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Assessing the strategic applications of remote sensing for addressing illicit artisanal and small-scale gold mining activities

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Abstract Global demand for gold is growing through the manufacture of jewellery and electronic products. The growing demand for gold is met through both large and small-scale mining. Thus, there is also an increasing number of informal Artisanal and Small-scale Gold Mining (ASGM) activities in Africa, Southeast Asia, and South/Latin America. This paper, therefore, assesses the use of Remote Sensing (RS) towards monitoring and addressing illicit ASGM activities across the globe. A systematic literature review was combined with fieldwork and case study analysis of data. Specific case studies have been conducted in Columbia, Mongolia, and Ghana to assess the influence of cloud cover over RS data and detection of illicit ASGM activities, respectively. Considering the levels of application of RS for monitoring and addressing illicit ASGM, it is found that South America records highest in holistic applications, then followed by Africa and Asia. For country-specific applications of Remote Sensing for monitoring ASGM activities in Southeast Asia, Indonesia leads the chart, in Latin America, Brazil and Peru dominate while Ghana and D.R. Congo lead the Chart in Africa. Thus, these countries host hotspots of illicit ASGM activities across the regions. From the results, it is observed that Columbia has more cloud cover persistence than Mongolia and Ghana, thereby, making it feasible for monitoring and detection in the latter countries than the former.

Keywords Remote Sensing · ASGM · Artisanal and small-scale gold mining · Illegal mining

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Introduction

Globally, there is a steady rising demand for minerals and raw materials in response to the needs of modern living. Demand for gold and its products remains higher as the precious metal is characterised by security, stability, and longevity (Barney, 2018). Thus, global giant mining companies such as Barrick Gold, Newmont, AngloGold Ashanti, Kinross Gold, and Goldfields, are modifying their methods of operations and production in order to respond to this growing global demand for gold supplies (Mines, 2019). Large productions from these companies come from deposits of gold in developing countries in Africa, Southeast Asia, and Latin America. In parallel to activities of large companies, there is a surge in Artisanal and Small-scale Gold Mining (ASGM) activities in these regions, employing over 100 million people (Bank, 2020). According to UNEP (2019), the ASGM subsector contributes up to 12 to 15% of the world's gold. The subsector produces approximately 18% of Africa's gold export to global markets (O'Neill & Telmer, 2017a; Union, 2009).

ASGM is defined as mining operation that processes less than 300 tons of ore per day, through manual or semi-mechanised methods (Coulter, 2016). Nevertheless, countries have also their specific legislation regarding ASGM classification. For example, Colombia classified small-scale mining when operations cover less than 150 hectares, and for it to be legalized, it requires approved planning and strict land recovery measures (Ibrahim et. al., 2021). Unfortunately, worldwide, ASGM is dominated by illicit activities, uses unapproved methods to mine in unapproved areas. Such illicit ASGM operations lead to environmental degradation and significant economic losses (UNEP, 2019). Common environmental degradation caused by illicit ASGM activities include land degradation, deforestation, soil, and water contamination using mercury in ore processing. Various attempts aimed at monitoring and addressing the environmental impacts of illicit ASGM have chalked little success due to the dearth knowledge about ASGM activities in different regions. Hence, robust monitoring mechanisms are required to mitigate, address, or reduce the environmental impacts associated with ASGM practices. Over the last century, UN agencies and NGOs have raised awareness on the consequences related to the use of mercury in illicit ASGM activities. Examples include the GEF/UNDP/UNIDO'S Global Mercury Project in 1994 (Spiegel et al., 2015).

To this end, the Minamata Convention was introduced in 2013 to regulate the use of mercury in ore processing. Thus, the convention focuses on the ASGM subsector in its Article 7 requires that countries that observe significant ASGM takes place "shall take steps to reduce, and where feasible eliminate, the use of mercury and mercury compounds in, and the releases to the environment of mercury from such mining and processing" (Article 7, Paragraph 2) (Spiegel et al., 2015). The convention requires its member countries, known as Parties, with more than insignificant ASGM, to develop and implement "National Action Plans" (NAPs) for reducing mercury use and pollution risks in ASGM. An effective NAP requires a comprehensive approach that includes environmental data, technical capacity, and detection of the presence of mercury around ASGM operation areas to propose tailored solutions that are context specific (Telmer & Veiga, 2009). This includes baselines for understanding the ASGM phenomenon and its implications at the local level. Yet, most of the places where illicit ASGM activities occur often have no reliable data on the magnitude of it. This is due to a lack of robust database on the location, size and impacts of ASGM.

To facilitate an effective implementation of Article 7 of the Minamata Convention by the Parties, the applications of Remote Sensing (RS) have been incorporated in a series of projects such as PlanetGOLD (led by UNEP and Conservation International with specific international programmes in 23 developing countries), socio-economic ASGM Research Methodology (UNITAR) and the Global Mercury Partnership (stakeholders include governments, industry, NGOs, and academia) of UNEP (UNITAR, 2016). These projects rely on RS technology and tools to help countries observe and identify illicit ASGM activities in the landscape. RS generates relevant data to help properly identify illicit ASGM sites and their impacts, which are often hidden in the most remote and marginalized countryside areas (Telmer & Stapper, 2007). RS allows the detection of ASGM sites using available spaceborne or airborne data and detects impacts directly such as deforestation or through proxies such as high-water turbidity (Moomen et al., 2022). RS provides comprehensive coverage over large areas, offering cost-effective and timely data collection compared to ground surveys. It allows for continuous monitoring, overcoming logistical challenges and safety concerns associated with on-site inspections. Furthermore, RS facilitates systematic analysis and enables detection of ASGM activities in remote or inaccessible regions. Hence, to formulate active policy interventions towards addressing the challenges associated with illicit ASGM in countries where these are prolific, a good knowledgebase is required. Currently, this knowledgebase is most efficiently provided by the various means of RS (satellite, RADAR, and Unmanned Aerial Vehicles) with near real-time and easy to store and access digital data.

Consequently, the main objective of this paper is to assess how effectively RS has been employed for monitoring the activities of illicit ASGM across all the affected regions of the globe. Specifically, this paper seeks to find answers to the following questions: (i) is there sufficient incorporation of RS technologies in illicit ASGM research? (ii) To what extent has RS been used for monitoring illicit ASGM activities in areas where these activities are prolific? (iii) is the deployment of RS technologies in these areas feasible for monitoring illicit ASGM? (iv) What are the results found in the applications of RS technologies for monitoring illicit ASGM activities across the globe? and, (v) do these results inform policy towards formalisation and effective regulation of illicit ASGM activities in specific countries? Further, analysis of case-studies focuses on the methods of satellite image processing and analysis for monitoring illicit ASGM activities in Africa and Latin America over the past decade.

Background on global applications of remote sensing for monitoring ASGM activities

The history of RS started with its wider applications for the monitoring of natural resource development largely in North America, Europe, Australia and Eastern Asia (Campbell & Wynne, 2011; Cohen, 2000). Since the late 1940s, spaceborne sensors have been used for monitoring natural resources and natural capital growth in these regions (Cracknell, 2018). Black and white aerial photography was the main RS tool used in monitoring activities. Of late, rapid technological improvements in sensor and computational technologies have expanded the utility of RS in these applications. These improvements include the surge in spaceborne data of higher spatial, spectral, and temporal resolutions and having various freely available dataset (e.g. the Landsat and Copernicus programs). Regarding data access, the availability of cloud-based and digital Data Cube platforms have facilitated big data handling and allow the reintegration of archival and historical data to monitor land-use changes, which find relevant applications for illicit ASGM activities (Cracknell, 2018; Lillesand et al., 2015). The methodologies identify areas of mining activity, estimate production, and monitor changes over time. The resulting satellite image analysis is then integrated with data collected on-the-ground to show the presence and potential environmental implications of illicit ASGM practices in these regions (Isidro et al., 2017).

The use of various spaceborne RS technologies, including Synthetic Aperture Radar (SAR) as well as optical multispectral and hyperspectral imagery, provide critical information with regards to land use and land cover monitoring (Ngom et al., 2020). As a main challenge with the use of optical RS imagery is the presence of cloud-cover and haze (Almeida-Filho & Shimabukuro, 2002; Li et al., 2015), SAR opens up monitoring opportunities in regions with high cloud-cover (Moomen et al., 2022). For instance, with SAR Interferometry, multiple radar images taken of the same area at different times are used for change detection in places where ASGM is practiced (Ji et al., 2011). Two general approaches used in this regard are: InSAR, which typically uses successive SAR images of the same setting and pass to improve the data in a scene and; Repeat Pass Interferometry, which also uses various SAR scenes of the same area from different passes of satellite (Wang et al., 2020). Yet, the relatively low amount of information presented by the technology may lead to misclassification issues and omission of vital land use details identification. Thus, a combination of SAR and optical imagery overcome various technology limitations for medium to high-resolution sensors (Ammirati et al., 2020). These approaches are used to model and develop signatures for detecting mercury use in illicit mining sites are detected in Inner Mongolia, China (O'Neill & Telmer, 2017b; Telmer & Stapper, 2007).

Scope and methodology of the literature review

Both scientific and grey literature were examined using a systematic literature review process to identify examples of the use of RS technologies as the primary means of monitoring illicit ASGM activities across the globe. It includes publications referring to numerous works and examples on ASGM monitoring using RS, strictly focusing on both illicit ASGM activities. Although the literature shows a history between the use of RS technologies for mapping, measuring, and monitoring various aspects of mining cycles (large or small) (Kasmaeeyazdi et al., 2021), the focus of this paper allows the exclusion of these other applications that are not illicit ASGM related.

Literature review encompasses both peer reviewed and non-reviewed scientific and non-scientific publications, technical reports from governmental and various UN agencies, NGOs, community-based and civil organisations that are concerned with illicit ASGM activities, as well as global and country-specific technology initiatives commissioned for monitoring illicit ASGM activities. Searched databases include personal databases and research group, Internet (Google searches), Google Scholar, Web of Knowledge, Science Direct, PubMed and ResearchGate. Keywords used include the following, which were launched individually and in combinations in single and multiple queries: "Remote sensing", "Satellite Detection", "Small-scale Mining", "Small scale Gold Mining", "Artisanal Mining", "Artisanal and Small-scale Gold Mining", "Applications of remote sensing in Artisanal and Small-scale Mining" and "satellite imagery for monitoring ASGM". Following recommendations on the use of systematic literature review methods, 60 records were recovered within online scientific libraries and examined to identify tailored publications addressing applications of RS for monitoring and assessment of ASGM activities.

Results

Table 1 in appendix shows detailed inventory of applications of RS for Monitoring and Mapping ASGM activities across the world. It confirms that ASGM activities are most common in tropical and subtropical countries as observed by UNEP (2019) and Tsang et al. (2019). From case-by-case studies at the regional and sub-regional levels, Fig. 1 shows global distribution of scientific applications of RS for monitoring illicit ASGM activities for the two decades. The region with the highest applications of RS for the monitoring and management of illicit ASGM is Latin America with a maximum of 32 case studies. Sub-Saharan Africa has the second highest applications with a maximum of 26 case studies and regional Asia records the least applications.

For country-specific applications of RS for monitoring illicit ASGM activities, Fig. 2 shows the disparities in Asia.

Most of the use cases are in Southeast Asia with Indonesia recording the highest. From the results, it could be inferred that in Southeast Asia, Indonesia records prevalence of illicit ASGM activities. Only one publication refers to a case study in China. It is, however, evident from the number of miners involved in artisanal gold mining per country that China probably have the most illicit ASGM activities among these countries (ASM, 2023). This could be a case of underreporting in literature or a demonstration of lack of correlations between number of studies using

Table 1 Remote Sensing Data usage by source and region

Region	Source of Data
Sub-Saharan Africa	Landsat, RADAR, UK-DMC2, Google Earth, Sentinel-2,
Asia/Oceania	Landsat, Google Earth, Sentinel, Pleiades and SPOT
Latin America	CBERS-2 CCD, RapidEye, Landsat, Sentinel-2, WorldView, QuickBird, PlanetScope,

Sub-Saharan Africa		Latin America		Asia/Oceania	
Platform / Data	Percent	Platform / Data	Percent	Platform / Data	Percent
Earth Explorer / Landsat	51.6%	CBERS-2 CCD	2.0%	Landsat	42.9%
Sentinel	19.4%	QuickBird	6.0%	PlanetScope	21.4%
UK-DMC2	3.2%	Sentinel 1	8.0%	Sentinel 1	14.3%
Planet Scope	9.7%	Sentinel 2	18.0%	Pleiades	7.1%
Sentinel 1	9.7%	RapidEye	2.0%	SPOT	14.3%
Digital Globe	3.2%	Landsat	48.0%		
SPOT	3.2%	PlanetScope	6.0%		
		WorldView	2.0%		
		PlanetScope	4.0%		
		LiDAR	2.0%		
		SPOT	2.0%		

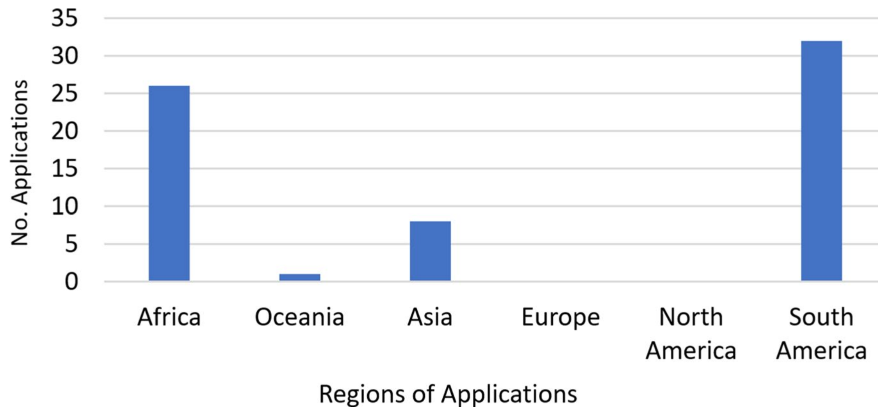

Fig. 1 Global Applications of RS for Monitoring illicit ASGM activities

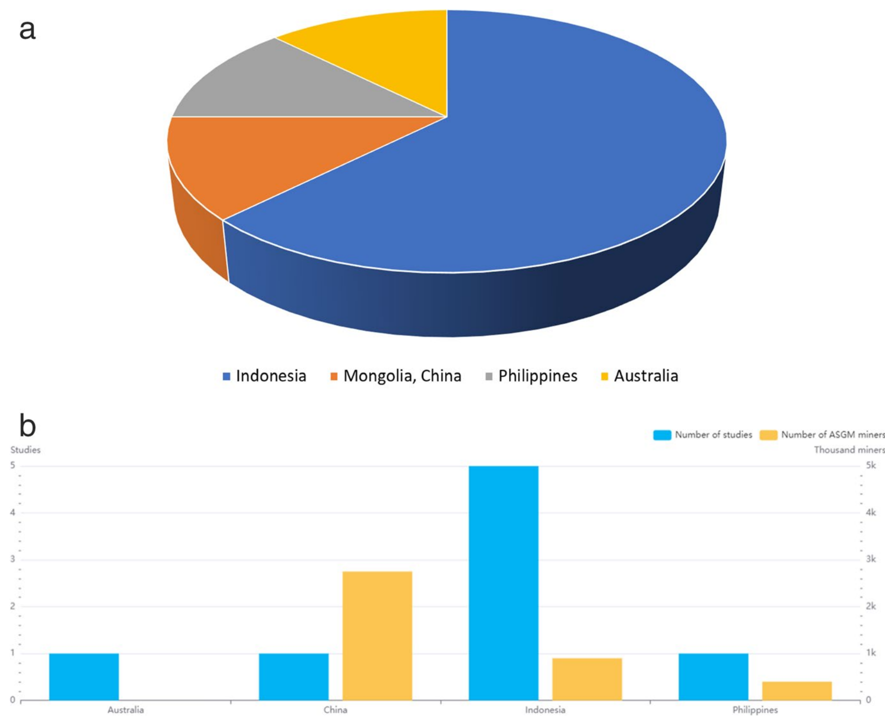

Fig. 2 **a**. Distribution of Applications of RS for monitoring illicit ASGM activities in Asia and Oceania. **b**. Distribution of number of miners involved in artisanal gold mining per country (ASM, 2023)

RS and actual prevalence of illicit ASGM on the Grounds. Figure 3 shows the country specific applications of RS tools and techniques for monitoring illicit ASGM activities in South/Latin America. From the results, Brazil and Peru have the highest applications of RS for monitoring illicit ASGM activities. Ecuador and Guyana record the least applications of the technologies for monitoring illicit ASGM activities. The data are quite in agreement with what can be inferred by the number of miners involved in ASGM activities except for Colombia which, compared to Peru, is probably more affected by ASGM activities (ASM, 2023; Fig. 3). This confirms the scientific speculations that illicit ASGM activities in the Amazon Forest remain persistent and challenging.

In Fig. 4, while Ghana observes the highest applications of RS for monitoring illicit ASGM activities, D.R. Congo and Nigeria also record high applications of RS for monitoring illicit ASGM activities in Africa. Even though about two-thirds of all application case studies have been carried out in Ghana in terms of ASGM, illicit ASM activities are more prevalent in D.R. Congo than in Ghana (Brown et al., 2020a; Garret, 2007; WHO-UNEP, 2015).

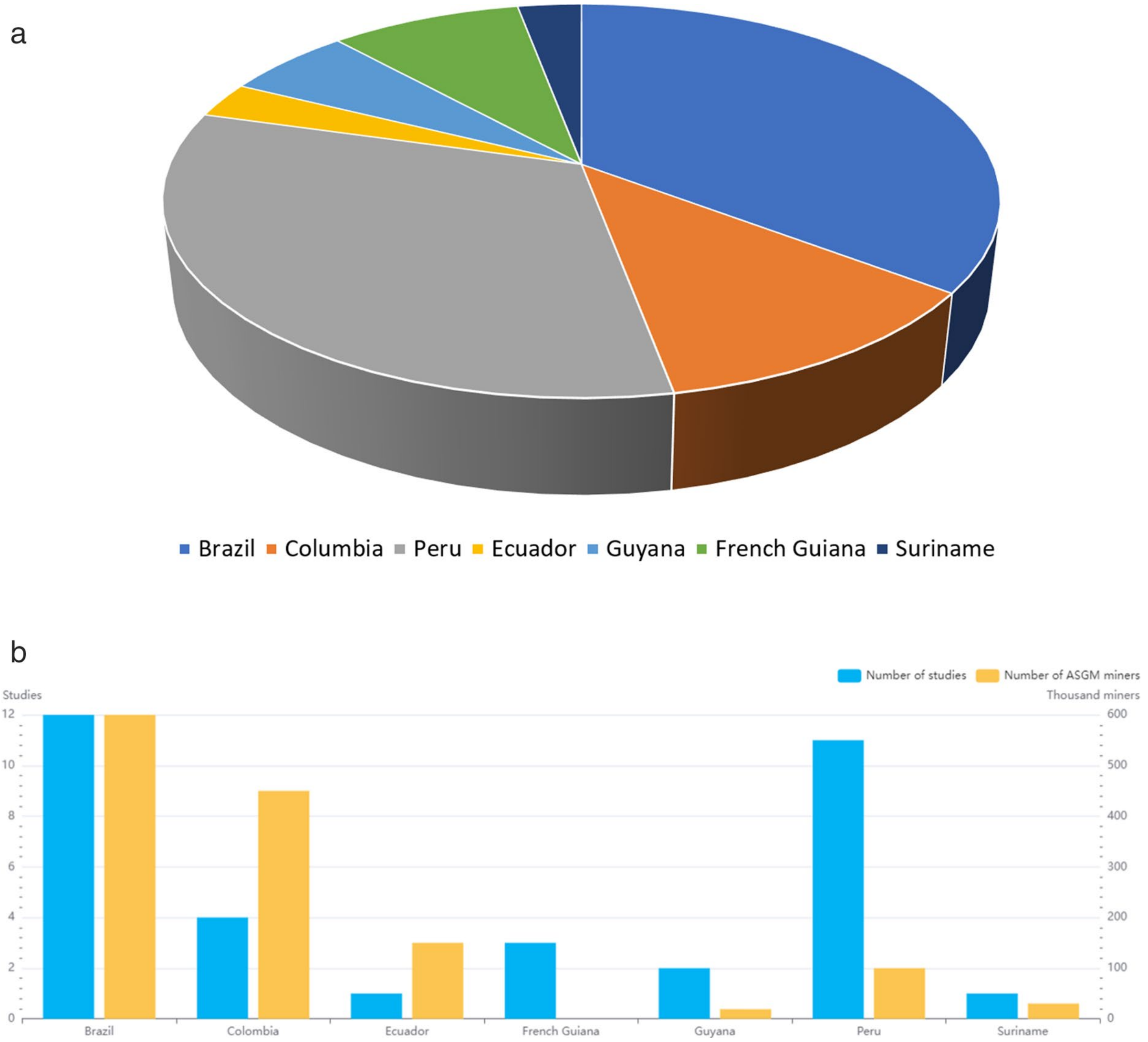

Fig. 3 **a**. Distributions of Applications of RS for monitoring illicit ASGM activities in South/Latin America. **b**. Distributions of number of miners involved in artisanal gold mining per country (ASM, 2023)

In addition, the high number of miners involved in ASGM activities in D.R. Congo, especially, and Nigeria suggests the difference in ASGM activities between these 3 countries is not as large as it is suggested by the number of RS applications recorded in literature (ASM, 2023; Fig. 4). Similar to the case of China, this difference in scientific reports cannot be attributed to access to RS data since there is also a growing proliferation of free Earth Observation and satellite data now than 20 years ago. A suspected challenge could be cloud or canopy cover, barring data acquisition and analysis.

Table 1 provides details of the observed sources of RS data used in the case studies analysed across the world and the percentage distribution at a regional scale. From Table 1, it is observed that most cases use freely available remote sensing data for mapping illicit ASGM areas. Apart from Latin America, no case studies used China-Brazil Earth Resources Satellite (CBERS) data. Commercial datasets such as QuickBird, RapidEye, PlanetScope, and WorldView data are largely used in Latin America. About 55% of RS data used in monitoring illicit ASGM activities in Sub-Saharan

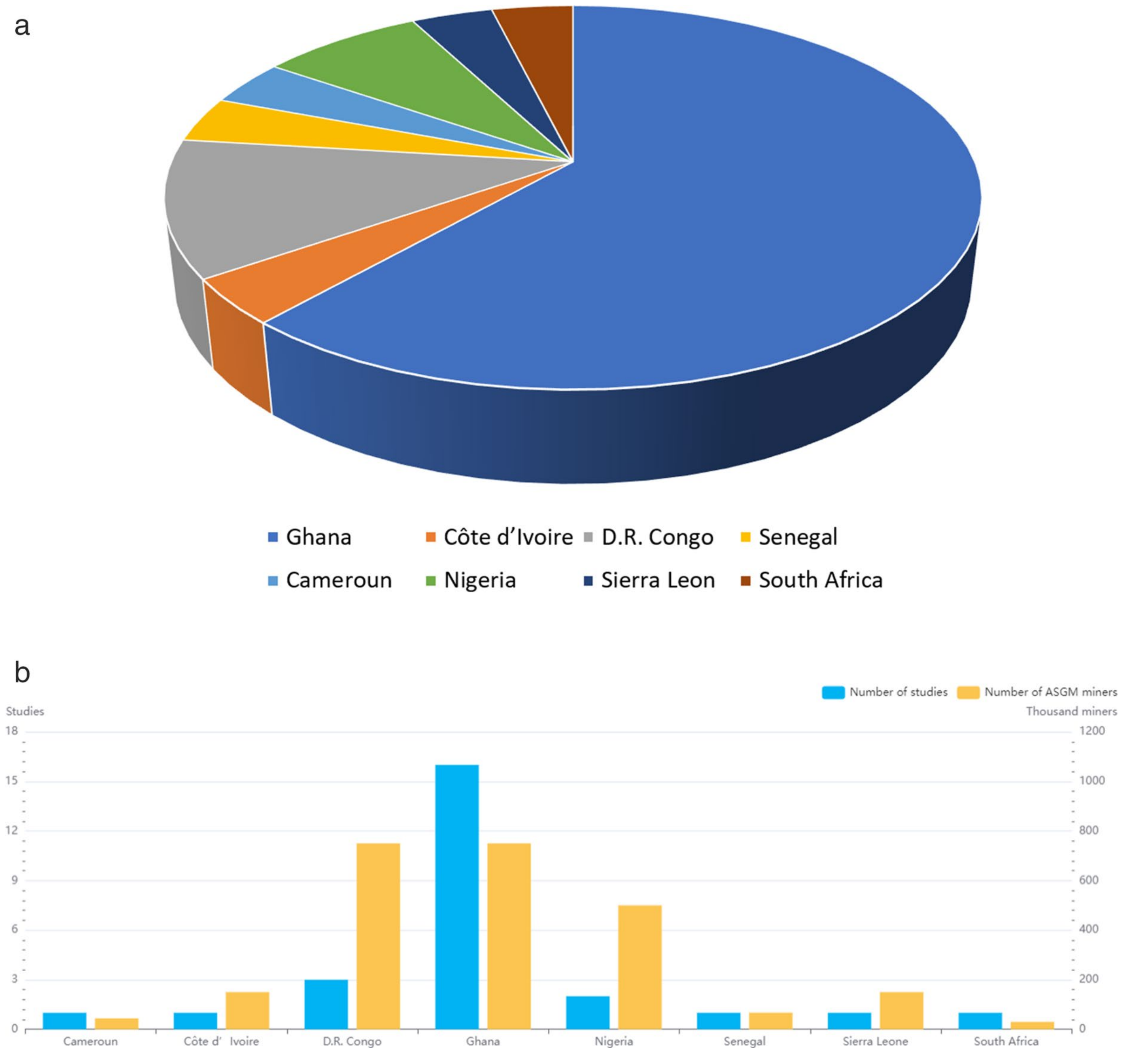

Fig. 4 **a**. Distribution of applications of RS for monitoring illicit ASGM activities in Africa. **b**. Distribution of number of miners involved in artisanal gold mining per country (ASM, 2023)

Africa emanate from Landsat, 48% in Latin America and 42.9% in Asia/Oceania come from Landsat. Only 3.2% of RS data used in this region originate from Surrey Satellite Technology Limited (SSTL), UK Disaster Monitoring Constellation (DMC) (UK-DMC). It is also observed from Table 2 that Pleiades and SPOT data have been widely used by observations in Asia.

Based on regional analysis of Ghana, Mongolia-China and Columbia in Africa, Asia, and America, respectively, it is observed that persistence of clouds in certain parts of the world influences the type of RS data used. For example, this study observes the absence of persistent cloud cover in Sub-Saharan Africa and thus the relatively high utilization of optical data and lower usage of radar-based technologies. Figure 5 shows cloud persistence across Ghana, Mongolia-China, and Columbia, respectively, over the rainy seasons of 2021 and 2022 as attained from cloud probability estimations of

Table 2 Summary of RS Applications for monitoring illicit ASGM across the globe

Serial No	Region	Record	Case Study Area
1	Asia	K. Telmer and D. Stapper, "Evaluating and monitoring small scale gold mining and mercury use: Building a knowledge-base with satellite imagery and field work," *United Nations Industrial Development Organization: Victoria, BC, Canada,* 2007	Indonesia
2	Asia	Wang, S., Lu, X., Chen, Z., Zhang, G., Ma, T., Jia, P., & Li, B. (2020). Evaluating the Feasibility of illegal open-pit mining identification using InSar coherence. *Remote Sensing*, *12*(3), 367	Mongolia, China
3	Asia	Julzarika, A. (2018). Mining land identification in Wetar Island using remote sensing data. *Journal of Degraded and Mining Lands Management*, *6*(1), 1513	Indonesia
4	Asia	UNITAR's Operational Satellite Applications Programme (2016)	Indonesia
5	Asia	Isidro, C. M., McIntyre, N., Lechner, A. M., & Callow, I. (2017). Applicability of earth observation for identifying small-scale mining footprints in a wet tropical region. Remote Sensing, 9(9), 945	Philippines
6	Asia	Kimijima, S., Sakakibara, M., & Nagai, M. (2021). Detection of Artisanal and Small-Scale Gold Mining Activities and Their Transformation Using Earth Observation, Nighttime Light, and Precipitation Data. *International Journal of Environmental Research and Public Health*, *18*(20), 10,954	Indonesia
7	Asia	Kimijima, S., Sakakibara, M., Nagai, M., & Gafur, N. A. (2021). Time-Series Assessment of Camp-Type Artisanal and Small-Scale Gold Mining Sectors with Large Influxes of Miners Using LANDSAT Imagery. *International Journal of Environmental Research and Public Health*, *18*(18), 9441	Indonesia
8	Asia	Bruno, D. E., Ruban, D. A., Tiess, G., Pirrone, N., Perrotta, P., Mikhailenko, A. V., … & Yashalova, N. N. (2020). Artisanal and small-scale gold mining, meandering tropical rivers, and geological heritage: Evidence from Brazil and Indonesia. *Science of The Total Environment*, *715*, 136,907	Indonesia
9	Latin America	K. Telmer and D. Stapper, "Evaluating and monitoring small scale gold mining and mercury use: Building a knowledgebase with satellite imagery and field work," *United Nations Industrial Development Organization: Victoria, BC, Canada,* 2007	Brazil
10	Latin America	Almeida-Filho, R., & Shimabukuro, Y. E. (2002). Digital processing of a Landsat-TM time series for mapping and monitoring degraded areas caused by independent gold miners, Roraima State, Brazilian Amazon. *Remote sensing of Environment*, *79*(1), 42–50	Brazil
11	Latin America	Telmer, K., Costa, M., Angélica, R. S., Araujo, E. S., & Maurice, Y. (2006). The source and fate of sediment and mercury in the Tapajós River, Pará, Brazilian Amazon: Ground-and space-based evidence. *Journal of environmental management*, *81*(2), 101–113	Brazil
12	Latin America	Almeida-Filho, R., & Shimabukuro, Y. E. (2000). Detecting areas disturbed by gold mining activities through JERS-1 SAR images, Roraima State, Brazilian Amazon. *International Journal of Remote Sensing*, *21*(17), 3357–3362	Brazil
13	Latin America	Ibrahim, E., Lema, L., Barnabé, P., Lacroix, P., & Pirard, E. (2020). Small-scale surface mining of gold placers: Detection, mapping, and temporal analysis through the use of free satellite imagery. *International Journal of Applied Earth Observation and Geoinformation*, *93*, 102,194	Columbia
14	Latin America	Lobo, F. D. L., Souza-Filho, P. W. M., Novo, E. M. L. D. M., Carlos, F. M., & Barbosa, C. C. F. (2018). Mapping mining areas in the Brazilian amazon using MSI/sentinel-2 imagery (2017). *Remote Sensing*, *10*(8), 1178	Brazil

Table 2 (continued)

Serial No	Region	Record	Case Study Area
15	Latin America	Lobo, F. D. L., Costa, M., Novo, E. M. L. D. M., & Telmer, K. (2016). Distribution of artisanal and small-scale gold mining in the Tapajós River Basin (Brazilian Amazon) over the past 40 years and relationship with water siltation. Remote Sensing, 8(7), 579	Brazil
16	Latin America	Ibrahim, E., Jiang, J., Lema, L., Barnabé, P., Giuliani, G., Lacroix, P., & Pirard, E. (2021). Cloud and Cloud-Shadow Detection for Applications in Mapping Small-Scale Mining in Colombia Using Sentinel-2 Imagery. *Remote Sensing*, *13*(4), 736	Columbia
17	Latin America	Anaya, J. A., Gutiérrez-Vélez, V. H., Pacheco-Pascagaza, A. M., Palomino-Ángel, S., Han, N., & Balzter, H. (2020). Drivers of forest loss in a megadiverse hotspot on the pacific Coast of Colombia. Remote Sensing, 12(8), 1235	Columbia
18	Latin America	Caballero Espejo, J., Messinger, M., Román-Dañobeytia, F., Ascorra, C., Fernandez, L. E., & Silman, M. (2018). Deforestation and forest degradation due to gold mining in the Peruvian Amazon: A 34-year perspective. Remote Sensing, 10(12), 1903	Peru
19	Latin America	Finer, M., & Mamani, N. (2020). Reduction Of Illegal Gold Mining In The Peruvian Amazon. MAAP# 121:	Peru
20	Latin America	Finer, M., & Mamani, N. (2021). New Illegal Gold Mining Hotspot in Peruvian Amazon–Pariamanu. MAAP# 137	Peru
21	Latin America	Asner GP, Llactayo W, Tupayachi R, Luna ER. Elevated rates of gold mining in the Amazon revealed through high-resolution monitoring. Proc Natl Acad Sci U S A. 2013 Nov 12;110(46):18,454–9. https://doi.org/10.1073/pnas.1318271110. Epub 2013 Oct 28. PMID: 24,167,281; PMCID: PMC3832012	Peru
22	Latin America	Asner, G. P., Llactayo, W., Tupayachi, R., & Luna, E. R. (2013). Elevated rates of gold mining in the Amazon revealed through high-resolution monitoring. *Proceedings of the National Academy of Sciences*, *110*(46), 18,454–18,459	Peru
23	Latin America	Asner, G. P., & Tupayachi, R. (2017). Accelerated losses of protected forests from gold mining in the Peruvian Amazon. *Environmental Research Letters*, *12*(9), 094004	Peru
24	Latin America	Adamek, K., Lupa, M., & Zawadzki, M. (2021). Remote Sensing Techniques for tracking changes caused by illegal gold mining in Madre de Dios, Peru. *Miscellanea Geographica*, *25*(4), 205–212	Peru
25	Latin America	UNODC (2018). Alluvial gold exploitation: Evidence from remote sensing. United Nations Office on Drug and Crime	Columbia
26	Latin America	Elmes, A., Yarlequé Ipanaqué, J. G., Rogan, J., Cuba, N., & Bebbington, A. (2014). Mapping licit and illicit mining activity in the Madre de Dios region of Peru. *Remote Sensing Letters*, *5*(10), 882–891	Peru
27	Latin America	Lobo, F. D. L. (2015). *Spatial and Temporal Analysis of Water Siltation Caused by Artisanal Small-scale Gold Mining in the Tapajós Water Basin, Brazilian Amazon: An Optics and Remote Sensing Approach* (Doctoral dissertation)	Brazil
28	Latin America	Simionato, J., Bertani, G., & Osako, L. S. (2021). Identification of artisanal mining sites in the Amazon Rainforest using Geographic Object-Based Image Analysis (GEOBIA) and Data Mining techniques. *Remote Sensing Applications: Society and Environment*, *24*, 100,633	Brazil
29	Latin America	Fonseca Gomez, A. (2021). *Detecting Artisanal Small-Scale Gold mines with LandTrendr multispectral and textural features at the Tapajós river basin, Brazil* (Master's thesis, University of Twente)	Brazil

Table 2 (continued)

Serial No	Region	Record	Case Study Area
30	Latin America	Feemster, C., LaJoie, P., Vallejos, M., & Wright, P. (2020). Amazonia Disasters: Assessing Methods for Gold Mining-related Deforestation Detection in Amazonia Using NASA Earth Observations	Peru
31	Latin America	Ammirati, L., Mondillo, N., Rodas, R. A., Sellers, C., & Di Martire, D. (2020). Monitoring land surface deformation associated with gold artisanal mining in the Zaruma City (Ecuador). *Remote Sensing*, *12*(13), 2135	Ecuador
32	Latin America	Bruno, D. E., Ruban, D. A., Tiess, G., Pirrone, N., Perrotta, P., Mikhailenko, A. V., … & Yashalova, N. N. (2020). Artisanal and small-scale gold mining, meandering tropical rivers, and geological heritage: Evidence from Brazil and Indonesia. *Science of The Total Environment*, *715*, 136,907	Brazil
33	Latin America	Csillik, O., & Asner, G. P. (2020). Aboveground carbon emissions from gold mining in the Peruvian Amazon. *Environmental Research Letters*, *15*(1), 014006	Peru
34	Latin America	Hook, A. (2019). Mapping contention: Mining property expansion, Amerindian land titling, and livelihood hybridity in Guyana's small-scale gold mining landscape. *Geoforum*, *106*, 48–67	Guyana
35	Africa	Manu, A., Twumasi, Y. A., & Coleman, T. L. (2004, September). Application of remote sensing and GIS technologies to assess the impact of surface mining at Tarkwa, Ghana. In *IGARSS 2004. 2004 IEEE International Geoscience and Remote Sensing Symposium* (Vol. 1). IEEE	Ghana
36	Africa	Boakye, E., Anyemedu, F. O. K., Quaye-Ballard, J. A., & Donkor, E. A. (2020). Spatio-temporal analysis of land use/cover changes in the Pra River Basin, Ghana. *Applied Geomatics*, *12*(1), 83–93	Ghana
37	Africa	Forkuor, G., Ullmann, T., & Griesbeck, M. (2020). Mapping and monitoring small-scale mining activities in Ghana using sentinel-1 time series (2015–2019). *Remote Sensing*, *12*(6), 911	Ghana
38	Africa	Basommi, P. L., Guan, Q., & Cheng, D. (2015). Exploring Land use and Land cover change in the mining areas of Wa East District, Ghana using Satellite Imagery. *Open Geosciences*, *7*(1)	Ghana
39	Africa	Snapir, B., Simms, D. M., & Waine, T. W. (2017). Mapping the expansion of galamsey gold mines in the cocoa growing area of Ghana using optical remote sensing. *International journal of applied earth observation and geoinformation*, *58*, 225–233	Ghana
40	Africa	Owusu-Nimo, F., Mantey, J., Nyarko, K. B., Appiah-Effah, E., & Aubynn, A. (2018). Spatial distribution patterns of illegal artisanal small scale gold mining (Galamsey) operations in Ghana: A focus on the Western Region. *Heliyon*, *4*(2), e00534	Ghana
41	Africa	Barenblitt, A., Payton, A., Lagomasino, D., Fatoyinbo, L., Asare, K., Aidoo, K., … & Wood, D. (2021). The large footprint of small-scale artisanal gold mining in Ghana. *Science of The Total Environment*, *781*, 146,644	Ghana
42	Africa	Nyamekye, C., Ghansah, B., Agyapong, E., & Kwofie, S. (2021). Mapping changes in artisanal and small-scale mining (ASM) landscape using machine and deep learning algorithms. -a proxy evaluation of the 2017 ban on ASM in Ghana. *Environmental Challenges*, *3*, 100,053	Ghana
43	Africa	Abaidoo, C. A., Jnr, E. M. O., Arko-Adjei, A., & Prah, B. E. K. (2019). Monitoring the extent of reclamation of small-scale mining areas using artificial neural networks. *Heliyon*, *5*(4), e01445	Ghana

Table 2 (continued)

Serial No	Region	Record	Case Study Area
44	Africa	Obodai, J., Adjei, K. A., Odai, S. N., & Lumor, M. (2019). Land use/land cover dynamics using landsat data in a gold mining basin-the Ankobra, Ghana. Remote Sensing Applications: Society and Environment, 13, 247–256	Ghana
45	Africa	DeWitt, Jessica D. West Virginia University. ProQuest Dissertations Publishing, 2016. 10,246,332	Côte d'Ivoire
46	Africa	Luethje, F., Kranz, O., & Schoepfer, E. (2014). Geographic object-based image analysis using optical satellite imagery and GIS data for the detection of mining sites in the Democratic Republic of the Congo. *Remote Sensing*, *6*(7), 6636–6661	Democratic Republic of the Congo
47	Africa	Gallwey, J., Robiati, C., Coggan, J., Vogt, D., & Eyre, M. (2020). A Sentinel-2 based multispectral convolutional neural network for detecting artisanal small-scale mining in Ghana: Applying deep learning to shallow mining. *Remote Sensing of Environment*, *248*, 111,970	Ghana
48	Africa	Patel, K., Rogan, J., Cuba, N., & Bebbington, A. (2016). Evaluating conflict surrounding mineral extraction in Ghana: Assessing the spatial interactions of large and small-scale mining. *The Extractive Industries and Society*, *3*(2), 450–463	Ghana
49	Africa	Ngom, N. M., Mbaye, M., Baratoux, D., Baratoux, L., Catry, T., Dessay, N., … & Delaître, E. (2020). Mapping artisanal and small-scale gold mining in Senegal using Sentinel 2 data. *GeoHealth*, *4*(12), e2020GH000310	Senegal
50	Africa	Kyba, C., Giuliani, G., Franziskakis, F., Tockner, K., & Lacroix, P. (2019). Artisanal and small-scale mining sites in the Democratic Republic of the Congo are not associated with nighttime light emissions. *J*, *2*(2), 152–161	Democratic Republic of the Congo
51	Africa	Rodrigue, N. F. (2019). Spatial Assessment of Impacts of Artisanal and Small-scale Mining on Land Cover and Environment, Batouri, Eastern Cameroun. *African Journal on Land Policy and Geospatial Sciences*, *2*(3), 85–96	Cameroun
52	Africa	Mensah, Foster Kwame, Stella Ofori-Ampofo, Mary Amponsah, Emil A. Cherrington, and Rebekke Muench. "Developing a Satellite Image-Based Mapping Service for Monitoring Illicit Artisanal and Small-Scale Gold Mining in Ghana." In *AGU Fall Meeting Abstracts*, vol. 2019, pp. GC53B-03. 2019	Ghana
53	Africa	Liman, H. M., Obaje, N. G., Sidi, A. A., & Nwaerema, P. (2021). Impact Evaluation of Artisanal and Small-Scale Mining on Land Use Land Cover: Implication for Sustainable Mining Environment in Niger State, Nigeria. *Journal of Earth Sciences and Geotechnical Engineering*, *11*(3), 33–45	Nigeria
54	Africa	Owolabi, A. O., Amujo, K., & Olorunfemi, I. E. (2021). Spatiotemporal changes on land surface temperature, land and water resources of host communities due to artisanal mining. *Environmental Science and Pollution Research*, 1–24	Nigeria
55	Africa	Asamoah, E. F., Zhang, L., Liu, G., Owusu-Prempeh, N., & Rukundo, E. (2017). Estimating the "Forgone" ESVs for small-scale gold mining using historical image data. *Sustainability*, *9*(11), 1976	Ghana
56	Africa	Hausermann, H., Ferring, D., Atosona, B., Mentz, G., Amankwah, R., Chang, A., … & Sastri, N. (2018). Land-grabbing, land-use transformation and social differentiation: Deconstructing "small-scale" in Ghana's recent gold rush. *World Development*, *108*, 103–114	Ghana

Table 2 (continued)

Serial No	Region	Record	Case Study Area
57	Africa	Foster Mensah et al. (2021). Centre for Remote Sensing and Geographic Information Services (CERSGIS), University of Ghana. SERVIR-West Africa; a program between NASA and the U.S. Agency for International Development (USAID) that uses remote sensing to provide support for protection of food and water resources and sustainable development	Ghana
58	Africa	Environment Protection Agency Sierra Leone, 2018. The ASGM Overview of Sierra Leone. Environment Protection Agency. Freetown, Sierra Leone	Sierra Leone
59	Latin America	Monitoring the Impact of Gold Mining on the Forest Cover and Freshwater in the Guiana Shield	Suriname, Guyana, French Guiana, and the Brazilian state of Amapá
60	Africa	Monitoring the development of artisanal mines in South Africa	South Africa
61	Latin America	Evaluación y medición de la expansión territorial de la minería informal en la cuenca alta del Ramis, Puno, Perú, usando imágenes satelitales	Peru
62	Latin America	Usage de la télédétection dans un contexte pluridisciplinaire: Impact de l'orpaillage, agriculture amérindienne et régénération naturelle dans une région du territoire Yanomami (Amazonie brésilienne)	Brazil
63	Latin America	Détection par l'imagerie satellite des sites d'orpaillage sur le territoire de la Guyane Française: Compte-rendu de mission en Guyane Française	French Guiana
64	Latin America	Apport de l'imagerie spatiale optique et radar pour la détection et le suivi des zones d'orpaillage en Guyane Française	French Guiana
65	Latin America	Evaluating Wildlife Vulnerability to Mercury Pollution From Artisanal and Small-Scale Gold Mining in Madre de Dios, Peru	Peru
67	Africa	2.5D change detection from satellite imagery to monitor small-scale mining activities in the Democratic Republic of the Congo	Democratic Republic of the Congo
68	Oceania	Object-based classification of semi-arid vegetation to support mine rehabilitation and monitoring	Australia

Sentinel-2. This dataset was attained using Google Earth Engine, a cloud-based data access point and computing environment (Gorelick et. al., 2017). Within regional boundaries presented, there is substantial heterogeneity in cloud cover persistence, especially in the case of Colombia. It is, however, important to note that there are local climatic variations across the countries. For instance, the South-western parts of Ghana experience thick cloud cover throughout most of the year than the Middle and Northern areas that observe clear weather conditions in most parts of the year (Awotwi et al., 2018). Notwithstanding, Ibrahim et al. (2021) used Sentinel-2 Imagery based Cloud and Cloud-Shadow detection for mapping illicit ASGM activities in Colombia.

Discussions

The results confirm UNEP's observation that occurrences of illicit ASGM activities are in Africa, Asia and Latin America (UNODC, 2018). The results show a wide disparity in the sources of data used, data types and resolutions in terms of accuracy of mapping illicit mining to support the detection of mercury usage across these illicit ASGM regions. Illicit ASGM characterization indicates that techniques such as dredging, open pit, and hard rock mining are used. Such activities have been detected and mapped using medium resolution spaceborne imagery (Ibrahim et.al. 2020), high and very high resolution spaceborne imagery (Finer & Mamani, 2021), and a combination of the two (DeWitt, 2016;

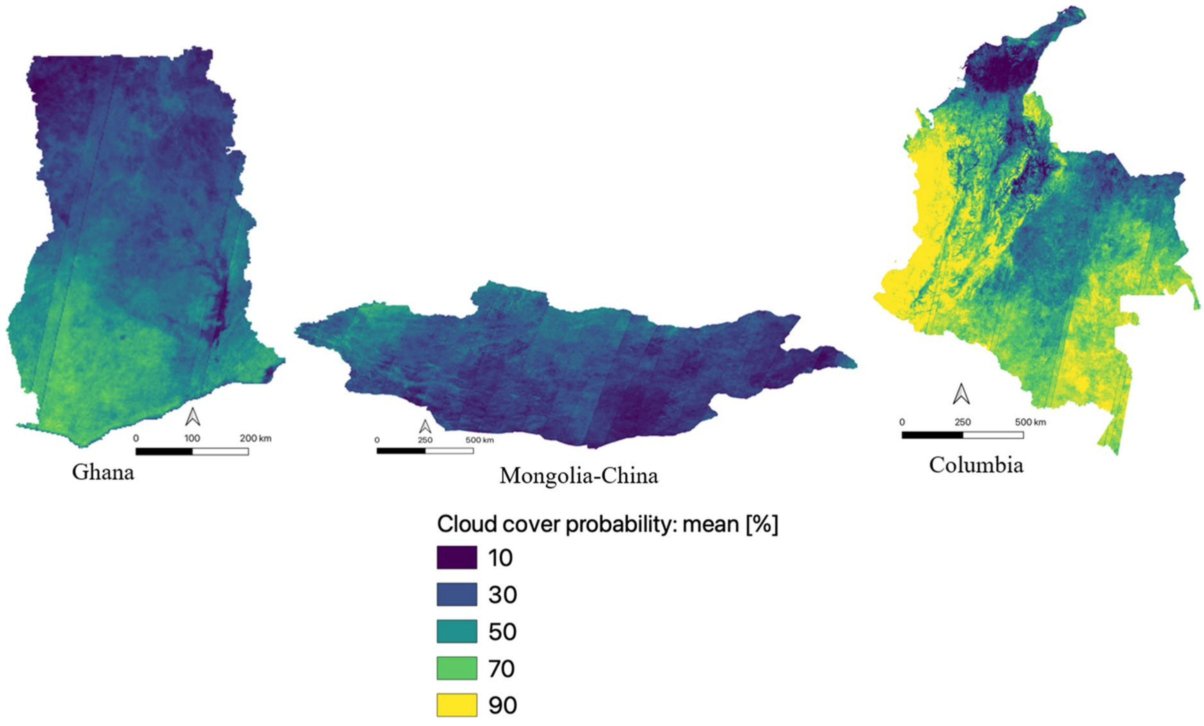

Fig. 5 Examples of cloud cover persistence over countries experiencing illicit ASG activities in Africa, Asia, and America, respectively

UNODC, 2018). RS usually enables monitoring and identifying illicit mining sites, detecting, and estimating mercury pollution levels through spectral signatures. For the observations of mercury at mine sites, the first step is detecting current water, soil and vegetation health, and comparing these to the back in time spectral signatures of the same variables at the same spot. Largely, Normalized Difference Vegetation Index (NDVI), Normalized Difference Water Index (NDWI), Soil Adjusted Vegetation Index (SAVI), etc. may be used in baseline studies. However, close microscopic observations of variances in the behaviours of spectral signatures could be undertaken on hyperspectral, multispectral, RADAR and LiDAR images for a robust methodology of mercury detection on mine sites rather than relying on macroscopic and proximate indices. It aids in assessing environmental impacts, informing policy decisions, and implementing mitigation strategies, crucial for sustainable ASGM management and mercury pollution control. The results of our research prove that medium and high-resolution monitoring approaches are generally applicable in Asia and Latin America and few in Sub-Saharan Africa probably due to resource availability or due to accessibility of sites during ground truthing.

Monitoring landscape changes due to illicit ASGM is challenging in these regions where very high resolution free RS data are limited or not available (Moomen et al., 2022). It is observed from the data analysis that Landsat (55.2%) and Sentinel-2 (20.7%) data are commonly used in monitoring illicit ASGM in Sub-Saharan Africa. Thus, the advent of tools, such as African Data Cube and the Digital Earth Africa, has become critical for creating fine-spatial resolution in the region (Agbaje & John, 2018; Giuliani et al., 2020). Regional circumstances also determine the applicability of these resources. For instance, while night lights detection products provide useful data for detecting illicit ASGM in other resource extraction contexts, these products show little significance in identifying illicit ASGM sites in Africa (Kyba et al., 2019). Environmental issues associated with illicit ASGM in these regions have become, increasingly, global concern, especially, in the wake of the 17 Sustainable Development Goals (SDGs) of the

UN. Data Cube can provide robust monitoring of these environmental concerns, while minimizing time and scientific knowledge desired to access, prepare and analyse large EO datasets (Caetano et al., 2022). However, there is still the need to explore high-resolution images deployment to improve ASGM monitoring and its impacts in Africa. It is obvious from the study that a combination of both high and medium resolution imagery, radar and optical images can help robust detection and monitoring of illicit ASGM activities and inform decisions for regulation.

Figure 6 shows that the countries with the highest values of gold production and/or ASGM miners, with a few exceptions such as China, Guyana, and French Guyana, have the largest amount of RS application studies. An important revelation from the results is that while Peru and Brazil have equal shares (10 cases each) of applications of RS for monitoring ASGM activities, both Indonesia and Ghana have over two-thirds majority case studies in Asia and Africa, respectively. This supports the published statistics that Peru, Brazil, Indonesia and Ghana are leading Gold producers in the world (WMD, 2019). The results also confirm the published indicators that Peru and Brazil are the leading Gold producers in Latin America (Brown et al., 2020b; WMD, 2021). On the other hand, the data is partly in contrast with the number of ASGM miners, which in Colombia are roughly three times larger than in Peru (ASM, 2023; Fig. 6). It is also noteworthy in the charts that Ghana holds the highest ASGM activities in Africa and consolidates its position as the leading gold producer in Africa since 2019 (Barenblitt et al., 2021; GCM, 2021; WMD, 2019). While the results in the graphs show that more case studies on applications of RS are done in the Americas than all other regions, a cross analysis of the data in the Tables shows that at individual country level, Ghana records the highest number of case studies than any other country. This trend could be attributed to site accessibility for ground truthing of satellite and other RS data. Nonetheless, access to data and site could be enhanced in all regions to facilitate robust monitoring and reporting on ASGM activities and associated mercury uses in all the respective regions (Miserendino et al., 2013; O'Neill & Telmer, 2017b; Telmer & Veiga, 2009). Thus, DeWitt (2016) suggests that mapping illicit ASGM requires high-resolution imagery for robust classification of complex patterns.

Conclusion

This paper assessed the applications of RS for global monitoring and management of illicit ASGM activities with a focus on Africa, Southeast Asia, and Latin America. High-quality data on illicit ASGM activities, and techniques for generating accurate, consistent, and regular data on illicit ASGM activities are lacking. High-resolution based methodologies are used in Asia/Oceania and Latin America, but more rarely in Africa, notably due to lack of very

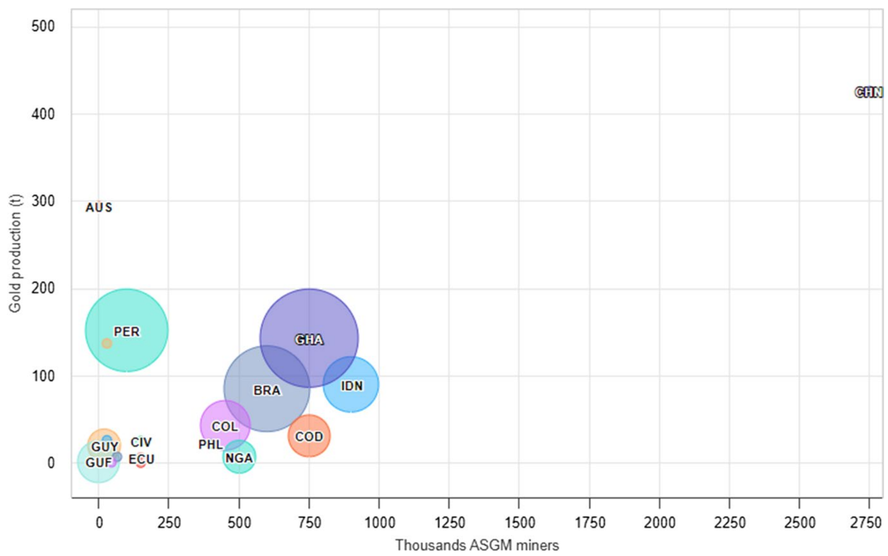

Fig. 6 Gold production in Tonnes (WMD, 2019) and number of ASGM miners (ASM, 2023) relative to the number of RS applications by country

high-resolution RS data and inaccessibility of sites during ground truthing. In this context, initiatives such as Digital Earth Africa can provide requisite data to inform policy towards formalisation and effective regulation of ASGM. Also, Digital Earth America and Data Cube program in South-East Asia can support monitoring of illicit ASGM activities impacts in the regions of concern. There is the need to use medium- and high-resolution satellite imagery; to combine various data fusion techniques such as optical, radar, lidar, in-situ, and crowded-sourced; conduct laboratory microscopic analysis of variances and co-variance spectral signature records of all heavy metals used on mine sites for easy detection without the relative need for Insitu data. Brazil, Ghana, Indonesia, and Peru appear to hold most use cases on their continent, which is correlated to their high rank in terms of gold production as well as their low site accessibility for field measurement –especially in Ghana. It is, therefore, recommended to make use of analysis ready data organized in data cubes in countries with limited access to data.

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Declarations

Conflict of interests The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. The authors declare the following financial interests/personal relationships which may be considered as potential competing interests.

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