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REVIEW ARTICLE

ENVIRONMENTAL IMPACT OF ILLEGAL GOLD MINING IN KATIOLA DEPARTMENT (CÔTE D'IVOIRE)

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ABSTRACT

Illegal gold mining in Katiola Department, a region rich in gold resources, has worrying environmental consequences. The objective of this study is to assess the environmental impact of illegal gold mining by identifying the damage caused by mining activities and proposing mitigation measures. The methodology used includes documentary research, the identification of illegal gold mining activities through mapping and remote sensing, direct field observation surveys and interviews, and finally, the proposal of impact mitigation methods. The analysis of the illegal gold mining situation revealed major environmental impacts such as the disappearance of vegetation cover, soil stripping and excavation, the reduction of arable land, and water pollution. Given the devastating damage, it is essential to strengthen monitoring of mining activities and rehabilitate damaged ecosystems.

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INTRODUCTION

Environmental degradation remains a major concern of government policies around the world today. From Rio de Janeiro in 1992 to Johannesburg in 2002, environmental issues have generated much discussion and recommendations for its conservation. Many factors contribute to environmental degradation, including pollution, agricultural and forestry practices, and more recently gold mining activities (1). In Côte d'Ivoire, small-scale gold mining is growing rapidly due to the richness of the subsoil in minerals and energy resources (2). This activity has grown to the point of attracting the attention of national and international authorities (3). This has resulted in the holding of numerous meetings and the conduct of various studies on legislative, regulatory and organizational aspects (4). In Katiola department, gold panning has grown significantly in recent years. This activity, most often carried out clandestinely, has many harmful consequences for the environment and for humans (5). Gold panning sites are undergoing irreversible transformations, marked by landslides and degradation of natural resources (6). It is therefore to alert the various stakeholders (state, local authorities and gold miners) to the importance of environmental protection that the study on the impact of clandestine gold panning in Katiola department was conducted. The general objective of this work

is to assess the environmental impact of illegal gold mining, by identifying the damage caused by mining activities and proposing mitigation measures.

MATERIALS AND METHODS

Study area : The department of Katiola is located in the Hambol region in the north-central part of Côte d'Ivoire. It extends between latitudes 8°08′15″N and 8°15′00″N, as well as longitudes 5°06′07″W and 5°15′00″W and covers an area of 19,122 km². The city of Katiola is the capital of the commune, department and region and is located approximately 402 kilometers from Abidjan, the economic capital. This study took place in three sites: Anzoumana 1 and Anzoumana 2 in the north (Fronan sub-prefecture) and Sotikro in the southeast (Timbé sub-prefecture) (figure 1).

Identification of the impacts of gold panningactivities

Mapping and remotesensing: This method uses satellite images and remote sensing data to observe and analyze environmental changes, particularly before and after the intensification of illegal gold mining activities. The images can visualize variations in vegetation cover, deforestation, the

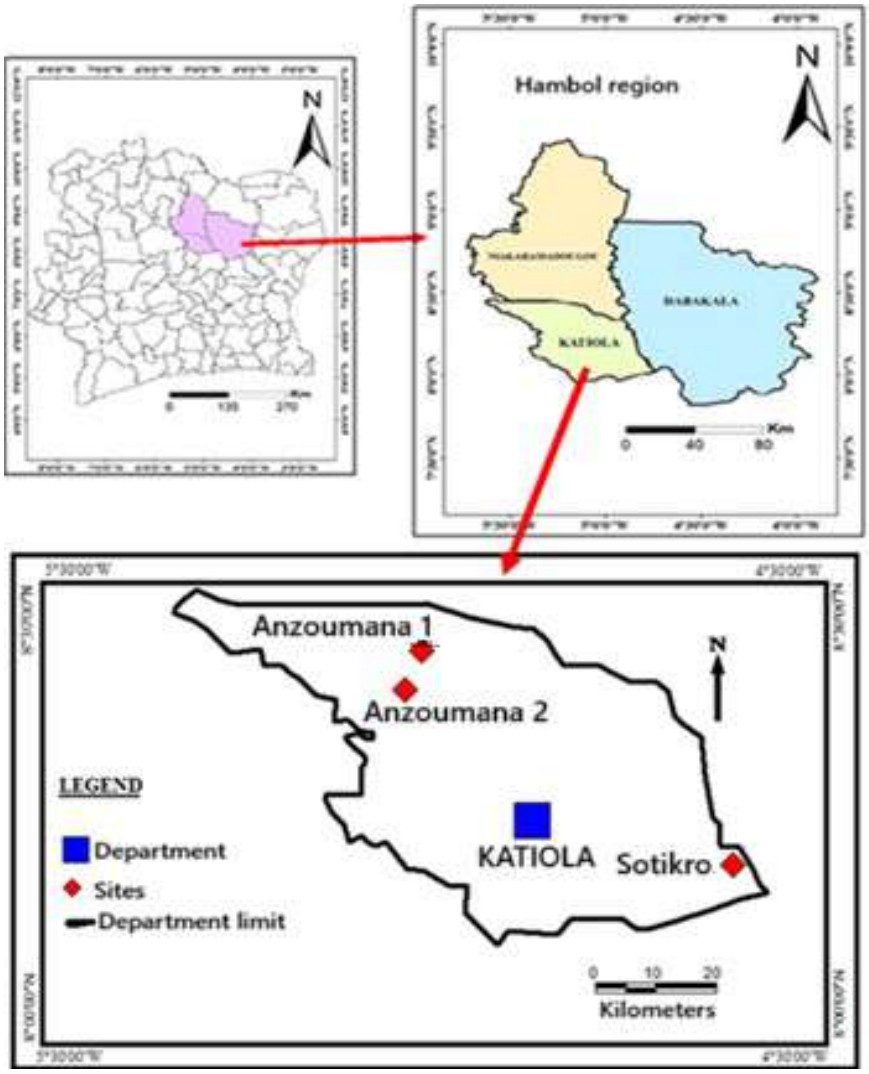

Figure 1. **Location of the study area**

expansion of gold mining areas, as well as signs of soil degradation, such as erosion or compaction. Comparing images before and after gold mining can provide an impact assessment and help identify the most affected areas.

Field surveys: Direct field observations complement satellite data and allow for a more detailed analysis of the effects of gold mining. These observations include examining mine sites and surrounding areas to identify signs of degradation such as erosion and loss of fertility. Interviews with local communities, miners, and authorities provide information on mining practices, residents' perceptions, and actions taken to reduce environmental impacts. These interviews also provide contextual information on local dynamics, regulatory policies, and natural resource management strategies. The impacts of illegal gold mining on the environment fall into two main categories:

Physical Impact

Increased erosion: Soil excavation and the destruction of vegetation cover weaken the land surface, making it more exposed to water and wind erosion. This degradation leads to the gradual disappearance of topsoil, which is essential for soil fertility.

Disruption of the hydrological regime: Uncontrolled extraction alters natural drainage, causing water to stagnate in abandoned pits and altering surface runoff. These changes can exacerbate erosion and affect water availability for ecosystems and agricultural activities.

Soil depletion: Deforestation and the removal of vegetation prevent natural soil regeneration. Deprived of organic matter and nutrients, soils gradually become less fertile, reducing their agricultural potential.

Ecological impact

Loss of fertility: Physical and chemical disturbances in soils reduce their ability to support plant life and produce agricultural crops.

Changes in biodiversity: Gold mining alters the natural habitats of animal and plant species, leading to a reduction in biodiversity in affected areas. Degraded soils no longer allow certain plant and animal species to thrive, affecting the entire ecosystem.

Determination of impact mitigation methods: This step aims to propose solutions to limit and repair the damage caused by illegal gold mining.

Rehabilitation of degraded soils: The rehabilitation of degraded soils will include stabilization techniques such as reforestation and grassing to prevent erosion and restore soil structure. Decontamination will be achieved through phytoremediation, using plants such as sunflowers to absorb heavy metals, and bioremediation, using microorganisms to neutralize pollutants. In addition, organic amendments, such as compost or manure, will be added to improve fertility and moisture retention.

At the same time, training programs on environmentally friendly mining methods and awareness campaigns on the dangers of illegal gold mining will be implemented to inform miners and the local population about sustainable practices. Decontamination methods include phytoremediation, which uses plants capable of absorbing heavy metals, as well as bioremediation techniques using microorganisms to decontaminate soils. Adding organic amendments also helps restore soil fertility.

Environmentalawareness and education: This involves training gold miners in more sustainable techniques and awareness campaigns on the dangers of illegal gold mining and its environmental impacts.

RESULTS AND DISCUSSION

Identification of impacts

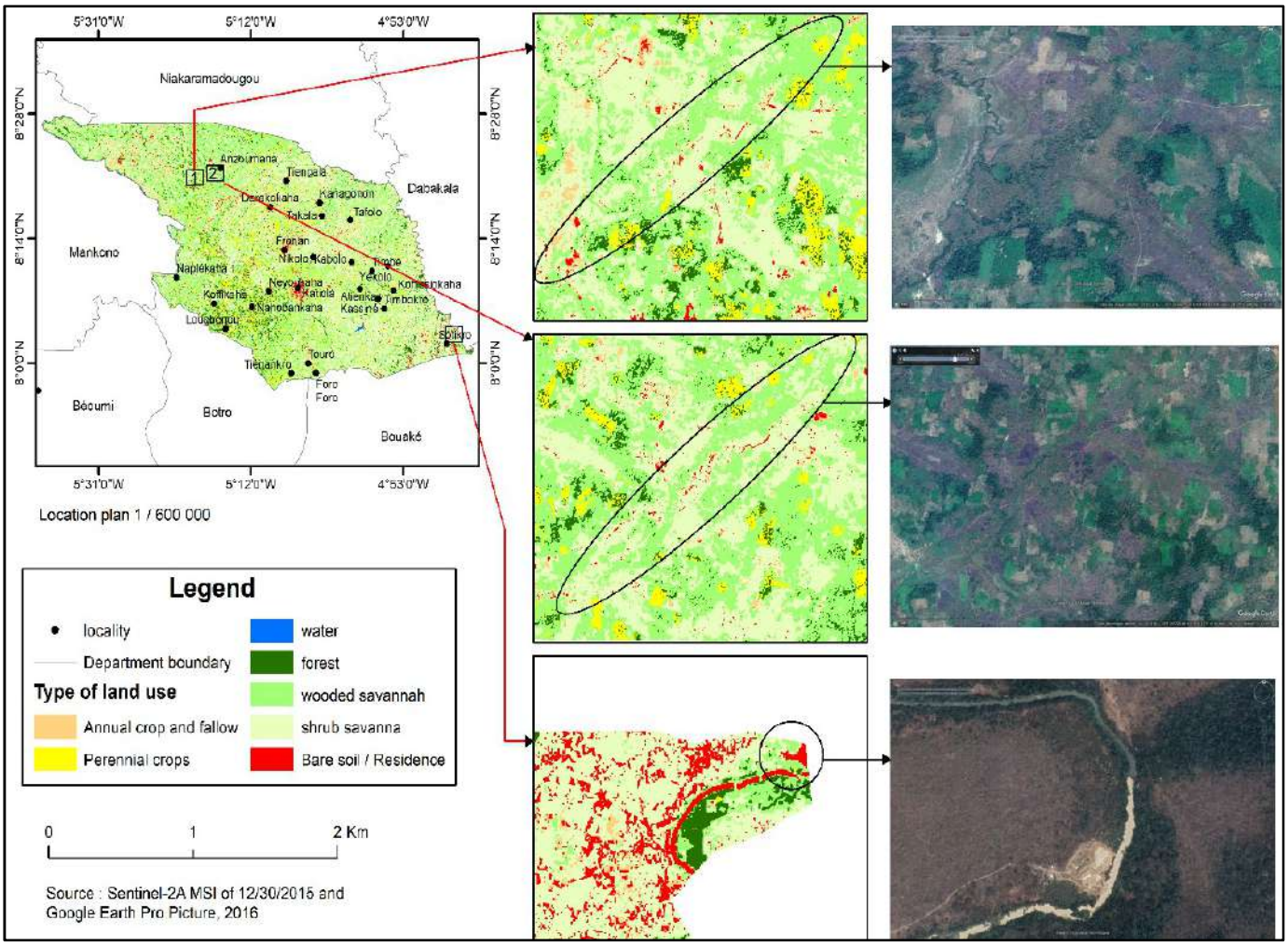

Figure 2. Land use map before mining activities in 2014

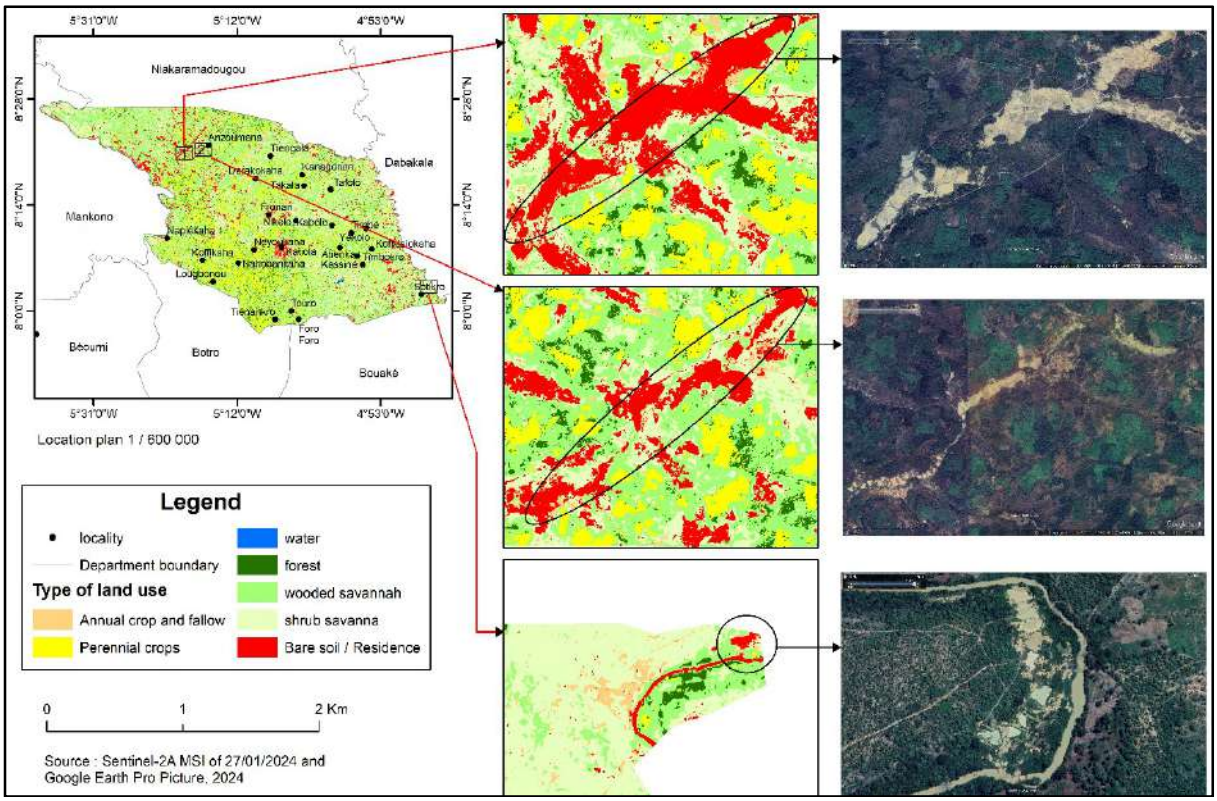

Figure 3. Current land use map with mining activities in2024

Land use: Between 2014 and 2024, land use in Katiola changed significantly, illustrating the impact of human activities. A 24% reduction in forested area was observed across the three sites, from 3,033 to 2,019 hectares. Figures 2 and 3 below illustrate the changes in land use in the Katiola department from 2014 to 2024, highlighting the impact of illegal gold mining on the land.

Différent stages of clandestine gold mining: Traditionally, gold miners used simple means (basins, calabashes) to recover alluvial gold before the discovery of gold veins. Generally speaking, clandestine gold panning is carried out according to the following steps:

Digging and supporting of mining holes: To access the deposit, the gold miners first dig a sub-vertical hole 0.5 to 1 meter in diameter (figure 4). The hole is dug using a pickaxe, hammer, shovel and other small pointed tools to break the rock. The operator descends into the hole using a rope connected to a winch and carries a battery-powered lamp attached to his forehead. The spoil is brought up in bags or buckets using the same rope. When the hole reaches a water table, the water is pumped out using a motor pump. Support consists of strengthening the walls of the pit using wood. This helps prevent landslides.

Figure 4. Digging

Figure 5. Manual crushing using a hammer

Crushing and grinding: Crushing involves reducing mineral blocks (seams) to small sizes using a hammer (figure 5) or crusher to allow the grinder to turn them into powder. Grinding is carried out using a mortar and pestle or a mill that produces a large amount of fine silica dust.

Figure 6. Washing table and mat

Washing and concentration: Washing is done in an artisanal way using inclined tables lined with pieces of fabric that facilitate the flow of water and light particles and retain the densest particles such as gold (figure 6). Sterile materials are eliminated as much as possible using ramps and thus increase the concentration of gold in the ores.

Product marketing: Gold is most often sold on-site. However, some miners prefer to sell it off-site or to unauthorized buyers, with the attendant risks. A gram of gold sells for approximately twenty-five thousand (25,000) CFA francs.

Impacts of illegal gold mining on the environment

Degradation of plant covert: Bush fires and the cutting of trees for the installation of gold miners as well as for the needs of support wood contribute to the destruction of the vegetation cover, to deforestation and to deforestation(figure7).

Stripping, Excavation and Soil Erosion: Striping involves removing the topsoil, which is primarily composed of plant matter. Excavation is the act of digging into the ground (figure 8).

Figure 7. Burnt vegetation cover and woodcutting

Artisanal miners remove the layer of soil, gravel, and sand covering gold deposits using shovels, picks, and sieves. In artisanal mining areas, during the rainy seasons, a natural process of erosion occurs through the detachment and transport of soil particles, resulting in a loss of nutritional properties for vegetation.These particles are deposited in waterways, accelerating their sedimentation and eutrophication.

Figure 8. Stripping and excavation of soils from gold sites

Rehabilitation of degraded land: According to the Food and Agriculture Organization of the United Nations (FAO), arable land refers to agricultural land that is suitable for crop production. This land provides the necessary conditions for plant growth, such as adequate soil texture, good drainage, sufficient nutrient levels, and adequate water availability. It is made available to gold miners by landowners to carry out their activities. During gold mining, soils and surface horizons are destroyed, inherent in the excavation of the flat several meters deep. In addition, the undug areas constituting the immediate environment are covered with unproductive soil extracted from the wells. As a result, vegetation will no longer be able to easily regenerate, and this surface loses its quality as arable land. These constant anarchic movements of workers on the site make many areas unsuitable for agriculture. Furthermore, these exposed soils are more easily eroded by heavy rains. These destroyed lands are left abandoned and unsuitable for agriculture (figure 9).

Figure 9. Lands abandoned by illegal immigrants

Disappearance of biodiversity: Soil is a dynamic and heterogeneous system even though it appears as an inert mass. It contains pores filled with water and air but also numerous organisms of multiple shapes and sizes inducing numerous habitats. Consequently, any alteration or degradation of the soil leads to a loss of biodiversity. Knowledge on soil biodiversity in the Katiola department is limited, although its assessment is essential to understand the impacts of artisanal gold mining.This activity profoundly modifies the edaphic environment, altering the structure, porosity and water retention capacity of the soil. These changes directly affect soil biodiversity, reducing the biomass and diversity of organisms. The destruction of riparian vegetation by gold miners (bush fires, tree cutting) further aggravates this situation, leading to a loss of biodiversity and an alteration of ecological functions.

Figure 10. Water polluted by gold panning activities

Water pollution: Runoff carries all forms of waste and pollutants into surface water. This pollution is indicated by the characteristic colors (figure 10). Groundwater can be polluted by the infiltration of toxic products such as cyanide used in the gold mining process.

Impact Mitigation Measures and Environmental and Social Management Plan

Impact mitigation measures: After identifying the damage caused, it is recommended to rehabilitate degraded land and raise awareness and educate the population about environmental issues.

Rehabilitationof degraded land: To ensure the effective restoration of degraded land and its reintegration into the natural and agricultural environment, physical and chemical stability must be ensured.

Physical stability: This involves restoring soil structure to limit erosion, improve its bearing capacity, and encourage the return of vegetation. This phase includes several essential actions.

- **Backfilling excavations:** After gold extraction, many pits and galleries remain open, promoting erosion and preventing plant recolonization. Filling them with appropriate materials helps restore a stable terrain.
- **Improving soil structure:** Using techniques such as aerating compacted soil, adding organic matter, and amending it with stabilizing elements (biochar, compost) helps restore its physical properties.
- **Erosion control:** The installation of erosion barriers, terraces, and deep-rooted plantings helps stabilize soils by limiting runoff and sediment loss.

Chemical stability: It aims to restore the soil's chemical properties by reducing contamination caused by toxic substances used during gold mining, such as mercury and cyanide. This phase includes:

- Neutralizing pollutants: Some contaminated soils require specific treatments to immobilize or eliminate heavy metals. The use of complexing agents (chelators) or chemical oxidation techniques may be considered.
- Improving soil fertility: Adding organic (manure, compost, green manure) and mineral (limestone, phosphates) amendments helps restore a chemical balance favorable to plant growth.
- Phytoremediation: Is a remediation technique that uses plants capable of absorbing heavy metals present in the soil through their roots. These plants then store the metals in their leaves and stems, thus helping to clean up contaminated soils. For example, the sunflower (Helianthus annuus) can absorb lead and cadmium. In Katiola, where the soil is polluted by heavy metals due to gold mining, planting sunflowers could be an ecological and effective solution.
- Bioremediation uses microorganisms, such as bacteria or fungi, to decompose or neutralize pollutants present in the soil. These microorganisms transform toxic substances into non-hazardous compounds, thus contributing to the remediation of contaminated soils. For example, certain decomposing fungi such as Aspergillus and Penicillium can degrade mercury and arsenic released by gold mining activities, thus providing a natural and effective solution for cleaning polluted soils.

Environmental awareness and education

Training programs for sustainable mining practices: Educating gold miners on environmentally friendly mining techniques can significantly reduce negative impacts on the soil. Techniques such as **"**Gravity Separation**"**allow gold to be extracted without the use of mercury or cyanide.

Community awareness campaigns: Educating local people about the environmental and health risks of illegal gold mining is essential to changing behavior. Campaigns can include community workshops, visual materials (posters, videos), and local radio broadcasts.

Proposal for an Environmental and Social Management Plan (ESMP): The environmental and social management plan is a summary of impacts and mitigation measures. It allows for environmental and social monitoring and oversight for effective environmental protection. For the funds needed for infrastructure construction, reforestation, and other actions, a 5% levy per gram on gold sales has been proposed, including 3% for the development of impacted villages and 2% for the organization of the industry.

DISCUSSION

To assess the environmental impact of illegal gold mining, it was necessary to identify the harmful consequences and determine mitigation methods. This began with the interpretation of satellite images on the evolution of land use. The analysis of these images, coupled with field visits and information gathered from gold miners, made it possible to identify significant damage such as the degradation of vegetation cover, stripping, excavation and erosion of soil, the destruction of arable land, the disappearance of biodiversity and water pollution. Harmful environmental consequences of illegal gold mining are linked to the cutting of trees for the installation of camps and for the needs of support wood. Also, the bush is most often burned for the installation of construction sites. These practices lead to a destruction of the vegetation cover, accentuating deforestation. The loss and disappearance of vegetation cover are characterized by deforestation and clearing caused by illegal mining activities, thus exposing bare soils to erosion and degradation. According to (7), this destruction reduces soil fertility by eliminating vegetation that helps retain nutrients and water. (8)and (9)add that the disappearance of vegetation cover disrupts local ecosystems, leading to a loss of biodiversity (including the disappearance of medicinal plants) and disruptions to hydrological cycles (local climate). This justifies the urgency of regulating these practices to protect forests. Soil stripping is the process of removing the top layer of soil along with the removal of vegetation and other materials that cover the soil surface. Mining excavation involves extracting minerals and metals buried in the soil by digging galleries or pits. These actions, essential to the mining industry, present environmental and safety challenges. With their corollary erosion, they lead to the destruction of soil, especially arable land, with a significant decrease in agricultural yields. Clandestine mining activities occupy and degrade land formerly used for agriculture, thus reducing the area available for cultivation (10). This situation is exacerbated by soil pollution with toxic substances such as mercury and cyanide, which compromise the fertility of the remaining land (11). As a result, local farmers are unable to maintain sufficient agricultural production, leading to food insecurity for communities dependent on these lands. This loss of arable land also increases competition for agricultural resources, exacerbating land conflicts and social and economic tensions in the affected regions (12). Illegal mining activities destroy the natural habitats of soil microorganisms and invertebrates, which play a crucial role in maintaining soil structure and health (13). This leads to the loss or disappearance of soil biodiversity, decreasing the fertility and productivity of agricultural land. The absence of soil organisms affects nutrient cycles, reduces the soil's capacity to retain water, and increases the land's vulnerability to erosion. As a result, soils become less suitable for crop growth, leading to lower agricultural yields and compromising the food security of local communities. The destruction of subsurface ecosystems also impacts soil resilience to environmental disturbances, thus exacerbating agricultural and economic challenges in affected regions (14). The risks of water pollution related to gold mining practices come from the runoff and infiltration of cyanide and acidic waters as the main sources of contamination. Although the absence of arsenic is reassuring for now, the danger remains with the potential for acid mine drainage, a phenomenon where exposed sulfides generate acids, indicated by a yellowish coloration of the waters. This reaction, as highlighted by (15), is particularly worrying in regions where soils contain sulfide minerals. The variability of soils makes the prediction of this phenomenon complex, requiring specific tests to assess long-term risks and preventive measures. These elements indicate the need for continuous monitoring to protect water resources from irreversible degradation. The main challenges associated with illegal gold mining concern environmental protection, public health, and biodiversity conservation (16). It is crucial to implement integrated management policies that combine the suppression of illegal practices, awareness raising, and the development of economic alternatives for local populations. Strengthened cooperation between governments, international organizations, and local communities is essential to mitigate the environmental and social impacts of illegal gold mining. Soil and water pollution threatens local agricultural practices, compromising food security and the region's environmental balance. Katiola must be given particular attention as part of efforts to stem the impacts of illegal gold mining.

CONCLUSION

The general objective of this work is to assess the environmental impact of illegal gold mining, by identifying the harmful consequences caused by mining activities and proposing mitigation measures.The results obtained revealed a profound change in land use in Katiola between 2014 and 2024, illustrating the impact of human activities, particularly illegal gold mining. Indeed, a

24% reduction in the wooded area was observed across the three sites, falling from 3,033 to 2,019 hectares. The notable damage identified is the degradation of plant cover, stripping, excavation and erosion of soils, destruction of arable land, the disappearance of soil biodiversity and water pollution. In view of the observed impacts, it is imperative to adopt strategies to mitigate the effects of illegal gold mining and promote sustainable soil management. Three areas of action should be prioritized.

- Rehabilitation of degraded land: Backfilling of exploited sites, reforestation, and phytoremediation must be encouraged to restore ecological balance and preserve soil fertility.
- Strengthening the regulatory framework: Strict monitoring of mining activities and the application of dissuasive sanctions are necessary to limit the expansion of illegal gold mining.
- Involvement of local communities: Awareness-raising and the development of sustainable economic alternatives (ecological agriculture, regulated artisanal mining) must be encouraged to provide viable solutions for the population.

Soil and water pollution threatens local agricultural practices, thus compromising food security and the environmental balance of the region. Particular attention must be paid to Katiola as part of efforts to stem the impacts of illegal gold mining.

Compliance withethical standards

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