International Cartographic Association
Association Cartographique Internationale

Monitoring of mining sites using UAV and radar imagery around the Benue National Park (North-Cameroon)

Sylvain Aoudou Doua [a, *], Jean Cyrille Narké [b], Jean Paul Kevin Mbamba Mbamba [c]

[a] *Department of Geography, University of Maroua, Cameroon* – aoudoudou@gmail.com
[b] *National Institute of Cartography, Ministry of Scientific Research and Innovation, Cameroon*- narke168@gmail.com
[c] *Ministry of Forestery and Wildlife and University of Ngaoundere, Cameroon*- mbambakeve2003@gmail.com

* Corresponding author

Abstract:

Faced with the exacerbation of anthropic pressures due to the strong rush of populations towards mining in agropastoral areas and in conservation areas, the challenges of sustainable management of natural resources are now to develop the series of action in addition to repressive reactionism, realistic alternatives, as well as new approaches to effective management based on innovative techniques such as the use of UAVs. Gold panning is one of the major causes of the fragmentation and destruction of natural ecosystems, and of the rise in conflicts over and around the use of resources. It is also a real danger to human health and wildlife because of the use of chemicals and heavy metals. The use of UAVs to monitor mining sites in a context of environmental fragility and anthropogenic pressures is therefore crucial for taking stock of the situation, assessing the potential socio-environmental impacts and proposing effective solutions. The use of drones to monitor mining sites around the Benue National Park has enabled us to obtain high spatial resolution data using photogrammetry techniques and image processing. As a result of the various processing operations, the surface area impacted by mining activities, the number of holes and alluvial tunnels, and the watercourses impacted and/or destroyed have been accurately estimated. In addition, the collection of complementary data enabled us to take stock of the different actors involved, the stages and the chemicals products and tools used.

Keywords: Mining activities, Drone or UAV, Machine Learning, photogrammetry, National Park of Benue.

1. Introduction

The rise in the price of gold on the world market, the impoverishment of rural populations and the development of new mining techniques have led to a veritable ‘gold rush’, boosting this activity, which is unfortunately developing in and around conservation areas. This activity is a major source of livelihood for local people, but it also has severe environmental and social impacts: deforestation, soil and water pollution, landscape degradation, and health risks due to the use of chemicals such as mercury and cyanide (Hilson, 2016; Narké, 2025; The World Bank, 2019). Traditionally, the monitoring of these activities in order to assessing socio-environmental impacts has been based on conventional methods such as field surveys and the use of satellite imagery, which have limitations in terms of spatial resolution, acquisition frequency, cost and accuracy in assessment (Sonter & al., 2017). Faced with increasing anthropogenic pressures, particularly illegal mining, which is fragmenting ecosystems and exacerbating socio-environmental conflicts, how can AI and drones be integrated as innovative tools for the sustainable management of natural resources? How can these technologies be used to accurately monitor sites, assess their impact and find appropriate solutions to the challenges of conservation and the cohabitation of different uses ?

Satellite imagery, which has been much more widely used to date, can detect large-scale changes, but remains limited by resolution (≥10 m for Sentinel-2) and atmospheric phenomena such as cloud cover (Asner & Tupayachi, 2016). On the other hand, field surveys are very costly and difficult in areas of insecurity and/or difficult access. Photogrammetry techniques using UAVs (Unmanned Aerial Vehicles) are emerging as a promising technology for improving the accuracy of the assessment of likely impacts, and the speed and safety of mine monitoring, particularly in remote or difficult-to-access areas (Ndewe & al., 2024). They offer a number of advantages and can fill gaps thanks to their operational flexibility (Colomina & Molina, 2014), the provision of very high spatial resolution images (Toth & Jóźków, 2016) and the possibility of carrying different types of sensor (RGB, multispectral, LiDAR or thermal cameras).

The aim of this work is to carry out an inventory of mining sites, and to use photogrammetry and machine learning techniques to assess the potential impacts of the said activity on the socio-environmental level. In a context of environmental fragility and anthropic pressures, such monitoring is crucial if effective solutions are to be proposed.

2. Materials and methods

2.1 Geographical context

The complex of protected areas in the North Cameroon region (Figure 1) is located between latitudes 7°42‘and 9°00’ north and between longitudes 12°15‘and 15°064’ east. It comprises three national parks (Bénoué, Bouba-Ndjidda and Faro) and 32 zones of hunting interest (ZICs).

Advances in Cartography and GIScience of the International Cartographic Association, 5, 3, 2025.
32nd International Cartographic Conference (ICC 2025), 17–22 August 2025, Vancouver, Canada. This contribution underwent double-blind peer review based on the full paper. https://doi.org/10.5194/ica-adv-5-3-2025 |

Its geographical particularity, with its topographical and edaphic diversity, a climate characterised by two strongly contrasting annual seasons, and the influence of numerous watercourses, means that the region has Sudanian-type vegetation with an interlocking mosaic of plant units. The presence of species highly characteristic of the Sudanian zone and of species associated with the north of the Guinean zone results from its location between the Sudano-Sahelian sector and the northern escarpment of the Adamaoua plateau. The area is also rich in mineral resources and over the years has become a vast open-pit mining site (Narké, 2017).

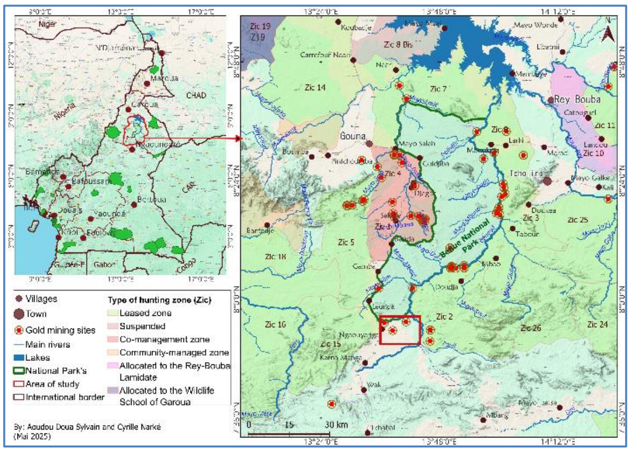

Figure 1. Figure Location of the Benue National Park.

2.2 Methodology

The study area was flown over by drone to obtain ortho-photos/videos. These images was used to distinguish and characterise both the details of the vegetation and its vertical structure. they will make it easier the analyses needed to draw up the land-use map and assess the potential environmental and socio-economic impacts of these activities. This work comprises three main phases : the data acquisition phase and the data processing and analysis phase.

2.2.1 *Data acquisition and field surveys*

In order to obtain the high-resolution images, we needed to achieve our objectives, the data was acquired mainly by using a civil drone, the DJI Phantom 4 Pro RTK, which is commonly used for agricultural and environmental applications because of its geospatial accuracy and high-performance sensors.

2.2.1.1 Materials used

- Drone Model: DJI Phantom 4 RTK (P4 RTK) ;

- Main sensor: RGB-type camera with 20 MP resolution (5472 × 3648 px), 1" CMOS size, 12-bit Colour Depth and Visible (R, G, B) spectral range ;

- RTK (Real-Time Kinematic) system: Real-time GNSS correction for centimetre-level accuracy (1-3 cm for planimetry, 2-5 cm for altimetry);

- Battery life : approximately 30 minutes per flight

- Range : Less than 2 km (depending on local regulations requiring visual flight).

2.2.1.2 Flight planning and calibration

- Software use : DJI G04 RTK (Ground Station) or QGIS ;

- Flying height: 60 to 80 m, depending on canopy and relief (Resolution approx. 2 to 10 cm/px) ;

- Image overlay : 70% frontal to ensure optimum 3D reconstruction ;

- Optimum flight time depending on atmospheric and weather conditions : Between 10am and 4pm (uniform light, reduced shadows, clear sky, wind < 10 m/s, no rain or fog, etc.) ;

- Calibration of the camera and launch to begin taking images according to the pre-established flight plan from the vector files (kml) prepared in advance. Once the images have been captured, they are recorded and imported into a specialised software programme for processing.

2.2.2 ***Data processing***

The data acquired by drone was processed using the specialist Agisoft Metashape tool. It was used to generate georeferenced orthomosaics, Digital Terrain Models (DTMs) and Digital Surface Models (DSMs). These products facilitated a detailed analysis of land use, including the number of pits dug for gold extraction and the number of agricultural plots and watercourses destroyed. Using artificial intelligence algorithms such as Random Forest and Deep Learning via QGIS and R, a supervised classification was produced to categorise the different types of land cover. Semantic segmentation using Deep Learning was used to automate the detection and categorisation of excavated pits according to their depth, and to calculate the areas affected.

Finally, the impact of the evaluation or quality control of methodological choices was quantified using parameters such as the Kappa coefficient, the F-score and the precision. Parametric analysis plays a critical role in assessing the sensitivity of results to methodological choices. Key parameters include image resolution, classification thresholds and algorithm configuration. This stage quantifies the impact of each variable on the reliability of the results obtained. The figure 2 summarises the methodological approach adopted.

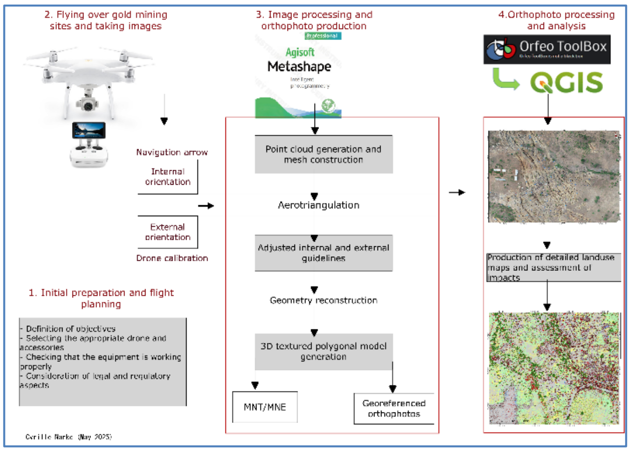

Figure 2. Methodological approach

3. Main results

Using the data obtained by UAV and cross-referencing them with other sources of information (field surveys, participatory surveys, documentary data, etc.) helped to characterise and map the largest current gold-panning site in the complex studied, and enabled us to assess the extent of this phenomenon on the plant cover.

3.1 Socio-economic profile of gold-panners and characterisation of gold-panning sites

This activity, which is much more common in the rainy season, is developing very rapidly in a local environment characterised by the continual arrival of migrants and great poverty among the rural population. Over 90% of mining is carried out on an artisanal basis by gold panners from a variety of backgrounds, and even from abroad (Nigeria, Chad, CAR), despite the ban imposed by the authorities responsible for managing natural resources. In our context, this exploitation is manifested by the anarchic and spectacular installation of thousands of artisanal gold miners in the ZICs and the core areas of the NPs. It is important to stress that this activity is developing very rapidly in a local environment characterised by continuous arrivals of migrants and great poverty among the rural population.

Figure 3 shows the orthomosaic produced after processing the photographs (images) obtained by drone, with more detail than Figure 4, which shows a view of the same area from the optical image (Sentinel 2) and the radar image (Sentinel 1).

Figure 3. Orthomosaic of the site studied.

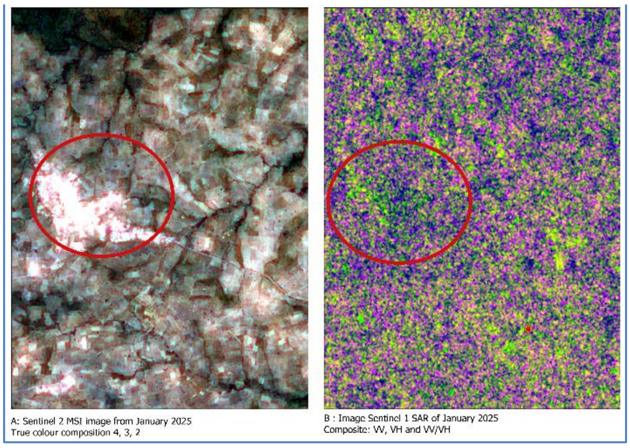

Figure 4. View of the study area from sentinel images 1 and 2.

La figure 5 gives an overview of the main gold extraction methods used in our study region.

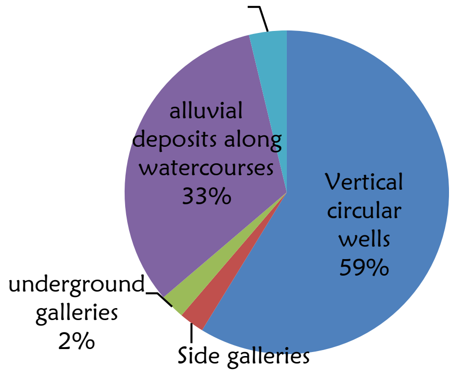

Figure 5. Various forms of mining in the area od study.

The depth and diameter of the vertical circular shafts vary according to the terrain, and can reach 10 to 30m and 2 to 30m respectively. The photo 1 shows an image of a gold panning site.

Figure 1. Aerial view of a gold-mining site, showing excavated pits and huts (houses) ; (13.615519E, 7.903578N).

3.2 Characterization of land use on the area of studied

Gold panning is also one of the causes of fragmentation of the vegetation landscape and wildlife habitat ; the destruction of forest galleries as a result of alluvial mining; the modification of the hydrographic network ; and the establishment of veritable villages in these protected areas. The land-use map (Figure 6) produced for a 200-hectare mining site shows the extent of the impact of gold panning on the natural environment.

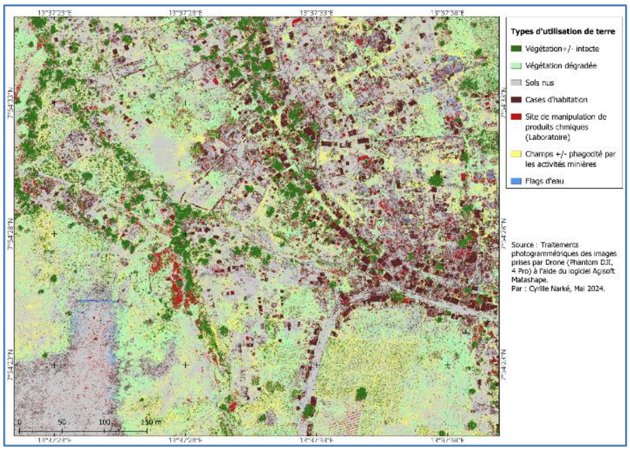

Figure 6. Spatial distribution of land use types.

Since 2019, there has been a sharp rise in this activity in the North region in general, and the area exploited has almost tripled. The statistical analysis in Figure 5 has enabled us to quantify the surface area and the percentage of land use in a 200-hectare gold panning site (Table 1).

	area (ha)	(%)

Table 1. Characterisation of land use on a 100-hectare gold-panning site overflown by drone

Table 1 shows that bare soil is the most represented category, occupying 47.15 hectares, or 23.57% of the total area. This indicates severe degradation of the soil in this area as a result of mining, leading to increased erosion, loss of fertility and a reduction in the natural regeneration capacity of the vegetation. Degraded vegetation covers 36.24 hectares, or 18.12% of the area, reflecting the severe degradation of plant ecosystems caused by mining activities, with negative impacts on biodiversity, soil quality and ecosystem services. Pits dug for gravel extraction occupy 33.08 hectares (16.54%); agricultural plots invaded by gold extraction pits cover 29.59 hectares, or 14.79% of the total area. Dwelling huts occupy 21.08 hectares, or 10.54% of the total area, reflecting the footprint of human habitation on the land.

Relatively dense vegetation covers 21.91 hectares (10.95%), representing areas that are still partially intact and where the vegetation is under relatively less pressure at present. Finally, water bodies cover 10.96 hectares, or 5.48% of the surface area. These bodies of water are used by the residents of this gold panning site as their main source of water for drinking, cleaning, washing clothes and washing gravel. It should also be noted that this intensive mining activity not only contributes to soil and habitat degradation, but can also lead to water and soil pollution from chemicals used in gold extraction, such as mercury and cyanide.

3.3 Environmental and social impacts of mining activities

3.3.1 *Environmental impacts*

The mining method generally has a negative impact on the environment both during and after mining. These include the destruction of wildlife and plant habitats, particularly gallery forests; the alteration of landscapes and loss of biodiversity; the opening up of spectacular holes; the overturning of the land, which is not conducive to the regeneration of plant cover ; the filling in of watercourses, which leads to imbalances in wildlife; soil, water and air contamination, etc.

According to Dudley (2014), protected areas play a fundamental role in conserving biodiversity, protecting fragile ecosystems and maintaining vital ecosystem services such as climate regulation, water purification and soil conservation. Activities described by some stakeholders as ‘cancer of the protected areas’, such as mining, transhumance and charcoal production, have very harmful impacts on the environment and represent serious threats to the achievement of conservation objectives as defined in the NDS30[1]. The aim is to promote actions that can minimise environmental impacts while enabling sustainable economic and social development (Lockwood & al., 2006). Figure 7 shows the extent of the impact of gold panning on the landscape, based on the depths of the pits dug by the miners.

[1] Cameroon's National Development Strategy 2030 (NDS30) is a planning framework aimed at transforming the country into an emerging economy by 2035. Based on three pillars (economic, social and environmental), it promotes inclusive growth, infrastructure modernisation, industrialisation, environmental sustainability and improved governance, in line with the UN's Sustainable Development Goals (SDGs).

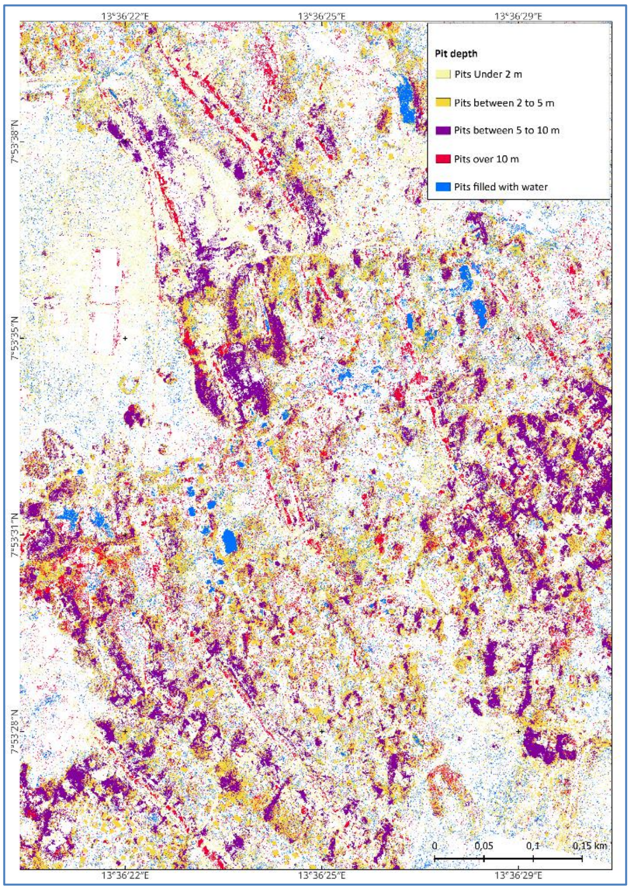

Figure 7. Spatial distribution of gravel extraction pits by depth

This figure 7 show the spatial distribution of pits dug by gold miners according to their respective depth; and we have five categories of pit according to their depth: There are pits less than 2 metres deep, pits 2 to 5 metres deep, pits 5 to 10 metres deep, pits more than 10 metres deep and pits filled with water of varying depths. Table 2 shows the distribution of these gold pits according to the surface area occupied by each category.

	(Ha)	(%)
m		
10 m		
water		

Table 2. Répartition des fosses en fonction de leur profondeur respective

We divide the surface area of pits dug for mining purposes by depth as follows: Pits less than 2 metres deep account for the largest surface area at 30.15 hectares, or 29.95% ; they are followed in turn by those 2 to 5 metres deep (23.06 hectares, 22.91%), those 5 to 10 metres deep (19.85 hectares, 19.72%), and those more than 10 metres deep (11.99 hectares, 11.92%). Pits filled with water, although less extensive (15.60 hectares, 15.50%), are also present in the distribution, and reveal more clearly the harmful nature of this activity for both the population and the fauna. Children and other animals often drown in these water-filled pits. According to Aoudou & al (2018), the area degraded by mining was 972 hectares. What's more, the residue of the chemicals used remains in the water, which could be harmful to human and animal health.

These areas can suffer impacts such as the alteration of adjacent terrestrial habitats, soil and water pollution, and hydrological changes that are detrimental to local biodiversity. Water-filled pits have adverse effects on groundwater quality and the ability of ecosystems to regenerate after mine closure. This analysis of mining pits by depth highlights the critical importance of adaptive, science-based environmental management strategies. This will not only help preserve biodiversity and essential ecosystem services, but also promote more sustainable and responsible mining, thereby responding to the growing challenges of environmental degradation associated with this intensive industrial activity.

The environmental issues at stake in the sustainable management of protected areas in the study region include: the protection of emblematic and endangered species; energy issues related to the fight against threats to the Benoué and Faro rivers; and the sustainability of navigation and maritime transport activities on the Benue. Between the Faro National Park and the Benoue National Park, areas or corridors for the safe migration of wildlife have been demarcated following discussions and consultations between the Biodiversity Conservation Department and local communities. Figure 8 shows a wildlife migration corridor in a very advanced state of fragmentation.

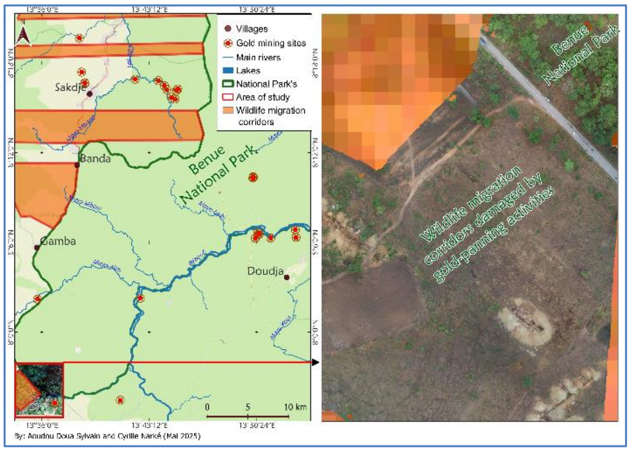

Figure 8. View of a wildlife migration corridor degraded by gold-panning activities.

In addition, there are conservation issues, such as compliance with international conventions that have been ratified and the obligations that must be met. This is the case of the Benue National Park that has been designated a UNESCO World Heritage Site and a Biosphere Reserve.

3.3.2 *Socio-economic impacts*

The cohabitation of gold panning with wildlife and even agricultural plots makes this activity a real threat because of the dangerous products used and the extent of the environmental damage observed. What's more, the use of

 https://doi.org/10.5194/ica-adv-5-3-2025 |

chemicals and heavy metals poses a real danger to both human health and wildlife. The photos show villages, agricultural plot and large holes dug by gold miners in the conservation areas, posing a real threat to wildlife. The photos 2 and 3, and figure 9 too shows some of the damage caused by mining around the Benue National Park.

Photo 2. agricultural plots swallowed up by gold mining

Photo 3. Watercourse polluted by chemicals

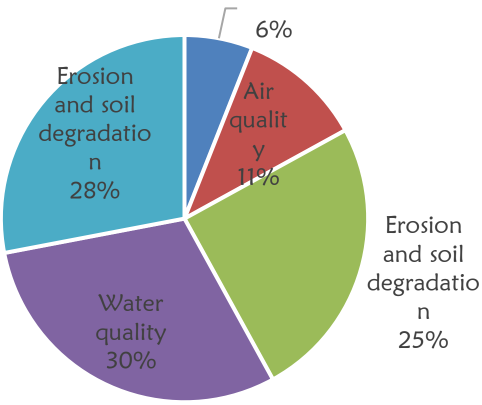

Figure 9. Proportion of environmental changes observed by gold miners.

4. Discussion and conclusion

This study demonstrates the potential of drones for monitoring and assessing the impacts of artisanal mining, confirming the observations of Vermeulen (2019) and Sonter et al. (2017) on the need for innovative tools in the face of ecosystem fragmentation. Thanks to their ability to acquire data with very high spatial resolution (≤5 cm), drones have made it possible to obtain results for this work such as : detailed mapping of the gold panning site, assessment of the areas impacted, precise identification of the number of pits and their depth, as well as a reliable estimate of the degradation of vegetation cover and watercourses. These results underline the fact that the use of UAVs surpasses traditional satellite methods (resolution ≥10 m) in this field.

By bridging the gap between ground and satellite surveys, Drones optimise data collection at lower cost, with operational flexibility that is crucial for proactive monitoring, as illustrated by the work of Lobo and al. (2023) on the detection of 30% more illegal sites. However, their large-scale deployment comes up against practical limitations : limited battery autonomy, sensitivity to weather conditions, and the complexity of processing voluminous data, challenges already addressed by Nex and Remondino (2014). The implications for conservation, mentioned by Alvarez and Al (2016), Diaz-Delgado and Mücher (2019) are clear : these technologies facilitate the adaptive management of ecosystems.

Despite these constraints, technological advances (long-life batteries, AI algorithms for automated analysis) point to a promising future for drones in the mining sector. Their integration, coupled with closer collaboration with local stakeholders and regulators, could amplify their role in environmental monitoring, the rehabilitation of degraded sites and the promotion of more sustainable mining. In this way, drones do more than simply document impacts: they pave the way for informed decision-making based on accurate, up-to-date data, which is essential if we are to reconcile economic development with the preservation of ecosystems.

5. References

Alvarez-Berríos, N., Campos-Cerqueira, M., Hernández-Serna, A., Amanda Delgado, C. J., Román-Dañobeytia, F., & Aide, T. M. (2016). Impacts of Small-Scale Gold Mining on Birds and Anurans Near the Tambopata Natural Reserve, Peru, Assessed Using Passive Acoustic Monitoring. *Tropical Conservation Science*, *9*(2), 832-851. https://doi.org/10.1177/194008291600900216

Aoudou Doua, S., Narké, J. C., & Mayen Ndjiong, B. (2018). *Evaluation of the Advanced Minning Front Craft in and around National Parks of the Benue and Bouba-Ndjidda in North Cameroon*. *10*(4), 461-475. https://doi.org/10.4236/jgis.2018.104024

Asner, G. P., & Tupayachi, R. (2016). Accelerated losses of protected forests from gold mining in the Peruvian Amazon. *Environmental Research Letters*, *12*(9), 094004. https://doi.org/10.1088/1748-9326/aa7dab

Colomina, I., & Molina, P. (2014). Unmanned aerial systems for photogrammetry and remote sensing: A review. *ISPRS Journal of Photogrammetry and Remote Sensing*, *92*, 79-97. https://doi.org/10.1016/j.isprsjprs.2014.02.013

Diaz-Delgado, R., & Mücher, S. (2019). *Drones for Biodiversity Conservation and Ecological Monitoring*. MDPI. https://doi.org/10.3390/books978-3-03921-981-0

Hilson, G. (2016). Farming, small-scale mining and rural livelihoods in Sub-Saharan Africa: A critical overview. *The Extractive Industries and Society*, *3*(2), 547-563. https://doi.org/10.1016/j.exis.2016.02.003

Lockwood, M., Worboys, G., & Kothari, A. (2006). *Managing Protected Areas: A Global Guide*. ResearchGate. https://www.researchgate.net/publication/262688810_Managing_Protected_Areas_A_Global_Guide

Narké, J. C. (2017). *Fragmentation des habitats et rupture de la connectivité écologique entre les parcs nationaux de la Bénoué et du Faro* [Mémoire de Master]. Maroua.

Narké, J. C. (2025). *Analyse de la dynamique des paysages végétaux du complexe d'aires protégées de la région du nord(Cameroun)* [Thèse de Doctorat PhD]. Maroua-Cameroun.

Ndewe, A. A., Ejuande, E. W., & Fogwe, Z. N. (2024). L'Intelligence artificielle : Une opportunité pour le développement de l'artisanat minier Camerounais. *Communication, technologies et développement*, *15*. https://doi.org/10.4000/123j0

Nex, F., & Remondino, F. (2014). UAV for 3D mapping applications: A review. *Applied Geomatics*, *6*(1), 1-15. https://doi.org/10.1007/s12518-013-0120-x

Sonter, L., Herera, D., Barret, D., & Galford, G. (2017). *Mining drives extensive deforestation in the Brazilian Amazon—PubMed*. https://pubmed.ncbi.nlm.nih.gov/29044104/

The World Bank. (2019). *Gender Dimensions of Artisanal and Small-Scale Mining A Rapid Assessment Toolkit—CommDev*. https://commdev.org/publications/gender-dimensions-of-artisanal-and-small-scale-mining-a-rapid-assessment-toolkit/

Toth, C., & Jóźków, G. (2016). Remote sensing platforms and sensors: A survey. *ISPRS Journal of Photogrammetry and Remote Sensing*, *115*, 22-36. https://doi.org/10.1016/j.isprsjprs.2015.10.004

Vermeulen, C. (2019). *Utilisation des drones pour le suivi des aires protégées en RDC*. https://www.academia.edu/72677113/Utilisation_des_drones_pour_le_suivi_des_aires_prot%C3%A9g%C3%A9es_en_RDC

Watson, J. E. M., Dudley, N., Segan, D. B., & Hockings, M. (2014). The performance and potential of protected areas. *Nature*, *515*(7525), 67-73. https://doi.org/10.1038/nature13947