Spatial Analysis of Mining Intensity in Buffer Zones of Protected Areas of the Ecuadorian Amazon

Henry Lojan-Tenesaca[1], Isabel Adriana Chuizaca-Espinoza[2,3], Andrés Velástegui-Montoya[1,3], Paulo Escandón-Panchana[4,5], Fabiola D. Yépez-Rincón[6], Kevin Rodriguez González[6]

[1] Faculty of Engineering in Earth Sciences, ESPOL Polytechnic University, Guayaquil, Ecuador – henlojan@espol.edu.ec
[2] Earth Observation and Geoinformatics Division, National Institute for Space Research (INPE), São José Dos Campos, Brazil – isabel.espinoza@inpe.br
[3] Laboratory of Geoinformation and Remote Sensing, Faculty of Engineering in Earth Sciences, ESPOL Polytechnic University, Guayaquil, Ecuador – dvelaste@espol.edu.ec
[4] Departamento de Ingeniería Cartográfica y Topografía, Universidad Politécnica de Madrid (UPM), Madrid, Spain – pc.escandon@alumnos.upm.es
[5] Escuela de Ciencias Ambientales, Universidad Espíritu Santo, Samborondón, 0901952, Ecuador
[6] Universidad Autónoma de Nuevo León, Faculty of Civil Engineering, Department of Geomatics, San Nicolás de los Garza, Nuevo León, México – (fabiola.yepezrn, krodriguezge)@uanl.edu.mx

Keywords: Ecuadorian Amazon, Mining Pressure, Gold Mining, Spatial Analysis, Kernel Density Estimation, Environmental Governance.

Abstract

The Zamora Chinchipe province, in the Ecuadorian Amazon, concentrates 18% of the country's continental protected areas and simultaneously records the highest intensity of gold mining activity in the Amazonian region, creating a critical tension between conservation and extraction. This study evaluates the spatial distribution and intensity of mining activity, expressed in mining points/km², in the buffer zones of six protected areas of the National System of Protected Areas (SNAP) in Zamora Chinchipe, through the integration of MapBiomas Ecuador 2023 land use and land cover maps, produced at 30 m spatial resolution via Random Forest classification, and the application of the Kernel Density Estimation (KDE) method in a GIS environment. The MapBiomas mining class, validated with an overall accuracy exceeding 85% for Ecuador, captures surface disturbance associated with artisanal and small-scale gold mining at landscape scale, providing a reliable and replicable input for spatial pressure analysis. The results reveal that 89% of medium and high-intensity hotspots are located less than 500 m from permanent water bodies, demonstrating the strong hydrographic dependence of alluvial mining. Significant differences are identified according to governance model: state-administered areas such as Podocarpus National Park and Cerro Plateado Biological Reserve show the highest mining intensities, while territories under local or community management such as Yacuambi and Tiwi Nunka record minimal pressures. This study demonstrates the potential of open-access satellite data and spatial analysis as accessible and replicable tools for guiding conservation policies in the face of mining expansion in the Ecuadorian Amazon.

1. Introduction

The Amazon represents one of the most biodiverse ecosystems on Earth and plays a fundamental role in global climate regulation, the maintenance of the hydrological cycle, and the provision of essential ecosystem services for human well-being (Albert et al., 2023; Flores et al., 2024). However, in recent decades, growing anthropogenic pressures such as agricultural expansion, industrialization, and population growth have intensified environmental degradation, promoting forest cover loss and increasing carbon emissions (Moulatlet et al., 2023). Among extractive activities, mining stands out as one of the main forces of territorial transformation and a primary source of metals and minerals worldwide (Mestanza-Ramón, Jiménez-Oyola, et al., 2023; Souza-Filho et al., 2020). Nevertheless, its expansion in the Amazon has generated significant environmental and social impacts including deforestation, landscape fragmentation, contamination of water bodies, and hydromorphological alteration of rivers, in both large-scale industrial operations and artisanal mining (Siqueira-Gay et al., 2020). These dynamics have made mining one of the main threats to the ecological integrity of the region and to local communities that depend directly on its natural resources.

The Andean-Amazonian region of Ecuador faces a growing tension between the conservation of high-biodiversity ecosystems and the expansion of extractive activities, primarily Artisanal and Small-Scale Gold Mining (ASGM) (Álvarez-Berríos et al., 2021). The province of Zamora Chinchipe represents a case of this contradiction: it concentrates more than 600,000 hectares under state and community protection regimes, representing approximately 18% of the total protected areas of continental Ecuador, while simultaneously recording the highest intensity of diesel consumption associated with heavy machinery in the country, with a monthly average of 741 gallons per vehicle, compared to the national average of 190 gallons in 2024 (Cortinhas Ferreira Neto et al., 2024). This paradox demonstrates the magnitude of the extractive pressure exerted on the boundaries and buffer zones of ecosystems that are strategically important for conservation.

Gold mining in the Ecuadorian Amazon is not a recent phenomenon. For generations, local communities have practiced artisanal gold extraction as an economic subsistence strategy, configuring a historical and complex relationship between human systems and natural resources (Mestanza-Ramón, Cuenca-Cumbicus, et al., 2022). However, over the past two decades, the intensification and mechanization of gold mining, driven by the sustained increase in international gold prices and the greater availability of heavy machinery, have profoundly modified the scale and nature of environmental impacts (Mestanza-Ramón, Mora-Silva, et al., 2022). This process has transformed a traditional low-impact practice into a significant driver of deforestation, hydrological alteration, and ecological degradation, with increasingly evident social and territorial repercussions.

https://doi.org/10.5194/isprs-archives-XLIX-B3-2026-995-2026

In response to these pressures, the Ecuadorian state has established a legal framework aimed at environmental protection. The Constitution of the Republic of Ecuador (2008) and the Organic Environmental Code (COA) (2017) established the National System of Protected Areas (SNAP) as a key instrument to guarantee the conservation of biodiversity and ecosystem services. In this context, the COA defines buffer zones as spaces adjacent to protected areas designed to mitigate the negative impacts of human activities (Constitución de la República de Ecuador, 2008; Código Orgánico Del Ambiente, 2017). However, Ecuadorian regulations provide the legal framework for the creation of buffer zones but still require strengthening of uniform technical criteria to guide their delimitation and management. The clear definition of these parameters would optimize territorial planning, improve the effectiveness of environmental control measures, and strengthen the conservation of Amazonian ecosystems. In provinces with high extractive dynamics such as Zamora Chinchipe, advancing toward more precise technical regulation represents a key opportunity to consolidate sustainable territorial planning.

Despite growing evidence of mining expansion in Amazonian territories, a significant gap persists in studies that systematically evaluate the intensity and spatial distribution of mining pressures, especially in the buffer zones of protected areas (Lapola et al., 2023). In the Ecuadorian case, most research on mining impacts has focused on specific analyses related to heavy metal contamination (Jiménez-Oyola et al., 2023) or the quantification of deforestation associated with mining activity (Rivera-Parra et al., 2021), without integrating a spatial vision that allows understanding the patterns of concentration and expansion of these pressures. The development of comprehensive studies on mining dynamics in the Amazon would strengthen the capacity of decision-makers to anticipate and mitigate cumulative impacts on ecosystems. Having this information would facilitate the formulation of more effective territorial planning and conservation policies, based on scientific evidence and oriented toward the ecological and social sustainability of the region.

In this context, geospatial monitoring through remote sensing and Geographic Information Systems (GIS) presents itself as an essential tool for evaluating the spatio-temporal dynamics of mining activity and its effects on vegetation cover (Borja et al., 2020; Escandón-Panchana et al., 2025). The growing availability of open-access satellite databases, such as those developed by MapBiomas, offers a valuable opportunity to perform long-term comparative analyses, detect land use changes, and generate environmental pressure indicators (Souza et al., 2020; Benítez-Ramírez et al., 2026). Likewise, the application of spatial density analysis techniques, such as the Kernel Density Estimation (KDE) method, allows the identification of critical zones of mining concentration, providing strategic inputs for environmental planning, territorial control, and the prioritization of restoration and conservation actions (Zhang et al., 2017). These geospatial tools help fill a methodological and operational gap in Amazonian environmental management, strengthening the integration between science, technology, and public policies. Within this framework of challenges and opportunities, the following research questions emerge: 1) How is mining intensity spatially distributed in the buffer zones of protected areas in Zamora Chinchipe? 2) Where are the hotspots or areas of greatest mining activity concentration?; 3) Which protected areas show greater vulnerability to mining expansion in their buffer zones?

This study aims to evaluate the intensity and spatial distribution of mining activity in the buffer zones of protected areas in the province of Zamora Chinchipe, with open-access satellite data from MapBiomas and KDE techniques, for the identification of mining pressure, contribution to sustainable management, and the conservation of Amazonian ecosystems.

2. Study Area

The study area encompasses the buffer zones of six protected areas located in the province of Zamora Chinchipe, in the southern Ecuadorian Amazon (Figure 1).

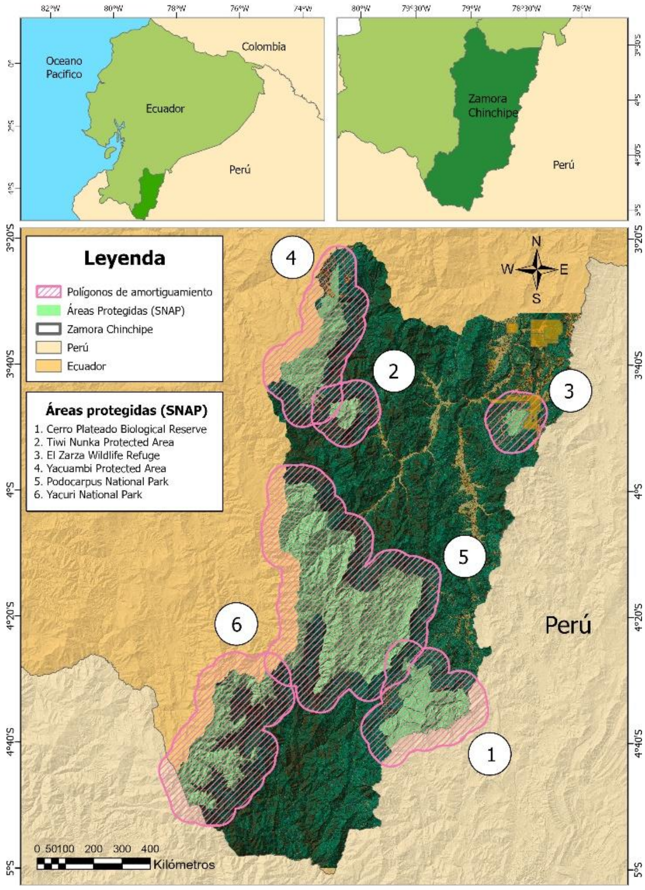

Figure 1. Study area showing six SNAP protected areas in Zamora Chinchipe province and their respective 5 km buffer zones.

With an approximate area of 10,584 km², the province is characterized by its strategic location in the Eastern Cordillera of the Andes, where a marked altitudinal gradient, ranging between 800 and 3,800 m.a.s.l., generates notable ecological heterogeneity, with the presence of humid montane forests and piedmont Amazonian forests (FAO, 2024; Quizhpe et al., 2019).

The humid subtropical climate predominates in the region, with annual precipitation between 2,000 and 4,000 mm and average temperatures of 18 to 24 °C, modulated by altitude (GAD Provincial de Zamora Chinchipe, 2015). The rugged topography, typical of the eastern cordillera, forms deep valleys and steep slopes, with the western foothills of the Cóndor and Tzunantza mountain ranges standing out as areas of more rugged relief (Balchin & Toyne, 1998; Freile et al., 2014).

Zamora Chinchipe province contains six protected areas belonging to the SNAP, under different management categories: Podocarpus National Park, Cerro Plateado Biological Reserve, Yacuri National Park, El Zarza Wildlife Refuge, Yacuambi Protected Area, and Tiwi Nunka Community Area. This study focuses on the buffer zones of these six protected areas, which together represent approximately 600,000 hectares under state, provincial, and community conservation regimes, equivalent to 18% of the total protected areas of continental Ecuador. These transition zones fulfill a strategic ecological role, acting as protection barriers against anthropogenic pressures and as biological corridors that facilitate connectivity between Andean and Amazonian ecosystems. Their analysis is essential for understanding the spatial dynamics of mining activities and their influence on ecosystems of high biodiversity and endemism.

3. Methodology

The methodology of this study integrates remote sensing, GIS, and spatial statistical analysis tools to characterize the intensity and geographic distribution of mining in the buffer zones of six protected areas in the province of Zamora Chinchipe. The methodological approach was structured in three phases: (i) acquisition and processing of geospatial data, (ii) spatial analysis of mining intensity using KDE, and (iii) identification and interpretation of critical mining pressure zones. This approach allows understanding the spatial patterns of mining activity in territories of high ecological sensitivity.

3.1 Data Acquisition and Processing

This phase used two main sources of geospatial information. The official boundaries of SNAP protected areas in Zamora Chinchipe province were downloaded from the Geoportal of the Ministry of Environment, Water and Ecological Transition (MAATE), which provides the updated official delimitation of conservation areas (Ministerio del Ambiente, 2025). Land use and land cover (LULC) data for 2023 were obtained from the MapBiomas Ecuador platform, Collection 3.0, a regional initiative that produces annual land cover maps from Landsat images with a spatial resolution of 30 m, using the Random Forest algorithm implemented in Google Earth Engine (Breiman, 2001; MapBiomas, 2025).

The Mining class identifies areas with exposed soil associated with surface extractive activities, including artisanal, small-scale, and industrial operations, without distinction of the type of mineral extracted or their legal or illegal status, with the majority being alluvial in nature (Holguín et al., 2024). Its classification employs 12 spectral variables derived from Landsat mosaics, including optical bands in the visible and infrared spectrum (blue, green, red, NIR, SWIR1, SWIR2) and spectral indices such as NDVI, NDWI, EVI2, and NUACI, selected for their capacity to discriminate mining exposed soil from spectrally similar land covers such as sandbars or urban areas (Holguín et al., 2024). The reference layer for the Ecuadorian Amazon was generated through exhaustive manual scanning of the territory with support from Planet images and Landsat mosaics. The results were subjected to spatial filters, with a minimum connection of 5 pixels equivalent to approximately 0.5 ha to eliminate isolated pixels, and temporal filters to correct inconsistencies in the historical series 1985–2024 (Holguín et al., 2024). The relevance of this source for the present study is based on the fact that typical ASGM operations in the Ecuadorian Amazon cover areas greater than 0.5 ha, ensuring their detection at the 30 m resolution employed (Álvarez-Berríos et al., 2021; Mestanza-Ramón, Mora-Silva, et al., 2022).

Data processing followed a geospatial approach in four stages: (1) delineation of buffer zones, generating 5 km buffers around the official boundaries of each protected area; (2) extraction of the Mining class from the LULC raster using the Set Null function, to isolate only the pixels corresponding to this category within the buffer zones; (3) clipping of the mining raster using the Clip tool, using the buffer polygons as a spatial mask; and (4) conversion of the resulting raster to vector point format (Raster to Point), where each point represents the centroid of a pixel classified as mining (900 m², equivalent to 30 × 30 m). All data were projected to the WGS 1984 UTM Zone 17S coordinate system to maintain geometric precision and ensure consistency in spatial analyses.

3.2 Spatial Analysis of Mining Intensity

The spatial intensity of mining activity was estimated using KDE, a non-parametric statistical technique that models the continuous distribution of a spatial variable from discrete observations (Gelb & Apparicio, 2024). The density function is defined as:

$$f(x) = \frac{1}{n \times h} \sum_{i=1}^{n} K\left(\frac{x - x_i}{h}\right) \quad (1)$$

where $f(x)$ represents the estimated density at location x, n is the number of observations, h the bandwidth, x_i the locations of the observed points, and K the kernel function, which assigns decreasing weights as distance from the central point increases. In this study, mining intensity is defined as the spatial density of pixels classified as mining per unit area, expressed in mining points per km² within the established search radius, so that high values of the estimator $f(x)$ indicate a greater concentration of extractive activity per unit of surface. The Epanechnikov kernel was used for its computational efficiency and its capacity to produce smooth estimates that reduce the risk of overfitting in areas with high spatial variability (Silverman, 1986).

The analysis parameters were: (1) output cell size of 500 m, balancing spatial resolution and processing capacity to avoid excessive smoothing that would prevent the identification of local concentrations; and (2) search radius of 2,500 m, defined based on the typical scale of artisanal and small-scale mining operations in the region. The analysis was executed independently for each buffer zone in ArcGIS Pro (ESRI, 2025), generating density maps under a unified color scale based on the global range of KDE values across the entire study area, ensuring comparability among the six protected areas analyzed.

3.3 Identification and Interpretation of Mining Hotspots

To facilitate the comparative interpretation of the KDE results, density values were classified into four intensity intervals using the natural breaks method, so that class boundaries reflected the most significant contrasts in the spatial concentration of mining activity. This categorization into four levels (low, medium, high, and very high intensity) allowed the identification of mining pressure gradients within the buffer zones, highlighting areas with the greatest accumulation of activity points (Shuo et al., 2021). Subsequently, thematic maps were generated with a continuous color scale, from yellow (low intensity) to dark red (very high intensity), visually showing the mining pressure hotspots. These cartographic representations allow comparison of the most vulnerable areas within buffer zones and prioritization of territorial management according to the detected threat level.

4. Results and Discussion

4.1 Spatial Analysis of Mining Intensity using the Kernel Density Estimator

The application of KDE generated continuous mining density maps for the buffer zones of the six protected areas analyzed, allowing the delimitation of extractive activity hotspots and the quantification of anthropogenic pressure gradients on Amazonian ecosystems (Figure 2).

The use of the Epanechnikov kernel and a cell size of 500 m maintained an adequate balance between spatial detail and data smoothing, avoiding distortions from overfitting in regions with abrupt variability. The search radius of 2,500 m appropriately reflected the scale of artisanal and industrial mining operations typical of the southern Ecuadorian Amazon. Density values were grouped into four intervals using natural break classification, which allowed clear differentiation of intensity gradients and prioritization of critical zones for conservation.

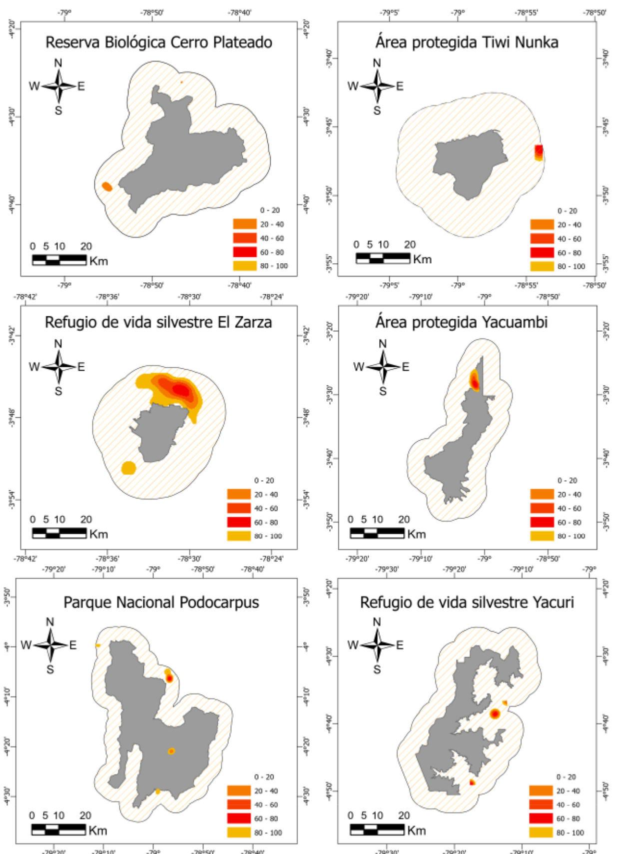

Figure 2. Kernel Density (KDE) maps showing the spatial distribution of mining intensity (mining points/km²) in the buffer zones of six protected areas of Zamora Chinchipe province, under a unified color scale. (a) Cerro Plateado Biological Reserve, (b) Tiwi Nunka Community Protected Area, (c) El Zarza Wildlife Refuge, (d) Yacuambi Protected Area, (e) Podocarpus National Park, and (f) Yacuri National Park.

4.2 Spatial Evaluation and Mining Intensity Patterns

The spatial analysis of mining density revealed a heterogeneous distribution of extractive pressures among the analyzed protected areas, conditioned by geographical factors (accessibility and proximity to hydrographic networks), socioeconomic factors, and environmental governance.

The results confirm that mining in buffer zones constitutes the main pressure front on Andean-Amazonian transition ecosystems, where areas of high biodiversity converge with communities that historically depend on gold extraction as an economic livelihood (V. Capparelli et al., 2021).

This duality demonstrates the tensions between conservation and development in Zamora Chinchipe, a province that concentrates continental protected areas of Ecuador and simultaneously shows the highest per capita consumption of diesel associated with heavy machinery in the country, an indirect indicator of the intensity of mining operations (Cortinhas Ferreira Neto et al., 2024).

4.3 Comparison of Mining Intensity Between Protected Areas

Cerro Plateado Biological Reserve

The Cerro Plateado Biological Reserve, with 50,000 hectares under state administration, presents the most intense hotspot of the provincial analysis (Figure 2a), located less than two kilometers from its southeastern boundary. The proximity to the core zone classifies this area as critically threatened, according to the criteria of the International Union for Conservation of Nature (IUCN) (Dudley, 2008; Geldmann et al., 2018).

This finding is particularly concerning given that the reserve belongs to SNAP category 1A, which prohibits all extractive activity. The high observed intensity demonstrates the lack of control and governance gaps, especially in areas of difficult access where state presence is minimal (Mestanza-Ramón, Monar-Nuñez, et al., 2023).

Tiwi Nunka Community Protected Area

The Tiwi Nunka Community Area, administered by the Shuar Kiim community, covers 5,091 hectares and shows the lowest mining intensity of the entire analysis, concentrated only in the northeastern sector of its buffer zone (Figure 2b). This result is attributed to a solid indigenous governance model based on continuous territorial control, cultural legitimacy, and traditional community authority (Rudel, 2021).

The ancestral surveillance system exercised by the 180 inhabitants of the community combines cultural and organizational mechanisms that have proven more effective than state administrative procedures. Surveillance includes continuous rounds by hunters and gatherers during their daily activities, immediate community alerts upon the presence of outsiders, and traditionally legitimized sanctions, such as physical expulsion from the territory and prohibition of re-entry (Lalander et al., 2021). The role of the Síndico, backed by the community assembly and the constitutionally recognized indigenous justice system, allows agile decision-making and immediate application of control measures, avoiding the bureaucratic processes that characterize state institutions.

The Shuar worldview, which considers the forest and rivers as living entities (nunkui), reinforces an environmental ethic that inhibits mining activity for spiritual and cultural reasons, considering rivers and forests as living entities whose disturbance affects spiritual balance and the community's traditional medicinal systems (Morocho Jaramillo et al., 2024; Salibová, 2020).

Despite the low internal mining impact, Tiwi Nunka faces external threats from diffuse contamination originating from the upper Yacuambi River basin, where mining operations exist 40–60 kilometers upstream, outside the direct analysis area. Monitoring conducted in 2023 detected total mercury concentrations between 0.08–0.15 µg/L in water and 0.6–1.2 mg/kg in sediments, values below the limits permitted by the World Health Organization (WHO) (1.0 µg/L), but demonstrating long-distance transport of contaminants and risk in aquatic food chains, which constitute an essential protein source for the community (Passarelli et al., 2024).

https://doi.org/10.5194/isprs-archives-XLIX-B3-2026-995-2026

The Tiwi Nunka experience demonstrates that indigenous territories with legal security, autonomy, and basic technical capacities can achieve conservation results superior to those of state protected areas with much larger budgets. This case reinforces the need to recognize and strengthen indigenous conservation systems as complementary strategies and, in many contexts, more effective than traditional state management models in the Ecuadorian Amazon.

El Zarza Wildlife Refuge

The El Zarza Wildlife Refuge, located in the Yantzaza canton, covers 3,643 hectares under state protection and presents two zones of high mining concentration in its eastern strip (Figure 2c). These medium to high intensity hotspots are located between 3 and 5 km from the official protected area boundary, with the most critical one situated at the northeastern extreme, near the Los Encuentros parish, following the course of a main drainage tributary of the Zamora River for approximately 2.8 kilometers.

The proximity of these mining pressure zones, classified as critically threatened according to IUCN criteria for category 4 protected areas (Williams et al., 2022), represents a direct risk to the ecological integrity of the refuge. Their hydrological connection with drainages that enter the protected area favors the transport of contaminants such as mercury and cyanide, derived from gold mining.

Environmental quality monitoring conducted in 2022 and 2023 reveals mercury concentrations in sediments of 1.8 to 3.2 mg/kg, values that greatly exceed the quality standards of the Environmental Protection Agency (EPA) (0.18 mg/kg) (Escobar-Camacho et al., 2024). These results demonstrate a significant transfer of contaminants from adjacent mining zones, highlighting the high hydrological vulnerability of the refuge and the fragility of its aquatic ecosystems in the face of upstream mining expansion.

Yacuambi Protected Area

The Yacuambi Protected Area, administered by the Provincial Autonomous Decentralized Government (GAD) of Zamora Chinchipe, shows a single low-intensity hotspot (light yellow) in the western sector of its buffer zone (Figure 2d). The reduced extent and discrete character of this focus contrast notably with the more extensive and concentrated patterns observed in state-managed areas such as Podocarpus and Cerro Plateado, reflecting the effectiveness of the local governance model implemented in Yacuambi.

This model combines continuous territorial presence, community patrolling, and specific environmental regulations that expressly prohibit mining in buffer zones. Ordinance 012-2019 of the provincial GAD establishes sanctions ranging from 10 to 50 unified basic salaries, generating a significant deterrent effect against the expansion of mining activities (Gad Municipal del cantón Zamora, 2025). This is compounded by the rugged topography, with average slopes of 35° and maximums reaching 60° at rocky outcrops, hindering human movement and limiting the entry of heavy machinery, acting as a natural barrier to extraction.

The contrast between Yacuambi and state areas demonstrates that effective local governance, sustained by community legitimacy, current regulations, and territorial control capacity, can significantly reduce mining pressure even in Amazonian contexts where extractive activity is widespread. The shared management model (GAD and communities) has demonstrated greater surveillance and response capacity than centralized state administration, characterized by sporadic institutional presence in the territory (Neira et al., 2022).

However, emerging threats could modify this favorable scenario in the medium term. Among them stands out the departmental road improvement project of 22 km of the Yacuambi road, scheduled to begin in 2026 and including gravel paving, roadway widening, and construction of four metal bridges. This project will reduce travel times by approximately 50%, increasing accessibility to currently remote areas of the western buffer. Additionally, two active mining concessions granted by the Mining Regulation and Control Agency (ARCOM), located between 4 and 6 kilometers from the protected area boundary, currently in advanced prospecting phase, could generate new access points, labor demand, and opportunistic artisanal mining, intensifying pressure on the protected area.

In this context, preventive land use planning and institutional strengthening of the provincial GAD are essential to ensure the sustainability of the conservation model and avoid a reversal of the environmental balance achieved in Yacuambi.

Podocarpus National Park

Podocarpus National Park, with an approximate area of 250,000 hectares under state protection, shows in its buffer zone the most extensive hotspots of highest mining intensity in the entire province (Figure 2e). These foci are concentrated mainly in the northwestern sector, closely linked to the upper Zamora River basin, where the combination of accessibility, moderate slopes, and alluvial gold deposits has favored the consolidation of multiple extractive operations. In total, four main foci of mining activity were identified during 2023, demonstrating complex spatial patterns associated with specific geological, topographic, and hydrological factors.

The central-eastern sector of the park shows hotspots of lower intensity, dispersed in tributaries of the Nangaritza River. This more fragmented pattern responds to the difficulty of access and more rugged topography, dominated by deep canyons and slopes greater than 40°, which limit mining expansion. In this area, traditional artisanal mining predominates, developed seasonally, mainly during the dry months of June to September, when the reduction of river flows allows working directly on riverbeds (Mestanza-Ramón, Mora-Silva, et al., 2022).

In the southern sector, hotspots are small and dispersed, with low to medium intensities, associated with access from the Zumba area and distributed along streams draining toward the Palanda River basin. This heterogeneous spatial pattern reflects the historical pressure of artisanal and small-scale mining in the region, where extractive activity has been maintained for decades as an essential economic alternative for rural communities with scarce employment opportunities and limited productive diversification (Mestanza-Ramón, Cuenca-Cumbicus, et al., 2022).

Overall, the spatial analysis of Podocarpus reveals a persistent and multifactorial mining dynamic, where the interaction between favorable physical conditions and socioeconomic factors makes the pressure on buffer zones permanent, compromising the ecological integrity of one of Ecuador's most biodiverse national parks.

Yacuri National Park

Yacuri National Park, with 100,000 hectares, shows a different spatial pattern from that observed in Podocarpus and Cerro Plateado. In its buffer zone, dispersed hotspots of low to medium intensity are recorded, mainly in the southwestern sector (Figure 2f). Approximately six discrete points of low intensity (light yellow) were identified, indicating incipient or intermittent mining pressure, probably associated with temporary or seasonal artisanal activities. These practices appear to respond more to hydrological cycles and local economic conditions than to consolidated and permanent mining operations.

The spatial distribution of hotspots coincides with areas of greatest accessibility from the population centers of Palanda and Valladolid, located 12 and 18 kilometers away, respectively. In this sector, moderate topography with slopes between 25° and 35° contrasts with conditions in the rest of the buffer, where more than 70% of the terrain shows inclinations greater than 40°, limiting extractive expansion. Activity foci are concentrated in streams draining toward the Palanda River basin, especially in the San Luis, El Carmen, and La Florida systems, characterized by low-gradient channels (longitudinal slope <5%) that facilitate the accumulation of coarse sediments and the formation of alluvial bars with gold potential (Carling & Breakspear, 2006).

The analysis suggests that Yacuri maintains localized and low-intensity mining pressure, conditioned mainly by topographic and accessibility factors rather than sustained extractive development. This pattern highlights the importance of preventive monitoring, especially in the face of eventual road improvements or fluctuations in gold prices that could reactivate artisanal mining in currently low-impact areas.

5. Conclusions

The geospatial analysis using KDE demonstrated that mining intensity in the buffer zones of Zamora Chinchipe responds to the interaction between biophysical and human factors. 89% of medium and high-intensity hotspots are located less than 500 meters from permanent water bodies, confirming the close dependence between gold mining and fluvial systems. This relationship is due to the alluvial geology of the territory, the need for water in mineral processing, and ease of access along low-gradient channels. Additionally, slope proved to be a key modulating factor: 78% of high-density foci are concentrated in areas with moderate inclinations (15 to 35°), which facilitates the use of machinery and the stabilization of work fronts.

The comparison between protected areas demonstrated that local and community governance models can achieve significantly better conservation results than centralized state schemes. Areas such as Tiwi Nunka (Shuar Kiim management) and Yacuambi (Provincial GAD) maintain the lowest levels of mining pressure thanks to continuous territorial presence, community surveillance, and social legitimacy of internal norms. In contrast, areas under state administration, such as Podocarpus, Cerro Plateado, and El Zarza, concentrate the most intense hotspots, demonstrating institutional control gaps and enforcement limitations. These findings highlight the need to strengthen shared management models and to legally recognize indigenous and municipal conservation systems as effective mechanisms of environmental governance.

The results confirm the value of open-access satellite data (MapBiomas) and KDE analysis as accessible and replicable tools for prioritizing control actions in areas of high vulnerability, especially in riparian corridors where extractive pressure is concentrated. However, this study has limitations inherent to the data sources used. The 30 m spatial resolution of Landsat images employed by MapBiomas limits the detection of very small-scale or seasonal mining operations that may not reach the detection threshold during periods of low activity. Likewise, the absence of systematic field verification restricts the validation of results to the local detail level, so the identified patterns should be interpreted as regional-scale territorial pressure indicators. Future work should integrate multitemporal analysis of the past 10 years evaluating mining expansion dynamics, combining higher-resolution images (Sentinel-2 and PlanetScope) with participatory monitoring to validate results and establish early warning systems that strengthen territorial management and preventive land use planning.

6. References

Albert, J. S., Carnaval, A. C., Flantua, S. G. A., Lohmann, L. G., Ribas, C. C., Riff, D., Carrillo, J. D., Fan, Y., Figueiredo, J. J. P., Guayasamin, J. M., Hoorn, C., de Melo, G. H., Nascimento, N., Quesada, C. A., Ulloa Ulloa, C., Val, P., Arieira, J., Encalada, A. C., & Nobre, C. A. (2023). Human impacts outpace natural processes in the Amazon. Science, 379(6630). https://doi.org/10.1126/science.abo5003

Álvarez-Berríos, N., L'Roe, J., & Naughton-Treves, L. (2021). Does formalizing artisanal gold mining mitigate environmental impacts? Deforestation evidence from the Peruvian Amazon. Environmental Research Letters, 16(6), 064052. https://doi.org/10.1088/1748-9326/abede9

Balchin, C. S., & Toyne, E. P. (1998). The avifauna and conservation status of the Río Nangaritza valley, southern Ecuador. Bird Conservation International, 8(3), 237–253. https://doi.org/10.1017/S0959270900001908

Benítez-Ramírez, D.M., Romero-Toledo, F.A., Escandón-Panchana, P., Velastegui-Montoya, A., 2026. Spatiotemporal dynamics of land use applied to sustainability in the Andes mountain range. Glob. J. Environ. Sci. Manag. (Articles in Press). https://doi.org/10.22034/gjesm.2026.03.15

Breiman, L. (2001). Random Forests. Machine Learning, 45(1), 5–32. https://doi.org/10.1023/A:1010933404324

Borja, M. O., Camargo, R., Moreno, N., Turpo, E., & Villacis, S. (2020). long-term land cover and land use mapping methodology for the Andean Amazon. The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, XLII-3/W12-2020, 373–378. https://doi.org/10.5194/isprs-archives-XLII-3-W12-2020-373-2020

Carling, P. A., & Breakspear, R. M. D. (2006). Placer formation in gravel-bedded rivers: A review. Ore Geology Reviews, 28(4), 377–401. https://doi.org/10.1016/j.oregeorev.2005.02.002

Código Orgánico Del Ambiente, https://sustanciasyresiduos.ambiente.gob.ec/producto/codigo-organico-del-ambiente/ (2017). www.lexis.com.ec

Constitución de La República de Ecuador, 449 Registro Oficial 25 (2008). www.lexis.com.ec

Cortinhas Ferreira Neto, L., Diniz, C. G., Maretto, R. V., Persello, C., Silva Pinheiro, M. L., Castro, M. C., Sadeck, L. W. R., Filho, A. F., Cansado, J., Souza, A. A. de A., Feitosa, J. P., Santos, D. C., Adami, M., Souza-Filho, P. W. M., Stein, A., Biehl, A., & Klautau, A. (2024). Uncontrolled Illegal Mining and Garimpo in the Brazilian Amazon. Nature Communications, 15(1), 9847. https://doi.org/10.1038/s41467-024-54220-2

Dudley, N. (2008). Guidelines for applying protected area management categories. IUCN. https://doi.org/10.2305/IUCN.CH.2008.PAPS.2.en

Escandón-Panchana, P., Velastegui-Montoya, A., Pico-Saltos, R., et al., 2025. Applications of geomatics in multidisciplinary knowledge fields. A review for decision-makers. Discov. Appl. Sci. 7, 1409. https://doi.org/10.1007/s42452-025-07928-9

Escobar-Camacho, D., Rosero-López, D., Ruiz-Urigüen, M., Barragán, K. S., Carpintero-Salvador, N., Daza, J. R., Aldous, A., Benítez, S., Tear, T., & Encalada, A. C. (2024). Mercury in aquatic ecosystems of two indigenous communities in the Piedmont Ecuadorian Amazon: evidence from fish, water, and sediments. Ecotoxicology, 33(4–5), 440–456. https://doi.org/10.1007/s10646-024-02764-w

ESRI. (2025). Kernel Density (Spatial Analyst). https://Pro.Arcgis.Com/En/pro-App/3.4/Tool-Reference/Spatial-Analyst/Kernel-Density.Htm.

FAO. (2024). Patrones de diversidad y distribución de plantas leñosas en una gradiente altitudinal entre la provincia de Loja y Zamora Chinchipe. https://Agris.Fao.Org/Search/En/Providers/124878/Records/67124a7c7f591113e2a57e48?Utm_source=chatgpt.Com.

Flores, B. M., Montoya, E., Sakschewski, B., Nascimento, N., Staal, A., Betts, R. A., Levis, C., Lapola, D. M., Esquível-Muelbert, A., Jakovac, C., Nobre, C. A., Oliveira, R. S., Borma, L. S., Nian, D., Boers, N., Hecht, S. B., ter Steege, H., Arieira, J., Lucas, I. L., … Hirota, M. (2024). Critical transitions in the Amazon forest system. Nature, 626(7999), 555–564. https://doi.org/10.1038/s41586-023-06970-0

Freile, J. F., Krabbe, N., Piedrahita, P., Buitrón-Jurado, G., Rodríguez-Saltos, C. A., Ahlman, F., Brinkhuizen, D. M., & Bonaccorso, E. (2014). Birds, Nangaritza River Valley, Zamora Chinchipe Province, southeast Ecuador: update and revision. Check List, 10(1), 54. https://doi.org/10.15560/10.1.54

Gad Municipal del cantón Zamora. (2025). Ordenanzas. Https://Zamora.Gob.Ec/Ordenanzas/.

GAD Provincial de Zamora Chinchipe. (2015). Plan de Desarrollo y Ordenamiento Territrorial.

Gelb, J., & Apparicio, P. (2024). Temporal Network Kernel Density Estimation. Geographical Analysis, 56(1), 62–78. https://doi.org/10.1111/gean.12368.

Geldmann, J., Coad, L., Barnes, M. D., Craigie, I. D., Woodley, S., Balmford, A., Brooks, T. M., Hockings, M., Knights, K., Mascia, M. B., McRae, L., & Burgess, N. D. (2018). A global analysis of management capacity and ecological outcomes in terrestrial protected areas. Conservation Letters, 11(3). https://doi.org/10.1111/conl.12434

Holguín, W., Aguilar, C., Terán, K., Rodríguez, A., & Josse, C. (2024). Documento de Bases Teóricas de Algoritmo (ATBD) MapBiomas Ecuador Colección 2.0. Fundación de Estudios Ecológicos Ecociencia. https://ecuador.mapbiomas.org/wp-content/uploads/sites/7/2024/11/ATBD-Ecuador-Coleccion-2.0-MapBiomas-Ecuador.pdf

Jiménez-Oyola, S., Valverde-Armas, P. E., Romero-Crespo, P., Capa, D., Valdivieso, A., Coronel-León, J., Guzmán-Martínez, F., & Chavez, E. (2023). Heavy metal(loid)s contamination in water and sediments in a mining area in Ecuador: a comprehensive assessment for drinking water quality and human health risk. Environmental Geochemistry and Health, 45(7), 4929–4949. https://doi.org/10.1007/s10653-023-01546-3

Lalander, R., Eguiguren-Riofrío, M. B., Vera, A. K., Espinosa, G., Reyes, M., & Lembke, M. (2021). Indigenous Gold Mining in the Kenkuim Shuar Community: A Decolonial and Postcapitalist Approach to Sustainability. Revista Iberoamericana de Estudios de Desarrollo = Iberoamerican Journal of Development Studies, 10(2), 178–202. https://doi.org/10.26754/ojs_ried/ijds.570

Lapola, D. M., Pinho, P., Barlow, J., Aragão, L. E. O. C., Berenguer, E., Carmenta, R., Liddy, H. M., Seixas, H., Silva, C. V. J., Silva-Junior, C. H. L., Alencar, A. A. C., Anderson, L. O., Armenteras, D., Brovkin, V., Calders, K., Chambers, J., Chini, L., Costa, M. H., Faria, B. L., … Walker, W. S. (2023). The drivers and impacts of Amazon forest degradation. Science, 379(6630). https://doi.org/10.1126/science.abp8622

MapBiomas. (2025). MapBiomas Ecuador. Plataforma de mapas y datos. Https://Ecuador.Mapbiomas.Org/.

Mestanza-Ramón, C., Cuenca-Cumbicus, J., D’Orio, G., Flores-Toala, J., Segovia-Cáceres, S., Bonilla-Bonilla, A., & Straface, S. (2022). Gold Mining in the Amazon Region of Ecuador: History and a Review of Its Socio-Environmental Impacts. Land, 11(2), 221. https://doi.org/10.3390/land11020221

Mestanza-Ramón, C., Jiménez-Oyola, S., Montoya, A. V. G., Vizuete, D. D. C., D’Orio, G., Cedeño-Laje, J., & Straface, S. (2023). Assessment of Hg pollution in stream waters and human health risk in areas impacted by mining activities in the Ecuadorian Amazon. Environmental Geochemistry and Health, 45(10), 7183–7197. https://doi.org/10.1007/s10653-023-01597-6

Mestanza-Ramón, C., Monar-Nuñez, J., Guala-Alulema, P., Montenegro-Zambrano, Y., Herrera-Chávez, R., Milanes, C. B., Arguello-Guadalupe, C., Buñay-Guisñan, P., & Toledo-Villacís, M. (2023). A Review to Update the Protected Areas in Ecuador and an Analysis of Their Main Impacts and Conservation Strategies. Environments, 10(5), 79. https://doi.org/10.3390/environments1005007

Mestanza-Ramón, C., Mora-Silva, D., D’Orio, G., Tapia-Segarra, E., Gaibor, I. D., Esparza Parra, J. F., Chávez Velásquez, C. R., & Straface, S. (2022). Artisanal and Small-Scale Gold Mining (ASGM): Management and Socioenvironmental Impacts in the Northern Amazon of Ecuador. Sustainability, 14(11), 6854. https://doi.org/10.3390/su14116854

Ministerio del Ambiente, A. y T. E. (2025). Superficie conservada a través del Sistema Nacional de Áreas Protegidas (SNAP). Https://Datosabiertos.Gob.Ec/Dataset/Superficie-Conservada-a-Traves-Del-Sistema-Nacional-de-Areas-Protegidas-2022.

Morocho Jaramillo, D. E., Mileto, C., & Vegas López-Manzanares, F. (2024). The Amazonian Architecture and Challenges Faced in Socio-Spatial Transformation Processes—Shuar and Achuar, Ecuador. Buildings, 14(3), 842. https://doi.org/10.3390/buildings14030842

Moulatlet, G. M., Yacelga, N., Rico, A., Mora, A., Hauser-Davis, R. A., Cabrera, M., & Capparelli, M. V. (2023). A systematic review on metal contamination due to mining activities in the Amazon basin and associated environmental hazards. Chemosphere, 339, 139700. https://doi.org/10.1016/j.chemosphere.2023.139700

Neira, F., Ribadeneira, S., Erazo-Mera, E., & Younes, N. (2022). Adaptive co-management of biodiversity in rural socio-ecological systems of Ecuador and Latin America. Heliyon, 8(12), e11883. https://doi.org/10.1016/j.heliyon.2022.e11883

Passarelli, I., Villacis Verdesoto, M. V., Jiménez-Oyola, S., Flores Huilcapi, A. G., Mora-Silva, D., Anfuso, G., Esparza Parra, J. F., Jimenez-Gutierrez, M., Carrera Almendáriz, L. S., Avalos Peñafiel, V. G., Straface, S., & Mestanza-Ramón, C. (2024). Analysis of Mercury in Aquifers in Gold Mining Areas in the Ecuadorian Amazon and Its Associated Risk for Human Health. Toxics, 12(2), 162. https://doi.org/10.3390/toxics12020162

Quizhpe, W., Benítez, Á., Cuenca, K., Uvidia, H., Huamantupa, I., Muñoz, J., & Cabrera, O. (2019). Forest Diversity and Structure in the Amazonian Mountain Ranges of Southeastern Ecuador. Diversity, 11(10), 196. https://doi.org/10.3390/d11100196

Rivera-Parra, J. L., Beate, B., Diaz, X., & Ochoa, M. B. (2021). Artisanal and Small Gold Mining and Petroleum Production as Potential Sources of Heavy Metal Contamination in Ecuador: A Call to Action. International Journal of Environmental Research and Public Health, 18(6), 2794. https://doi.org/10.3390/ijerph18062794

Rudel, T. K. (2021). Indigenous-Driven Sustainability Initiatives in Mountainous Regions: The Shuar in the Tropical Andes of Ecuador. Mountain Research and Development, 41(1). https://doi.org/10.1659/MRD-JOURNAL-D-20-00039.1

Salibová, D. (2020). Ayahuasca Ethno-tourism and its Impact on the Indigenous Shuar Community (Ecuador) and Western Participants. Český Lid, 107(4), 511–532. https://doi.org/10.21104/CL.2020.4.05

Shuo, Z., Jingyu, Z., Zhengxiang, Z., & Jianjun, Z. (2021). Identifying the density of grassland fire points with kernel density estimation based on spatial distribution characteristics. Open Geosciences, 13(1), 796–806. https://doi.org/10.1515/geo-2020-0265

Silverman, B. W. (1986). Density Estimation for Statistics and Data Analysis. Chapman and Hall. https://doi.org/10.1007/978-1-4899-3324-9

Siqueira-Gay, J., Sonter, L. J., & Sánchez, L. E. (2020). Exploring potential impacts of mining on forest loss and fragmentation within a biodiverse region of Brazil's northeastern Amazon. Resources Policy, 67, 101662. https://doi.org/10.1016/j.resourpol.2020.101662

Souza, C. M., Z. Shimbo, J., Rosa, M. R., Parente, L. L., A. Alencar, A., Rudorff, B. F. T., Hasenack, H., Matsumoto, M., G. Ferreira, L., Souza-Filho, P. W. M., de Oliveira, S. W., Rocha, W. F., Fonseca, A. V., Marques, C. B., Diniz, C. G., Costa, D., Monteiro, D., Rosa, E. R., Vélez-Martin, E., … Azevedo, T. (2020). Reconstructing Three Decades of Land Use and Land Cover Changes in Brazilian Biomes with Landsat Archive and Earth Engine. Remote Sensing, 12(17), 2735. https://doi.org/10.3390/rs12172735

Souza-Filho, P. W. M., Cavalcante, R. B. L., Nascimento, W. R., Nunes, S., Gastauer, M., Santos, D. C., Silva, R. O., Sahoo, P. K., Salomão, G., Silva, M. S., Ramos, S. J., Caldeira, C. F., Dall'Agnol, R., & Siqueira, J. O. (2020). The sustainability index of the physical mining Environment in protected areas, Eastern Amazon. Environmental and Sustainability Indicators, 8, 100074. https://doi.org/10.1016/j.indic.2020.100074

V. Capparelli, M., Cabrera, M., Rico, A., Lucas-Solis, O., Alvear-S, D., Vasco, S., Galarza, E., Shiguango, Lady, Pinos-Velez, V., Pérez-González, A., Espinosa, R., & M. Moulatlet, G. (2021). An Integrative Approach to Assess the Environmental Impacts of Gold Mining Contamination in the Amazon. Toxics, 9(7), 149. https://doi.org/10.3390/toxics9070149

Williams, B. A., Grantham, H. S., Watson, J. E. M., Shapiro, A. C., Plumptre, A. J., Ayebare, S., Goldman, E., & Tulloch, A. I. T. (2022). Reconsidering priorities for forest conservation when considering the threats of mining and armed conflict. Ambio, 51(9), 2007–2024. https://doi.org/10.1007/s13280-022-01724-0

Zhang, G., Zhu, A.-X., & Huang, Q. (2017). A GPU-accelerated adaptive kernel density estimation approach for efficient point pattern analysis on spatial big data. International Journal of Geographical Information Science, 31(10), 2068–2097. https://doi.org/10.1080/13658816.2017.1324975