste will become possible. This article also emphasizes that the complex issues associated with the regulation of mining sites cannot be solved without interdisciplinary and collaborative approaches combining different sources of knowledge, and involving the different actors, including researchers and local stakeholders. Within this framework, remote sensing data and their scientific interpretations provide maps, quantified interpretations, and reconstruction of the past evolution of the landscape. These data and products should be considered as pedagogic tools of great values that can be made easily accessible to the different actors via on-line platforms and dedicated applications, following a pioneering example being proposed in Senegal (Ngom and Mbaye 2021). Remote sensing data should be also used in a reflexive approach, that accounts for the economic, social, and ethical implications of ASGM regulations.

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