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Forest landscape degradation, carbon loss and ecological consequences of illegal gold mining in Ghana

Simon Abugre[1], Michael Asigbaase[1*], Samuel Kumi[2], George Nkoah[1] and Austin Asare[2]

*Correspondence:
Michael Asigbaase
michael.asigbaase@uenr.edu.gh
[1]Department of Forest Sciences, University of Energy and Natural Resources, Box 214, Sunyani, Bono Region, Ghana
[2]Department of Environmental Management, University of Energy and Natural Resources, Box 214, Sunyani, Ghana

Abstract

Ghana's recent legalization of mining in forest reserves introduces uncertainties about its impact on forest cover, biodiversity, and carbon stocks, amid already severe environmental degradation driven by illegal artisanal gold mining (galamsey). We analysed forest cover dynamics between 2018 and 2023 in the Oda River Forest Reserve and inventoried data from 12 plots in non-mined and mined (low, moderate and heavily) forest sites for its consequences on biodiversity and carbon stocks. Forest cover declined by 5.9%, shrinking from 16,959.89 ha in 2018 to 15,952.82 ha in 2023, while illegal gold mining expanded astronomically by 1917.6%, increasing from 52.78 ha to 1059.85 ha, with the most rapid expansion occurring between 2022 and 2023. The study revealed significant reductions in plant species richness and diversity across trees, shrubs, and climbers in mined areas, with heavily mined zones exhibiting a complete absence of vegetation. The Shannon diversity index and structural attributes such as tree height and diameter also significantly declined, reflecting the widespread ecological disruption caused by gold mining activities. Non-mined forest sites demonstrated higher biodiversity (S = 13.33, H = 2.41), greater structural complexity, and maintained the highest carbon stocks (689.11 Mg C ha^{-1}), emphasizing their role in mitigating climate change. In contrast, heavily mined forest areas exhibited complete carbon loss, resulting in substantial potential CO_2 emissions (2522.15 tCO_2e). Our results demonstrate the urgent need for effective land management policies, enforcement of mining regulations, and restoration efforts, including reforestation with native species. Addressing mining in forest reserves is critical to preserving biodiversity, mitigating climate change, and ensuring the resilience of forest ecosystems.

Keywords Mining, Forest reserves, Biodiversity, Carbon emission, Land use and land cover changes, Gold

1 Introduction

Forests are among the most valuable ecosystems globally, providing a wide range of ecosystem services essential for human survival and biodiversity conservation [13, 44, 78]. Globally, forests cover about 31% of the Earth's land area, accounting for approximately

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4.06 billion hectares [78]. Forest ecosystems serve as critical carbon sinks, sequestering around 7.6 billion metric tons of carbon annually [65], and houses over 80% of terrestrial species of animals, plants, and fungi [54]. Beyond their role in mitigating climate change, forests support the livelihoods of over 1.6 billion people worldwide and contribute significantly to global food security and water regulation, [10, 13, 34]. Locally, forest reserves in Ghana are pivotal for sustaining biodiversity, regulating microclimates, and providing essential resources for forest-dependent communities [14, 27, 34]. Ghana's forests account for approximately 9.2 million hectares, comprising both on-reserve and off-reserve areas, and are home to several endemic species of flora and fauna [13, 42]. However, despite their ecological and socio-economic importance, forests are increasingly under threat from anthropogenic activities [6, 12, 39, 73].

The threats to forests globally are multifaceted, including agricultural expansion, infrastructure development, logging, and mining [1, 18, 28], Global Forest Watch, 2024). Among these, illegal artisanal mining poses a particularly acute threat due to its capacity to cause irreversible ecological damage [7, 39]. Illegal artisanal mining activities often lead to deforestation, habitat fragmentation, and soil erosion, thereby compromising the structural and functional integrity of forest ecosystems [72]. In Ghana, the situation is no different, with illegal artisanal gold mining emerging as a primary driver of forest loss and ecosystem degradation. Gold mining, particularly in forest reserves, has escalated in recent years, exacerbated by the government's legalization of mining in these protected areas [80]. Additionally, the policy shift has the potential to compound mining-driven forest encroachment, significantly impacting biodiversity and ecosystem services [3, 73, 80].

The environmental impacts of mining extend beyond deforestation. The removal of forest cover leads to the destruction of habitats, resulting in the loss of flora and fauna diversity [19, 23, 60]. Many forest reserves in Ghana, particularly those recognized as biodiversity hotspots, face significant threats from mining activities in general and illegal artisanal mining in particular, while already degraded reserves remain pressured [1, 23, 60, 73]. These reserves host a rich array of plant species, including economically valuable timber and non-timber species. However, severe mining activities disrupt seed dispersal, regeneration processes, and soil nutrient cycles, leading to a decline in plant diversity and the degradation of ecosystem health [19, 23, 26, 28, 56]. At the regional scale, the loss of biodiversity diminishes the resilience of ecosystems to climate change and other environmental stressors, while at the global scale, it contributes to the ongoing biodiversity crisis, with over 1 million species at risk of extinction (Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services [47, 50]).

Another critical consequence of mining in forest reserves, particularly illegal artisanal mining, is its impact on carbon stocks and greenhouse gas emissions [65], Global Forest Watch, 2024). Forests act as major carbon reservoirs, storing approximately 662 gigatons of carbon in their biomass and soil [46, 65], Global Forest Watch, 2024). The destruction of forest cover through mining releases significant amounts of carbon dioxide into the atmosphere, contributing to global warming. In Ghana, deforestation and land-use changes, primarily driven by mining, account for 24% of the country's total greenhouse gas emissions [24, 42], Global Forest Watch, 2024). The loss of carbon stocks not only undermines Ghana's commitments to the Paris Agreement but also threatens the global goal of limiting temperature rise to 1.5 °C above pre-industrial levels (IPCC,

2018). Furthermore, the legalization of mining in forest reserves in Ghana (Environmental Protection—Mining in Forest Reserves—Regulation 2022 (L.I. 2462) highlights critical gaps in policy and research; it is unclear how this policy shift impact biodiversity, carbon stocks and emissions due to illegal artisanal mining. Moreover, while the economic contributions of gold mining are undeniable, the ecological costs have received limited attention [71, 80]. Existing studies have largely focused on deforestation trends, with minimal emphasis on the impacts of mining on biodiversity and carbon stocks [65, 71]. Therefore, the study sought to address these gaps by providing a comprehensive assessment of the impacts of illegal artisanal gold mining on forest cover dynamics, plant diversity, and carbon stocks in Ghana. By integrating ecological, spatial, and carbon accounting approaches, the study aims to generate robust evidence to inform sustainable land-use policies and practices in Ghana.

The findings of this research have broader implications for global environmental goals and development agenda. The study aligns with the African Union's Agenda 2063, which emphasizes sustainable resource management and biodiversity conservation as pillars for achieving a prosperous and environmentally sustainable Africa [4]. It also contributes to the United Nations Sustainable Development Goals (SDGs), particularly Goal 3 (Good Health and Well-being), Goal 13 (Climate Action), Goal 15 (Life on Land), and Goal 12 (Responsible Consumption and Production) [79]. Additionally, the study supports the objectives of the UN Decade on Ecosystem Restoration (2021–2030), which seeks to prevent, halt, and reverse ecosystem degradation worldwide [78]. By examining the ecological impacts of gold mining in forest reserves, this research provides critical insights to guide restoration efforts and promote sustainable land-use development in Ghana and beyond.

2 Materials and methods

2.1 Description of study area

The study was conducted in the Oda River Forest Reserve, located in the Ashanti Region of Ghana. This forest reserve spans an area of 164.43 square kilometers and straddles two political districts: Amansie South and Amansie Central (GSS, 2021) (Fig. 1). Approximately 80% of the reserve lies within the Amansie Central District, whose capital is Jacobu, while the remaining 20% falls within the Amansie South District, with Manso Adubia as its capital (GSS, 2021). The Amansie Central District is located at 6° 06′ 01.0″ N and 1° 53′ 13.4″ W, while the Amansie South District lies at 6° 13′ 58.9″ N and 1° 57′ 02.4″ W. Together, these districts cover a total surface area of approximately 2,074 square kilometers (800.78 square miles), representing about 5.9% of the total land area of the Ashanti Region (GSS, 2021). The Amansie Central and Amansie South Districts benefit from a strategic location within Ghana's forest zone, where the forest plays a crucial role in enhancing the local climate, thereby supporting agricultural production. These districts are predominantly agrarian, providing employment opportunities for a majority of the population both within and beyond their boundaries. In addition to agriculture, they hold significant potential for gold deposits and are home to extensive natural forest vegetation, further contributing to their economic and ecological importance [38].

The predominant vegetation in the Amansie Central and South Districts is semi-deciduous forest, with notable tree species including *Milicia excelsa* (Welw.) C.C.Berg,

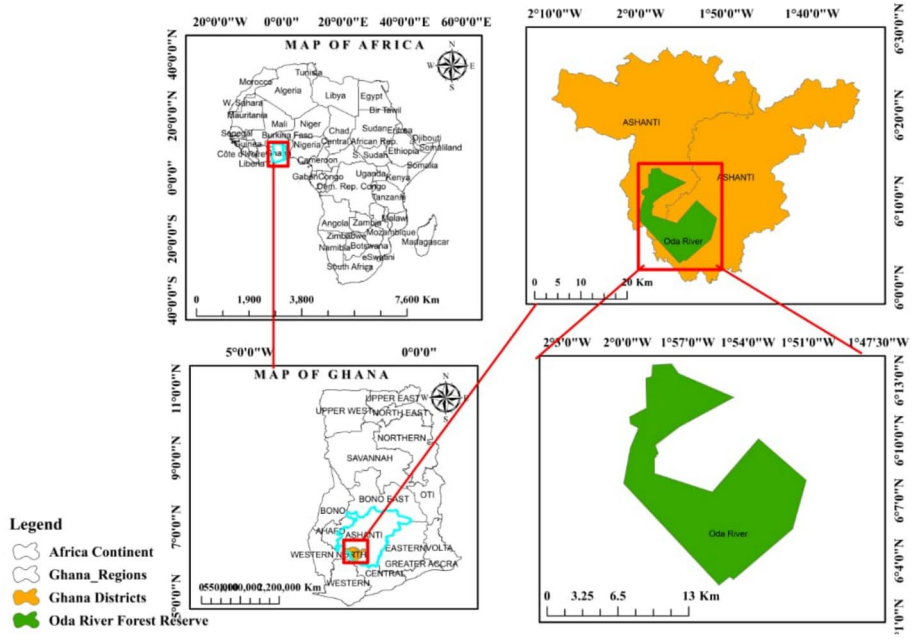


Fig. 1 Map of study area showing the location of Oda River Forest Reserve and bordering districts

Triplochiton scleroxylon K.Schum., *Entandrophragma angolense* (Welw.) C.DC., *Khaya ivorensis* A.Chev. and *Entandrophragma cylindricum* (Sprague) Sprague. The districts are home to two major forest reserves: Oda and Subin. However, the vegetation has been significantly degraded due to human activities such as bushfires, unsustainable logging, and unauthorized gold mining. Consequently, primary forest exists only in scattered patches, while secondary forest has become more widespread [63]. The Oda, Offin, and Fena are the three major rivers in the district, complemented by several seasonal and perennial water bodies. The Offin River flows along the southeastern border, serving as the boundary between the Ashanti and Central Regions. However, anthropogenic activities such as gold dredging and illegal logging along these water bodies have significantly reduced the size of the rivers. These activities not only threaten the ecological health of the rivers but also pose serious environmental and livelihood challenges for the surrounding communities.

2.2 Data collection and processing

The study utilized Sentinel-2A images as the primary remote sensing data, chosen for their high-resolution imagery and extended temporal availability (Table 1; Zhao, 2019). Images from 2018, 2020, 2022, and 2023 were obtained from the European Space Agency (ESA) Sentinel Scientific Data Hub and covered the study area within Landsat path 193 and row 056 (European Space Agency, undated). The periods 2018, 2020, 2022 and 2023 were selected for the study because mining activities started in the Oda Forest Reserve in 2018. Pre-processing corrects for geometric and radiometric distortions associated with the images [16, 27, 70]. The radiometric correction was performed in TerrSet IDRISI using the Dark-object subtraction algorithm to convert the raw DN (digital numbers) values to surface reflectance. The geometric correction was done by projecting all the images onto the UTM zone 30 North projection system. The composite images were clipped to a defined area of interest in ArcMap 10.5. Sentinel-2A's reflective

Table 1 Sentinel 2A and classes of land cover types

Number	Satellite	Acquisition date	Tile Identifier	References
1	Sentinel 2A	2018–01–10	N0510_R065_T30NXN	European Space Agency, undated
2	Sentinel 2A	2020–12–26	N0510_R065_T30NXN	
3	Sentinel 2A	2022–01–04	N0510_R065_T30NXN	
4	Sentinel 2A	2023–08–13	N0510_R065_T30NXN	
Classes of land cover types				
1	Forest: Lands of more than 0.5 hectares, with a tree canopy cover of more than 10 percent, which are not primarily under agricultural or urban land use. It also includes open forest areas			
2	Mined site: A land cover category that includes areas where there are mining activities			

bands, covering visible, near-infrared, and short-wavelength infrared wavelengths, were resampled to a consistent 10 m resolution to ensure uniformity in analysis and enhance classification accuracy.

A supervised Maximum Likelihood Classification (MLC) technique, widely used for land cover studies [16], was employed to classify land cover into two signature classes: forest and mining (Table 1). Training areas were developed by selecting polygons for each class, and training pixels were derived for classification. Band combination (RGB = Shortwave Infrared- Near Infrared -Green or 12-8-3 for Sentinel-2A) was used for enhanced visualization. Classification accuracy was tested using a confusion matrix based on ground truth Regions of Interest (ROIs). Post-processing involved applying a filtering technique to generalize classified images by replacing isolated pixels with the most common neighbouring class [88]. The Kappa coefficient (K) was calculated for each year to assess classification accuracy. This statistic evaluates the agreement between classified and reference data while accounting for random chance [32, 33]. Kappa values range from 0 (chance agreement) to 1 (perfect agreement). Values below 0.4 indicate poor agreement, 0.4–0.55 indicate fair agreement, 0.55–0.7 represent good agreement, 0.7–0.85 indicate very good agreement, and values above 0.85 signify excellent agreement [57, 64]. Figure 2 summarises the workflow.

2.3 Change detection

Change detection was conducted to identify, visualize, and analyze land cover changes within the study area. Pixel-based post-classification techniques were used, as they are widely recognized for their speed, convenience, descriptive nature, and ease of interpretation [76]. The analysis covered four time periods: two years from 2018 to 2020, two years from 2020 to 2022, one year from 2022 to 2023, and five years from 2018 to 2023. Training data were extracted and used to train Maximum Likelihood Classification (MLC) models for each of the four time periods. Feature selection was applied to identify the best-performing models. For consistency, the same training and test samples were used across the different time periods, as the intervals between them were relatively short and closely aligned with the reference data. The trained models were then applied to classify the images, producing land cover maps for each time period. Post-classification filtering was performed to refine the maps while maintaining the original precision. To ensure unique change values for each direction of land cover transition, the classification output of the initial time period was reclassified using the formula: $r = c \times$

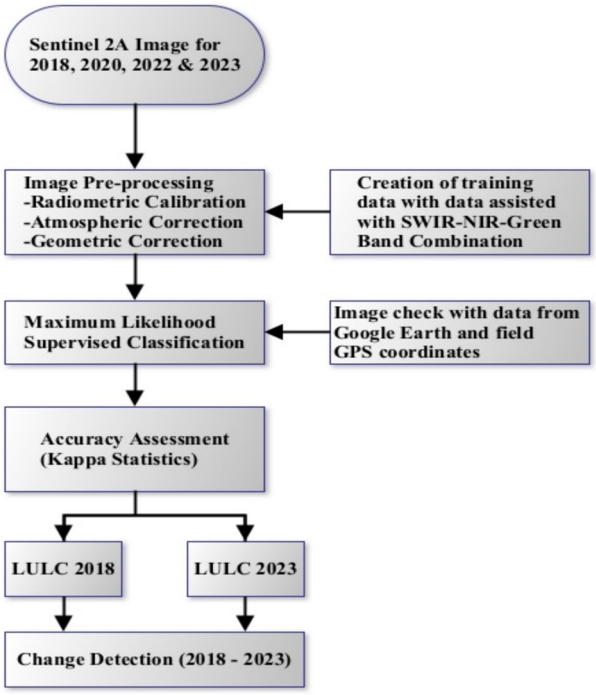


Fig. 2 Methodological flow chart showing the process followed to produce the land use and cover change maps. GPS is Global Positioning System, LULC is land use and land cover change, and SWIR-NIR is shortwave infrared -near infrared

5 + 1, where 'c' represents the initial class, and 'r' is the new class. The newer image was subsequently subtracted from the older image, generating a transition matrix table with unique values for each direction of change. This method provided a detailed and systematic analysis of land cover dynamics, enabling the identification of specific patterns and directions of change over the study period.

2.4 Tree inventory

A systematic approach was employed to assess the diversity of tree species across different mining intensities within compartments 13, 14, and 17. Mining sites in each compartment were categorized into three intensity levels: heavy (where almost all vegetation was removed), moderate (40–70% vegetation removal), and low (less than 40% vegetation removal). Non-mined areas (no vegetation removed), where no mining activity had occurred, were also included as a control. The level of vegetation removal was visually determined by four experts. In each compartment, one plot measuring 25 m × 25 m was established in each of the mined (low, moderate and heavy) and non-mined areas, resulting in a total of 12 plots in the three compartments (i.e. three plots *per* mining intensity). Nested within these main plots were smaller plots measuring 5 m × 5 m and 1 m × 1 m. The main plots (25 m × 25 m) were used to inventory all standing tree species with a diameter at breast height (dbh) greater than 10 cm (e.g. [20]), as well as lianas and climbers. In the 5 m × 5 m nested plots, saplings with a girth between 2 cm and less than 10 cm, as well as shrubs, were inventoried. Seedlings with a girth of at least 2 cm were recorded within the smallest 1 m × 1 m nested plots. Plants were identified to the species level with the assistance of two experienced botanists from the Forestry Commission, an expert field technician from the Council for Scientific and Industrial

Research, and two local informants, following the guidelines provided by Hawthorne and Jongkind [43]. The diameter at breast height (1.30 m above the ground) for all tree species was measured using a diameter tape and recorded. Heights of trees and saplings were estimated using a hypsometer, while the heights of seedlings were measured with a linear tape. Although our plot sizes may limit the interpretation of our findings at larger scales (e.g. regional or sub-regional), such stratified, gradient-based sampling designs are widely used in ecological research to generate robust insights in data-scarce and logistically constrained contexts (Thiele et al., 2023). Our approach aligns with similar studies that have successfully identified meaningful ecological patterns using comparable plot sizes (e.g. [17, 35]).

2.5 Analysis

Species richness was estimated as the number of species *per* plot while plant diversity was assessed via Shannon–Wiener diversity index (Eq. 1).

$$\mathrm{H}' = -\sum_{i=1}^{\mathrm{S}} P_i \ln\left(P_i\right) \tag{1}$$

where H' = Shannon Weiner diversity index, S = number of species, In = natural log, P_i is the proportion of individuals in the sample belonging to the ith species i.e. (n_i/N); n_i = number of the individual of species, and N = importance value index or total number of the individuals of all species.

Aboveground biomass carbon stocks in trees were estimated using Eq. 2 [30] while belowground carbon stocks were estimated based on Eq. 3 (Cairns et al. 1997). To estimate species-specific wood densities, we sourced data from global databases, including the Global Wood Density Database and the World Agroforestry Centre's repository [29, 81]. In instances where a tree species was absent from these databases, we adopted a hierarchical imputation approach: first, by assigning the mean wood density of congeneric tree species present within the same plot, and where no congeners were available, by applying the mean wood density of all tree species recorded in that plot, consistent with methods employed in similar ecological assessments [20]. This imputation applied to fewer than 3% of the total tree species, thus minimally influencing overall estimates. The estimated biomass was converted to carbon stock by multiplying by 0.47 (IPCC, 2006). To estimate carbon dioxide emissions resulting from mining, we calculated the difference in mean carbon stocks between non-mined and mined sites and multiplied this value by the molecular conversion factor of 44/12 to convert carbon loss (in tonnes of C) into potential carbon dioxide emissions (in tonnes of CO_2), following IPCC conventions for carbon accounting [48, 49].

$$\mathrm{AGB}_{\mathrm{est}} = 0.0673 \times \left(p\mathrm{D}^2\mathrm{H}\right)^{0.976} \tag{2}$$

where AGB is aboveground biomass (kg), p is wood density (g cm^{-3}) and DBH is diameter at breast height (cm) and H is total height (m).

$$\mathrm{BGB} = \exp\left(-1.085 + 0.926 * \ln\left(\mathrm{AGB}\right)\right) \tag{3}$$

To assess the impact of mining on plant diversity, carbon stocks and potential carbon emission, a one-way ANOVA was conducted followed by a Tukey post hoc test. Mean values were considered significant at $\alpha = 0.05$.

3 Results

3.1 Impact of mining on forest cover dynamics between 2018 and 2023

The classification results demonstrate a high level of reliability, with overall accuracies consistently exceeding 86%, signifying strong agreement between classified and reference data (Table 2). Both the producer's and user's accuracy for all land-use classes across all years exceeded 0.60 while the Kappa coefficient, which quantifies classification agreement beyond chance, ranged from 0.81 to 0.88, indicating a strong level of agreement. The overall classification accuracy was recorded for the 2018 period was 91%, followed by 2020 (90%), 2022 (89%), and 2023 (86%), reflecting a consistently high classification performance across the years.

The results of this study highlight the significant impact of gold mining on land use and land cover (LULC) dynamics in the Oda River Forest Reserve between 2018 and 2023 (Fig. 3a and b). Over the five-year period, forest cover experienced a steady decline, reducing from 16,959.89 ha in 2018 to 15,952.82 ha in 2023, representing a total loss of 5.9% (Tables 3 and 4). In contrast, mining areas expanded dramatically from 52.78 ha in 2018 to 1,059.85 ha in 2023, reflecting an alarming 1,917.6% increase. The most rapid expansion of mining activities occurred between 2022 and 2023, emphasizing the intensifying pressure on forest resources. These findings underscore the dual threats of deforestation and biodiversity loss posed by mining activities, which continue to drive significant land cover changes in the reserve.

3.2 Impact of mining on plant community structure and diversity

The results demonstrate that mining activities drastically reduced plant species richness across various plant categories, with heavily mined areas exhibiting a complete absence of plant species (Fig. 4). This was particularly evident for trees, where non-mined areas had the highest species richness (mean = 13.33, SEM = 0.96) compared to low and moderate mining areas, which showed intermediate richness values (mean = 8.00 and 2.67, respectively). For shrubs, non-mined areas exhibited the highest species richness (mean = 5.33, SEM = 0.16), while low mining areas had lower richness (mean = 4.00, SEM = 0.27), and heavily and moderately mined areas recorded no shrub species. A similar trend was observed for liners and climbers, where non-mined areas had a mean species richness of 6.33 (SEM = 0.68), while low mining areas exhibited reduced richness (mean = 1.67, SEM = 0.79). Heavily and moderately mined areas consistently recorded no species for all plant categories. These findings highlight the severe ecological disruption

Table 2 Accuracy assessment for the classified image

	2018		2020		2022		2023	
LULC Categories	PA	UA	PA	UA	PA	UA	PA	UA
Forest	0.91	0.84	0.97	0.76	1	0.72	1	0.6
Mining	0.93	0.8	0.91	0.84	0.91	0.82	0.89	0.82
Overall Accuracy	0.91		0.9		0.89		0.86	
Kappa	0.88		0.87		0.85		0.81	

NB: PA Producer accuracy, *UA* User accuracy, LULC = Land use and land cover

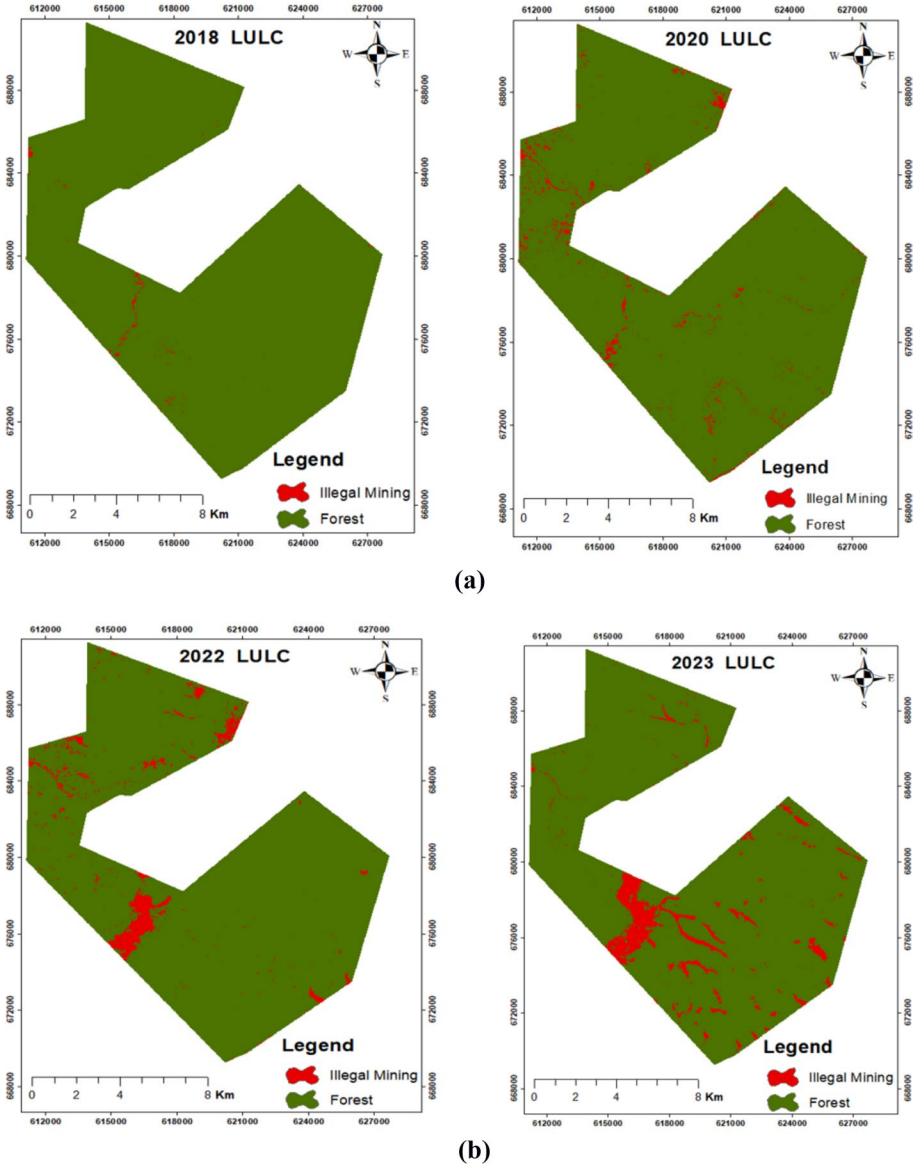


Fig. 3 **a** Land use and land cover (LULC) classes maps for the period 2018 and 2020 **b** Land use and land cover (LULC) classes maps for the period 2022 and 2023

Table 3 Distribution of land use and land cover (LULC) categories (in ha) and the annual rate of change in 2018, 2020, 2022, and 2023

LULC	Mining (ha)	Forest (ha)
2018	52.78	16,959.89
2020	348.76	16,663.91
2022	689.23	16,323.44
2023	1059.85	15,952.82
2018–2020 (%)	1.7	− 1.7
2020–2022 (%)	2.0	− 2.0
2022–2023 (%)	2.2	− 2.2
2018–2023 (%)	5.9	− 5.9

Table 4 Change Detection (ha) matrix showing LULC changed patterns from 2018 to 2023

		2023			
		Mining	Forest	Initial total	Gross loss
2018	Mining	32.82	19.96	52.78	19.96
	Forest	1027.03	15,932.86	16,959.89	1027.03
	Final total	1059.85	15,952.82	17,012.67	
	Gross gain	1027.03	19.96		
	Net Change	1007.07	− 1007.07		

2018–2023

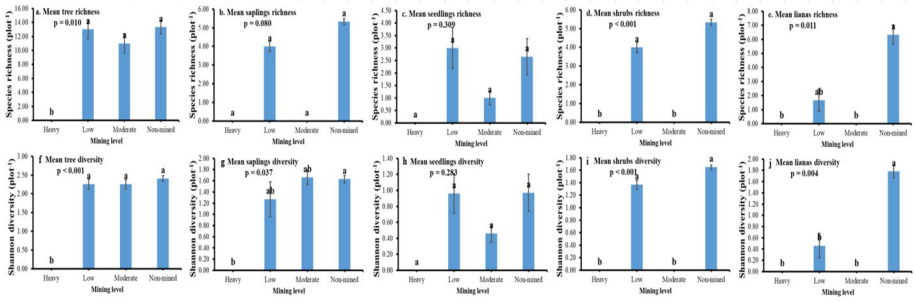


Fig. 4 Species richness and diversity of plant categories across the different mining intensities

caused by mining, as mining activities result in the destruction of habitats necessary for supporting plant communities.

The Shannon diversity index, a measure of species diversity that considers both abundance and evenness, was significantly lower in mined areas across all plant categories (Fig. 4). For trees, non-mined areas recorded the highest Shannon index (mean = 2.41, SEM = 0.07), while heavily mined areas had zero, indicating a complete loss of plant species diversity. Similarly, for shrubs, non-mined areas exhibited a Shannon index of 1.65 (SEM = 0.03), while low mining areas had a reduced index of 1.37 (SEM = 0.07). Heavily and moderately mined areas recorded no diversity for shrubs. Liners and climbers also showed significant reductions in diversity, with non-mined areas achieving the highest Shannon index (mean = 1.78, SEM = 0.11). Low mining areas exhibited reduced diversity (mean = 0.46, SEM = 0.22), while heavily and moderately mined areas had no diversity. Taken together, our results indicate that even low-intensity mining activities reduce species diversity, while heavy and moderate mining activities lead to complete ecosystem homogenization (Fig. 4).

Gold mining significantly impacted the structural attributes of plants, including height and diameter, across all categories (Fig. 5). Trees in non-mined areas were taller (mean height = 19.88 m, SEM = 0.44) and the larger in size (mean DBH = 45.32 cm, SEM = 2.08). Moderate and low mining areas showed reduced height and DBH values, with moderate mining areas having the highest DBH (mean = 50.40 cm) and low mining areas showing a mean DBH of 26.05 cm. Heavily mined areas recorded no trees, highlighting the severe disruption caused by mining activities. However, shrubs in non-mined areas were taller (mean height = 3.00 m, SEM = 0.33) and larger in size (mean = 2.84 cm, SEM = 0.30). Low mining areas exhibited reduced height and DBH values (mean height = 2.02 m, SEM = 0.15; mean DBH = 2.00 cm, SEM = 0.09), while heavily and moderately mined areas had no shrubs. Liners and climbers followed a similar pattern, with non-mined areas having the tallest individuals (mean height = 42.60 m, SEM = 6.12) and the largest

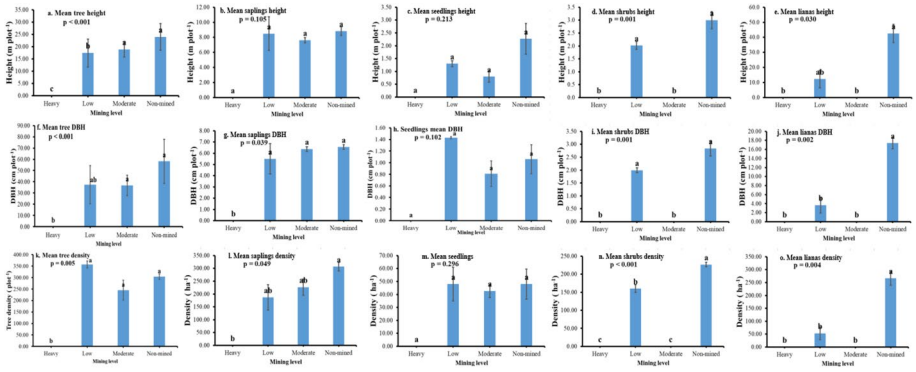


Fig. 5 Structural characteristics of different plant categories across different mining intensities

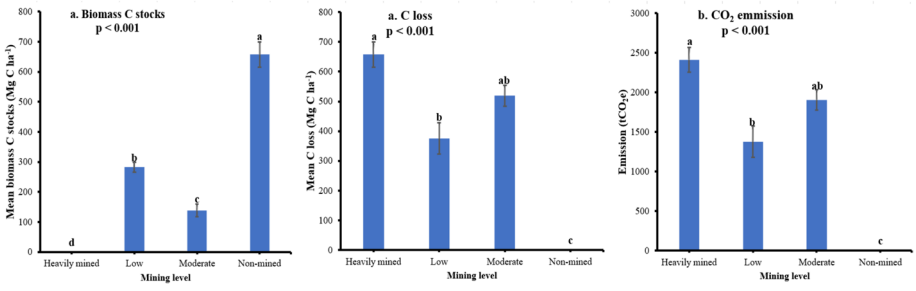


Fig. 6 Potential CO_2 emission across mined sites compared to non-mined sites

DBH (mean = 17.43 cm, SEM = 1.26). Low mining areas exhibited intermediate values (mean height = 12.30 m, SEM = 5.81; mean DBH = 3.67 cm, SEM = 1.73), while heavily and moderately mined areas recorded no individuals.

3.3 Potential CO_2 emission across mined and non-mined forest landscape

The study presents a clear positive correlation between the intensity of mining and the associated carbon emissions. The results indicated that non-mined areas had the highest mean total carbon (C) stock at 657.4 ± 42.4 Mg C ha^{-1}, with no carbon loss or emissions (Fig. 6). Conversely, heavily mined areas showed a complete loss of carbon stock, resulting in the emission of 2411.0 ± 155.3 tCO_2e. Moderate and low mining intensities also resulted in substantial carbon losses and emissions, albeit to a lesser extent than heavy mining. Specifically, compared to heavily mined sites, moderate mining resulted in 26.7% less carbon loss and potential emissions *per* hectare, while low mining resulted in 75.0% less carbon loss and potential emissions *per* hectare.

4 Discussion

4.1 Impact of gold mining on forest cover dynamics

The high overall accuracy (0.86–0.91) and Kappa coefficients (0.81–0.88) demonstrates the model's strong ability to differentiate between mining and forest areas– critical for assessing environmental change in the study landscape [33, 41, 53]. The fact that the producer's and user's accuracies for all LULC classes consistently exceeded 0.6 across the years, indicated that the classification model effectively distinguished between different site-use types with a high degree of reliability [61, 68].

The observed trends in loss of forest cover align with previous studies that have documented the environmental degradation caused by mining in Ghana [9, 51, 89]. For instance, Obodai et al. [89] reported extensive deforestation and habitat loss in mining-affected areas, with forest reserves becoming focal points for gold mining activities due to their rich mineral deposits. Similarly, Asner et al. [21] highlighted that gold mining in tropical forest regions, including Ghana, has resulted in widespread deforestation, habitat fragmentation, and soil degradation. Furthermore, the progressive deforestation observed aligns with global patterns where illegal mining has been identified as a primary driver of forest loss and biodiversity depletion, particularly in tropical regions [6, 21, 39]. It further mirrors findings in the Amazon rainforest, where mining activities have similarly resulted in extensive deforestation and habitat fragmentation [72]. The economic profitability of artisanal and small-scale gold mining, coupled with high global demand for gold, is a significant motivating factor for these activities [89, 90]. Advances in mining technology have further enabled deeper and more extensive exploitation of forested areas, exacerbating the problem [74, 75]. The observed trends of deforestation between 2018 and 2023 may also point to a spillover effect whereby displaced farmers clear additional forested areas for agricultural expansion, compounding the deforestation problem. Studies by Amponsah et al. [9] in the Atewa Range Forest Reserve reported that mining activities displaced farming communities, triggering agricultural intensification and further forest loss. This underscores the interconnectedness of land use practices and the cascading effects of mining on agricultural systems and forest ecosystems.

The significant loss of forest cover has profound ecological implications on carbon sequestration, water regulation, soil fertility, and habitat for diverse flora and fauna [31]. The reduction in forest area by 5.9% over the study period potentially compromises these essential services and exacerbates climate change impacts. Furthermore, the fragmentation of wildlife habitats and the disruption of ecological corridors significantly affect biodiversity [59]. Studies have shown that habitat fragmentation limits species movement, reduces genetic diversity, and increases vulnerability to extinction [52]. In the Oda River Reserve, such fragmentation likely hampers wildlife migration and ecosystem resilience. Besides, the removal of vegetation and topsoil for mining exacerbates land degradation through soil erosion, compaction, and the formation of gullies, which collectively diminish land productivity [62].

Interestingly, Ghana's recent decision to legalize mining in forest reserves adds a complex dimension to these findings. While legalization aims to regulate mining activities and ensure environmental accountability, it also raises concerns about the potential intensification of forest exploitation [9]. Miners may interpret the policy as tacit approval of forest exploitation and without stringent environmental safeguards, such mining activities may accelerate forest loss, biodiversity decline, and disruption of ecosystem services, such as carbon sequestration and water regulation [7, 8, 52, 89]. Studies in similar contexts have shown that weak enforcement of regulations can lead to both legal and illegal mining coexisting, with overlapping negative impacts on ecosystems [21, 92]. If mining in forest reserves is to be sustainable, it must be accompanied by effective land management strategies, strict compliance monitoring, and significant investments in reforestation and habitat restoration. Community participation in decision-making

processes is crucial to ensuring that mining activities do not undermine conservation efforts or disrupt the livelihoods of local populations [90, 92].

4.2 Impact of gold mining on plant community structure and diversity

The findings demonstrate the severe ecological impacts of illegal mining on plant diversity and forest structure, highlighting significant declines across all plant categories, including trees, saplings, seedlings, shrubs, and climbers (Figs. 4 and 5). The absence of species richness and the complete lack of plant density in heavily mined areas exemplify the destructive nature of mining activities on forest ecosystems [39]. This aligns with previous studies that have documented similar outcomes, where mining operations result in deforestation, habitat destruction, and biodiversity loss [40, 45]. The stark contrast between heavily mined and non-mined areas underscores the disruptive extent of mining on forest ecosystems, with non-mined areas consistently exhibiting higher species richness, density, and diversity indices [58].

The Shannon index, a key measure of species diversity, highlighted the significant ecological imbalance caused by illegal mining. Non-mined areas recorded significantly higher Shannon index values across all plant categories, indicating greater species heterogeneity and ecological stability (Figs. 4 and 5). In heavily mined areas, the Shannon index dropped to zero for trees, saplings, and climbers, reflecting a complete loss of biodiversity. This pattern is consistent with findings from other studies that emphasize the homogenization of plant communities and the loss of ecological balance in mining-affected regions (Attuquayefio et al., 2005; Essandor et al., 2019; [50]). The significant reduction in tree density from 304.30 trees/ha in non-mined areas to zero in heavily mined areas further illustrates the magnitude of habitat destruction. These results corroborate earlier studies that have reported similar trends in mining-impacted areas, where vegetation loss is a direct consequence of large-scale deforestation and soil degradation [56, 67].

Gold mining activities also severely impacted the regenerative capacity of the forest, as evidenced by the absence of saplings and seedlings in heavily mined areas (Fig. 4). This finding is alarming, as it indicates a long-term disruption of natural regeneration processes. Saplings and seedlings are critical to the recovery and sustainability of forest ecosystems, and their absence in heavily mined areas suggests a collapse in ecological succession. Studies by Attuquayefio and Fobil [22] and Amuah et al. [11] have similarly shown that mining activities disrupt soil structure and nutrient availability, inhibiting plant growth and regeneration. The reduced DBH and height of saplings and shrubs in mined areas further emphasize the detrimental impact of mining on plant growth and maturity. Soil compaction, a common consequence of mining activities, likely contributed to these reductions by limiting root growth, water infiltration, and nutrient uptake [45, 55]. Moreover, the physical processes involved in mining, such as heavy machinery use and soil excavation, lead to the destruction of topsoil and the loss of essential soil microorganisms. These changes impair the forest's ability to support diverse plant communities and regenerate naturally [2, 40].

The negative effects of mining extended to shrubs and climbers (Figs. 4 and 5), which play vital roles in maintaining forest structure and biodiversity. The significant reduction in shrub density and height in mined areas highlights the extent to which mining disrupts forest ecosystems. Shrubs are essential for soil stabilization and habitat provision,

and their decline can lead to increased soil erosion and loss of ecosystem services [11, 36, 50]. Similarly, the complete absence of climbers in heavily mined areas underscores the severe ecological disruption caused by mining. Climbers rely on biotic interactions, such as seed dispersal and pollination, which are often disrupted by the removal of key plant and animal species in mining-affected areas [50, 66]. This disruption of ecological networks further compounds the loss of biodiversity and ecological functionality.

4.3 Potential impact of illegal mining on CO_2 emission

The results (Fig. 6) clearly illustrate the destructive impact of mining in forest reserves on carbon sequestration. Forests in non-mined areas maintain high carbon stocks, which are crucial for mitigating climate change. When these forests are disturbed by mining activities, the carbon stored in biomass is released back into the atmosphere, contributing significantly to greenhouse gas (GHG) emissions. This phenomenon is supported by numerous studies that highlight deforestation and land-use change as major sources of CO_2 emissions [25]. The carbon emissions resulting from illegal mining in the Oda River Forest Reserve align with findings from other regions experiencing similar activities. For instance, Rudel et al. [69] discuss how deforestation from mining and agriculture in the Amazon Basin contributes to regional and global CO_2 emissions. Similarly, Asner et al. [21] document the high carbon losses associated with gold mining in the Peruvian Amazon, noting significant reductions in forest carbon stocks and increased CO_2 emissions. The carbon stock density of Ghanaian forests ranged from 304 to 835 Mg C ha^{-1} in closed forests and 248–568 Mg C ha^{-1} in open forests [8], this translates to potential carbon loss upon heavy mining. When trees are felled, the carbon stored in their trunks, branches, and leaves is oxidized and released as CO_2. Additionally, soil disturbance from mining activities can release soil organic carbon (SOC), further exacerbating emissions [37]. This dual release from both biomass and soil underscores the severe impact of illegal mining on carbon dynamics. The Intergovernmental Panel on Climate Change (IPCC) emphasizes the importance of maintaining forest cover to mitigate climate change [49]. The significant carbon losses documented in this study highlight the need for urgent measures to curb illegal mining and protect forest ecosystems.

4.4 Implications for regional and global sustainable development goals

We acknowledge that the spatial scale of our study may limit the spatial representativeness of our findings. However, the observed loss of 1,007.07 hectares of forest in the Oda River Forest Reserve over a five-year period represents a concerning reduction in the area's carbon sink capacity. Continued forest degradation, as demonstrated in this study, may potentially compromise not only local and regional climate resilience but also undermine progress toward SDG 13, which calls for urgent action to combat climate change and its impacts. Beyond climate implications, the 5.9% decline in forest cover and the rapid 1917.6% expansion in mining activities highlight serious ecological concerns. These land cover changes suggest widespread habitat fragmentation, potential species loss, and a disruption of ecosystem functions– issues that directly contravene targets 15.1 and 15.2 of SDG 15 [73, 79]. These targets emphasize the conservation of terrestrial ecosystems and the sustainable management of forests. Consistent with the findings of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) (2019), habitat degradation remains among the most significant

drivers of biodiversity loss globally. The mining-induced deforestation documented in this study exemplifies these threats and reinforces the need for immediate environmental governance and restoration interventions.

Furthermore, the unsustainable expansion of mining within a designated forest reserve reflects not only escalating local socio-economic pressures but also systemic governance and policy implementation failures [3, 73]. The African Union's African Mining Vision (AMV) advocates for the transparent, equitable, and sustainable management of mineral resources to support inclusive development (African [5]). However, the current LULC trajectory in the Oda River Forest Reserve suggests a significant disconnect between the principles outlined in the AMV and actual practices on the ground. Weak enforcement of environmental regulations and inadequate land-use planning have likely contributed to the unchecked spread of mining activities at the expense of ecological integrity [3, 77].

Nevertheless, the study's findings also align with the priorities of the UN Decade on Ecosystem Restoration (2021–2030), which identifies the rehabilitation of degraded landscapes—including mining-affected areas– as essential to reversing global ecosystem decline [78]. As highlighted by Aronson et al. [15], restoration strategies such as reforestation, soil rehabilitation, and watershed management are critical tools for restoring ecosystem functionality. The case of the Oda River Forest Reserve underscores the urgent need to implement such frameworks to halt further degradation and support long-term ecological recovery.

5 Conclusions

The findings of this study demonstrate the ecological consequences of gold mining on forest cover, biodiversity, and carbon dynamics. Over the five-year period from 2018 to 2023, forest cover declined significantly, with a total loss of 5.9%, while mining areas expanded by 1,917.6%. These changes illustrate the dual threats of deforestation and environmental degradation posed by mining activities. Heavily mined areas were devoid of tree, shrub, and climber species, while non-mined areas maintained significantly higher species richness and diversity. Even in areas with low or moderate mining activity, significant reductions in plant abundance and diversity were observed, pointing to the pervasive impact of mining on forest ecosystems. Such biodiversity loss has far-reaching implications for ecosystem functionality, resilience, and the provision of critical services, including habitat provision and soil stabilization. The structural integrity of forest vegetation was also significantly affected by mining activities. Non-mined areas demonstrated significantly higher tree height and diameter at breast height (DBH), reflecting healthier and more mature forests capable of supporting diverse flora and fauna. In contrast, mined areas exhibited reduced structural attributes, with heavily mined areas entirely devoid of vegetation. This loss of structural complexity compromises the forest's ability to sequester carbon, regulate water cycles, and sustain wildlife populations, further exacerbating the environmental consequences of mining. Furthermore, mined areas showed substantial to complete carbon loss and significant potential CO_2 emissions which emphasize the need for urgent action to address mining challenges and restore degraded landscapes. The documented trends are in direct conflict with the goals of SDG 13 (climate action), SDG 15 (life on land), the UN Decade on Ecosystem Restoration, and the AU Agenda 2063. We concluded that mining in forest reserves threatens biodiversity and climate change mitigation via carbon sequestration.

To balance development with sustainability, we recommend enforcing strict no-mining zones within forest reserves, requiring pre-approved ecological restoration plans, and supporting community-led reforestation and monitoring efforts. Restoration efforts, including reforestation with native species and soil rehabilitation, are critical to restoring biodiversity and ecosystem functionality.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1007/s44415-025-00020-5.

Supplementary file1.

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Author contributions
MA; conceptualization, project administration, investigation, data curation, formal analysis, methodology, software, visualization, writing- original draft, supervision, writing–review and editing, and validation. SA: methodology, writing—review and editing, supervision, and project administration. SK: writing—review and editing, validation, visualization, and project administration. GN: resources, conceptualization, methodology, investigation, and writing- original draft. AA: methodology, formal analysis, writing—review and editing, and visualization.

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Data is provided within the manuscript or supplementary information files.

Declarations

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