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The sound of shovels at the heart of biodiversity: a Dilemma between Mining and Mammal Conservation in Itombwe Nature Reserve, DR Congo

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ABSTRACT

This study analyzes the dilemma between mining and mammal conservation in the Itombwe Nature Reserve, Democratic Republic of Congo. Using ethnocartography, ecological indices (Shannon, Simpson, Richesse), and Bayesian modeling (BGLMM and GAM), we tested the impact of artisanal and industrial mining on biodiversity. The results reveal that artisanal mining is the most destructive due to diffuse fragmentation and a constant "ecological noise" that saturates the sensory environment.

The study identifies a critical threshold of 5 km around mining sites, acting as a tipping point: within this distance, mammal communities are structurally disorganized. Species with low resilience, such as *primates*, *pholidotes*, and *proboscideans*, are at high riskof local extinction. Simulations show that a 100% mining expansion would reduce taxonomic richness from 7.51 to 5.05 species. Conversely, ecological restoration would allow for a vigorous recovery of diversity, particularly beyond the 5 km mobility radius. The survival of wildlife in Itombwe therefore requires moving beyond simple site management to adopt a landscape-based approach that includes strict buffer zones and limits on artisanal mining.

Keywords:
Biodiversity conservation, Resilience threshold (5 km), Artisanal and industrial mining, Bayesian modeling, Mammalian fauna, Itombwe Nature Reserve, Democratic Republic of Congo.

1. INTRODUCTION

Tropical protected areas play a central role in the conservation of global biodiversity, particularly in regions where ecosystems harbor high rates of endemism and threatened species. The Itombwe Nature Reserve, located in eastern Democratic Republic of Congo, is one of these internationally prioritized landscapes, especially for the conservation of mammalian fauna (Doumenge, 1997; Mutula, Mutugi, Githaiga, & Muzusangabo, 2025).

However, this reserve now finds itself at the heart of a major socio-ecological dilemma. On the one hand, the conservation of mammalian fauna is a national and international priority, supported by global commitments to biodiversity. On the other hand, the expansion of mining activities,

particularly artisanal mining, represents a means of subsistence for many local communities facing structural poverty, food insecurity, and a lack of alternative economic opportunities (Ajonina et *al.*, 2025; Alho, 2020; Arroyo-Rodríguez et *al.*, 2020).

Mining, whether legal or artisanal, leads to profound transformations of the landscape: deforestation, habitat fragmentation, soil and water pollution, road construction, and increased hunting pressure. These changes directly and indirectly affect the structure of mammal communities, altering their spatial distribution, diversity, and the ecological balance between species (Attuquayefio et *al.*, 2017; Cowan et *al.*, 2024; Kenedy-Siqueira et *al.*, 2025).

Despite the importance of these interactions, knowledge remains limited on how mining activities spatially reshape mammal communities in protected areas of Centr*al.* In particular, few studies integrate a detailed spatial analysis of mining pressures with ecological indicators and a probabilistic approach to assess the uncertainty associated with ecological data Africa (Bobo et *al.*, 2025; Gonzalez-Redin et *al.*, 2016)..

This study adopts this perspective by analyzing how mining creates a disturbance gradient within the Itombwe Nature Reserve, and how these gradient influences mammal species richness, diversity, and dominance. By combining GIS tools, ecological indices, and Bayesian modeling, this ***work aims to provide an integrated reading of the dilemma between mining and the conservation of mammalian wildlife in a protected landscape of local and global importance.***

2. METHODOLOGY

2.1. Study context: The Itombwe Nature Reserve (INR)

The research was conducted in the landscape of the Itombwe Nature Reserve (INR) (Figure 1. (a)), located in the province of South Kivu, in the eastern Democratic Republic of Congo. This sanctuary extends between 2°40' – 4°30' S and 27°50' – 29°10' E. It is located northwest of Lake Tanganyika and is bordered by the territories of Fizi, Mwenga, Uvira and Walungu (Mutula, Mutugi, Githaiga, Kalume, et *al.*, 2025; Mutula, Mutugi, Githaiga, & Muzusangabo, 2025).

Administratively, the reserve was officially recognized by Ministerial Decree No. 038/CAB/MIN/ECN-EF/2006 of October 11, 2006, under the auspices of the Ministry of the Environment, Nature Conservation, Water and Forests. Its spatial organization is divided into several administrative sectors and communities, notably the areas of Burhinyi, Luindi, Basile, Itombwe and Wamuzimu within the Mwenga sector, as well as the areas of Lulenge (Fizi) and Wakabongo (Shabunda). Its landscape is a complex mosaic of mountains (Highlands), sloping plateaus (Burundian) and peneplains (Ruzizien). The climate, varying from tropical mountain to equatorial, offers abundant rainfall (1200 to 3000 mm) favorable to an exceptional mammalian fauna (gorillas, chimpanzees, panthers, etc.) (Doumenge, 1997; Habiyaremye et *al.*, 2024).

The choice of the INR as a study system is dictated by its global importance as a biodiversity "hotspot", now threatened by a dilemma between mammalian survival and mining.

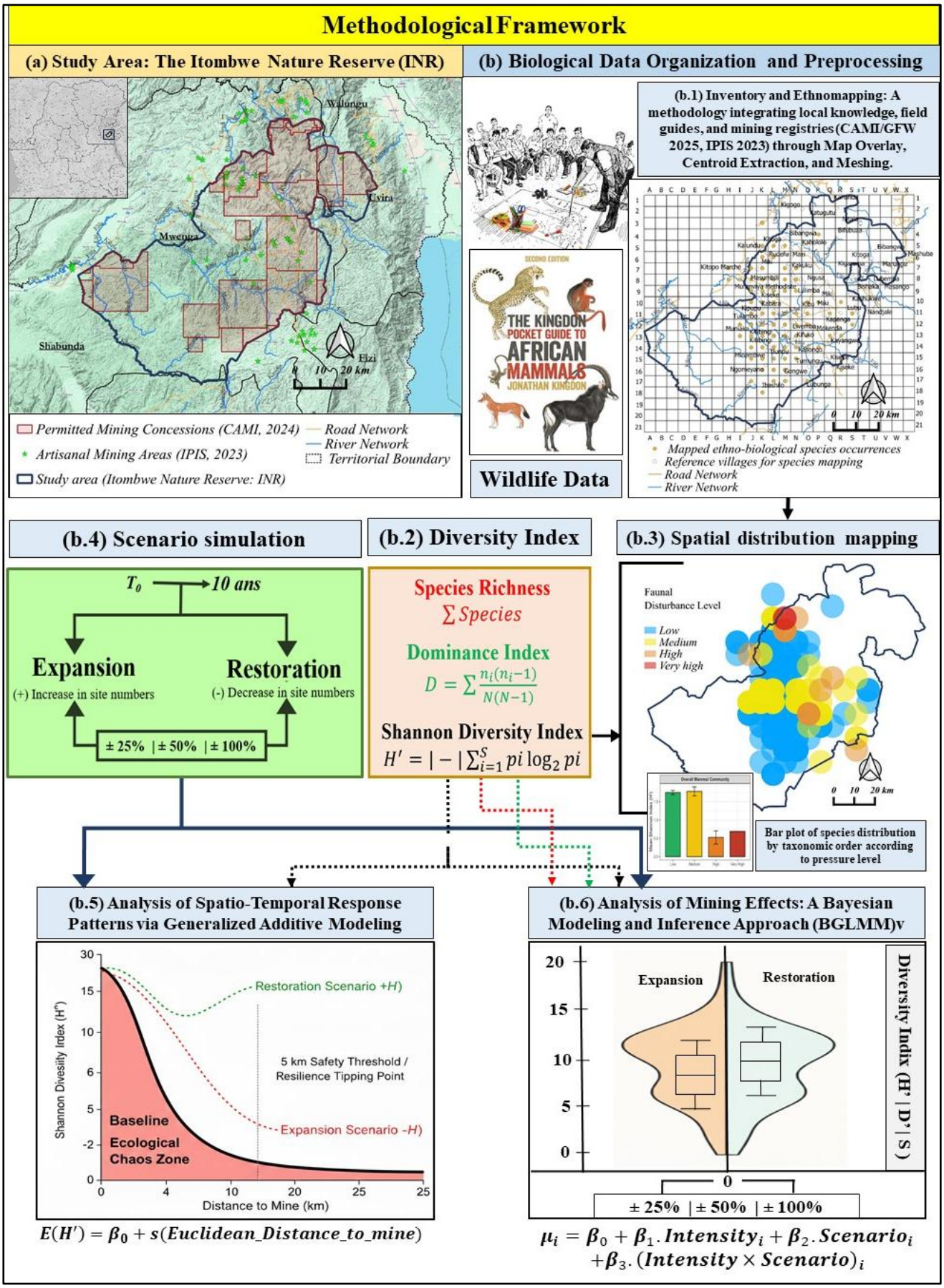


Figure 1. Methodological workflow: from ethnomapping to Bayesian inference of mining effects.

2.2. Organization and preparation of biological data

2.2.1. Inventory and Ethnocartography

Data collection was based on a participatory approach combined with rigorous scientific validation. The use of ethnocartography allowed us to spatially represent the distribution of species based on local knowledge, supplemented by historical inventories from Doumenge (1996). To certify each taxon, we relied on Kingdon's guide (Mammals of Africa), guaranteeing the accuracy of observations (signs of presence, feces, footprints, and testimonies) (Figure 1. (b)) (Abdul-Latiff et *al.*, 2021; Mazurek, 2013; Sandker et *al.*, 2010).

2.2.2. Spatial networking and calculation of ecological indicators

To visualize these data (Figure 1. (b.1)), a grid (mesh) was overlaid in QGIS with a radius of 5 km per cell (i.e., 25 km²), corresponding to the estimated free movement area for a species. From the centroids of each grid cell, we calculated three fundamental indices (Figure 1. (b.2)).(Kunakh et *al.*, 2023; Marchesan & Kolasa, 2024; Roswell et *al.*, 2021; E. H. Simpson, 1949):

i. **Species Richness**This index represents the total number of different species recorded in each grid cell. Its importance lies in measuring the gross loss of biodiversity.
ii. **Dominance Index**(, With D= Simpson's diversity index, n= Number of individuals per species and N=total number of individuals): This indicator is essential for detecting biotic homogenization, that is, the monopolization of niches by opportunistic species to the detriment of rare species.$D = \sum \frac{n_i(n_i-1)}{N(N-1)}$
iii. **Shannon Diversity Index**, denoted as H', expresses the overall level of diversity within a mammalian community by measuring the balance of individual distribution. The value of this index is obtained by the formula $(H' = |-| \sum_{i=1}^{S} pi \log_2 pi)$, where S represents the total taxonomic richness or the number of species present in the studied community. In this calculation, the variable pi corresponds to the proportion of individuals belonging to species i relative to the total number of observed individuals, which is the ratio $pi = ni/N$. Here, ni designates the number of individuals of species i, while N represents the total number of individuals recorded across all species. The use of the base-2 logarithm of the proportion pi allows for a precise weighting of each species' contribution to the overall diversity of the environment. Ultimately, this index measures the community balance, and its calculation is essential for assessing the stability as well as the resilience of the Itombwe ecosystem.

2.2.3. Construction of the spatial gradient of mining pressure

The analysis distinguishes two types of pressures: artisanal extraction (localized points via IPIS, 2023) and industrial extraction (extensive areas via Global Forest Watch, 2023).
The importance of this distinction lies in capturing the difference in spatial extent. We created 5 km buffer zones around the points and centroids of the industrial areas. The pressure gradient was standardized into four levels (Figure 1. (b.3)): Low (1), Medium (2), High (3), and Very High (4). This numerical coding allows us to integrate pressure as a continuous variable to correlate the physical distance from the mines with the biological response of the fauna (Deere et *al.*, 2020; Gonzalez-Redin et *al.*, 2016).

2.2.4. Analysis of simulation scenarios (EXP & RST)

Starting from the observed initial state (T_0), simulations were projected over a 10-year (T_{10}) period to assess the effectiveness of management policies. For each scenario, the diversity (H'), dominance (D), and richness (S) indices were recalculated using Excel (Figure 1. (b.4)) (Brunner & Naveau, 2023; Wang et *al.*, 2021):

i. **Expansion (EXP)**: Modeling an increase in mining footprint at levels of 25%, 50% and 100% to anticipate habitat degradation.
ii. **Restoration (RST)**: Modeling a reduction in mining pressures of 25%, 50% and 100% in order to measure the resilience potential of mammalian fauna.

2.2.5. Spatiotemporal response modeling (GAM)

This stage of the study relies on the application of a Generalized Additive Model (GAM) to mathematically model the nonlinear responses of mammalian fauna to anthropogenic pressures (Figure 1. (b.5)). For this analysis, the Shannon Diversity Index (H') was selected as the sole dependent variable. This methodological choice is based on the index's ability to synthesize biological complexity because, unlike raw richness or dominance, it is sensitive to both the number of species and the balance of their distribution. It thus constitutes the most robust indicator for identifying tipping points and ecological recovery trajectories along the distance gradient (Beasley, 2024; Brandt et *al.*, 2024; Gardner et *al.*, 2019; Lai et *al.*, 2024; Pedersen et *al.*, 2019; G. L. Simpson, 2024; Wang et *al.*, 2021; Wood, 2006).

The model is structured according to the equation:

$$E(H') = \beta_0 + s(Euclidean_Distance_to_mine)$$

Where (H') represents the expected value of the Shannon index and β_0 constitutes the intercept, corresponding to the reference value for diversity. The central element of the model lies in the application of a non-parametric smoothing function, denoted s, to the Euclidean distance separating each sampling point from the nearest mining site (point and/or surface). Unlike a classical linear approach, this spline smoothing function offers the flexibility necessary to capture complex relationships and identify areas of varying influence.

For data processing, the Euclidean distance was calculated between the centroid of each grid square in the study (mesh) and the nearest mining site, distinguishing between artisanal and industrial operations with permits. This direct measurement of physical proximity serves as a proxy for the intensity of pressure exerted by the mine.

The graphical analysis derived from the model aims to highlight the system's dynamics, particularly the phenomenon of ecological chaos manifested by critical instability in biodiversity within a 0 to 4 km radius of the sites. Finally, the model incorporates a 5 km threshold, identified as a pivotal zone corresponding to the Free Mobility Radius of species. This parameter is essential for geographically delimiting the area where degradation and recovery trajectories diverge, thus scientifically validating the safety distances necessary for reserve management.

2.2.6. Bayesian Modeling and Inference of Mining Effects (BGLMM)

To precisely quantify the uncertainty and validate the probability of the impacts observed in the simulations, the study uses a Bayesian Generalized Linear Mixed Model (BGLMM) (Figure 1. (b.6)) (S. J. Ceballos et *al.*, 2025; Hadfield, 2010; Xie et *al.*, 2025). This approach relies on a mathematical structure where the observed ecological index, denoted $\boldsymbol{y_i}$ (including species richness, the Shannon index, or Simpson's dominance), is modeled according to a normal distribution:

$$\boldsymbol{y_i \sim Normal(\mu_i, \sigma)}$$

In this equation, $\boldsymbol{\mu_i}$ represents the predicted mean, while σ $(sigma)$ the standard deviation, set at 7.05, models the natural variability or ecological background noise specific to the Itombwe forest. The predicted mean $\boldsymbol{\mu_i}$ is calculated using the following regression equation:

$$\boldsymbol{\mu_i = \beta_0 + \beta_1 . Intensity_i + \beta_2 . Scenario_i + \beta_3 . (Intensity \times Scenario)_i}$$

The statistical validation of this model relies on the use of 95% Credibility Intervals (CIs). Unlike classical statistical methods, these intervals define a concrete range of values within which the actual impact has a 95% probability of occurring. The decision criterion for validating an effect is the position of this interval relative to zero, which represents the absence of impact. An effect is considered statistically certain only if its credibility interval does not contain zero (G. Ceballos et *al.*, 2015; Michielsen et *al.*, 2023; Tam et *al.*, 2021).

For example, if the interval lies entirely within the negative range, it is mathematically confirmed that the factor under study reduces biodiversity. Conversely, if the interval contains or overlaps zero, the effect is considered uncertain, meaning that the observed variation could be due to chance or natural noise within the system.

The model incorporates several key variables and coefficients to explain the state of the wildlife. The "Intensity" variable corresponds to the levels of mining pressure (25%, 50%, 100%), while the "Scenario" variable distinguishes between the Expansion (EXP) and Restoration (RST) phases. The coefficients$\boldsymbol{\beta}$ (Beta) reflects the influence of these variables: $\boldsymbol{\beta_0}$ (the Intercept) establishes baseline diversity without additional pressure, $\boldsymbol{\beta_1}$ measures the impact of increased intensity, and $\boldsymbol{\beta_2}$ captures the effect specific to the scenario type. Finally, the interaction parameter $\boldsymbol{\beta_3}$ is crucial because it assesses how the effectiveness of a management measure (such as restoration) varies depending on the initial level of degradation (Carrasco et *al.*, 2022).

This statistical architecture makes it possible to estimate biodiversity for any future configuration in Itombwe, thus proving that diversity losses are mathematically correlated with management choices and the strength of mining activity.

3. RESULTS

3.1. Inventory, Vulnerability Dynamics and Resilience of Mammalian Fauna

This phase synthesizes data from ethnomapping and scientific validation to quantify the vulnerability of wildlife in Itombwe (INR). The inventory identified a total of 36 species distributed across 8 distinct taxonomic orders (Figure 2). The numerical distribution by order shows that *Cetartiodactyla* dominates with 10 species, followed by *Rodentia*, *Carnivora*, and *Primates* with 7 species each. The orders *Pholidota* (2 species), *Hyracoidea* (1 species), *Afrosoricida* (1 species), and *Proboscidea* (1 species) complete this inventory, which was validated by presence indicators and local accounts.

Figure 2 below illustrates this taxonomic vulnerability analysis by linking biological resilience scores (Panel B) to the composition of conservation statuses (Panel A). The risk model correlates the number of identified species with their biological recovery capacity, on a scale of 1 to 9, and their 2023 IUCN status.

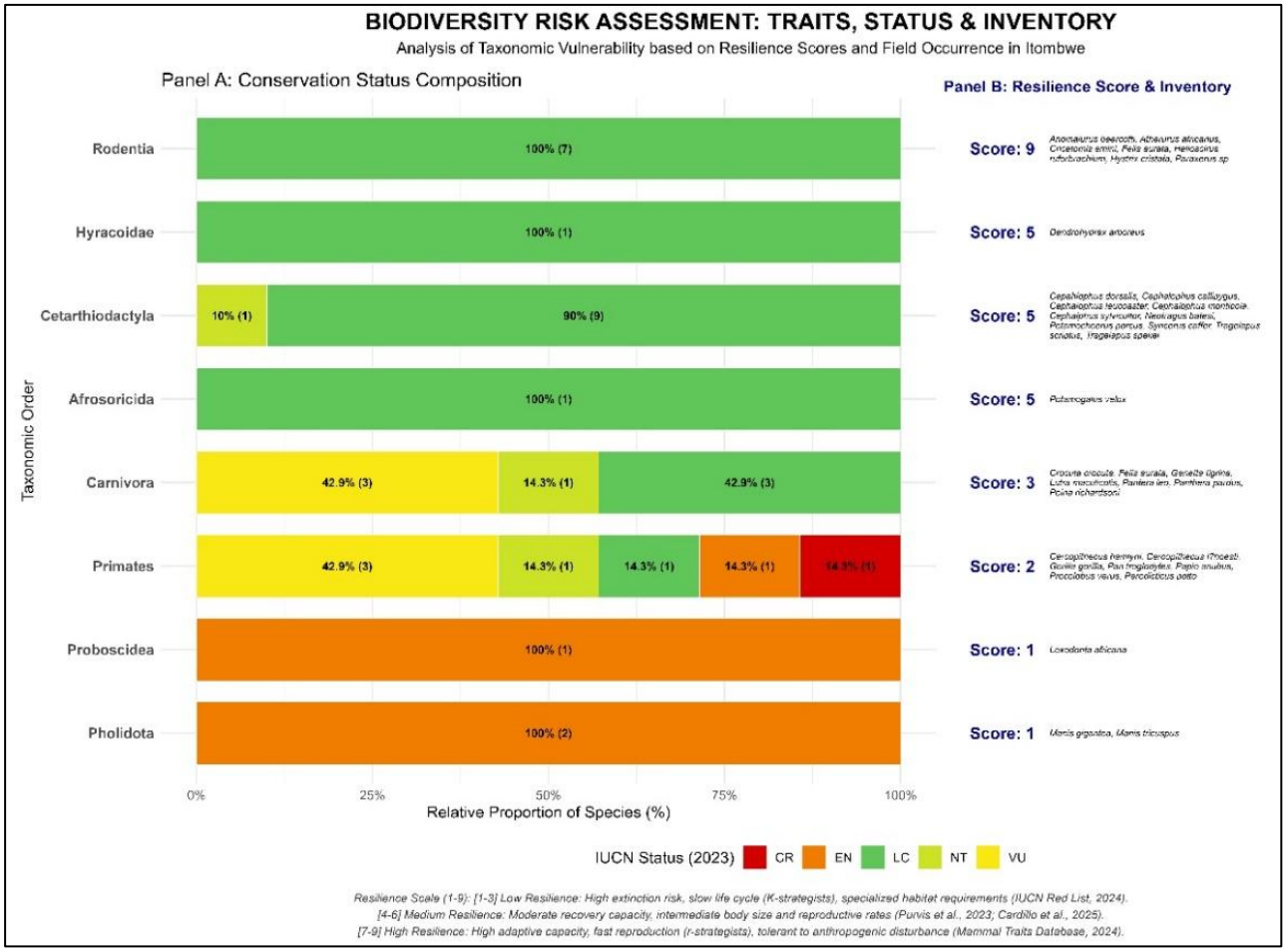


Figure 2. Taxonomic vulnerability analysis based on resilience scores and occurrence

Analysis of the combined data reveals that *Rodentia*, with 7 species and a high resilience score of 9, maintain 100% of their population in Least Concern (LC) status. Orders with a medium resilience score of 5, such as *Hyracoidea* (1 species) and *Afrosoricida* (1 species), also show complete stability in LC status, while *Cetartiodactyla* (10 species) exhibit slight vulnerability with 90% in LC and 10% in Near Threatened (NT) status. A marked decline is observed in *Carnivora* (7 species, score 3) where only 42.9% are in LC status compared to 42.9% in Vulnerable (VU) status and 14.3% in NT status. Primates (7 species, score 2) reach a critical fragmentation threshold

with 14.3% critically endangered (CR), 14.3% endangered (EN), 42.9% vulnerable (VU), and only 14.3% vulnerable (LC). Finally, *Proboscidea* (1 species) and *Pholidota* (2 species) exhibit the highest level of vulnerability with a critical resilience score of 1, placing 100% of their respective taxa, including *Loxodonta africana*, *Manis gigantea*, and *M. tricuspis*, in the "Endangered" (EN) category.

The data in Figure 2 demonstrate that the threat intensifies proportionally to the decrease in the resilience score. Species with high resilience maintain stability in the face of environmental disturbances, whereas, conversely, orders characterized by low resilience (Score ≤ 3) show a clear color transition towards red (CR) and orange (EN) on the graph, indicating a high risk of local extinction. The inventory confirms that for Primates, Pholidotes, and Proboscideans, biological traits such as slow growth and specific territorial requirements result in a majority classification in the most severe threat categories.

3.2. Comparative analysis of diversity (H') in the face of mining pressures

This study assesses the fate of mammals by correlating ethnomapping with mining occupation types (Figure 3). The Shannon index (***H'***) indicates biological value, while fate is defined by the mine's intrusion into the 5 km buffer: safety (Low), moderate danger (Medium), perceived danger (High), and imminent danger by inclusion (Very High).

Map analysis reveals two contrasting logics: the artisanal block, saturated with extraction points (green stars), fragments the habitat with constant ecological noise. Conversely, the industrial block imposes pressure per unit area (grey zone) where imminent danger (Very High) predominates, forcing direct cohabitation.

The taxonomic shift reveals that the artisanal model is the most destructive. *Proboscidea* and *Hyracoidae*, spared in the Low-risk zone (2.5 and 1.8 respectively), become locally extinct (H' = 0) at the Medium risk level for artisanal fishing, while reaching their maximum values (2.5 and 2.2 respectively) in the Very High-risk level for industrial fishing. *Pholidota* fall from 2.0 to 0.5 in the High-risk level for artisanal fishing, but maintain 0.9 in the High-risk level for industrial fishing. Similarly, *Primates*, *Carnivora*, *Afrosoricida*, and *Cetartiodactyla* all exhibit more robust values in the High-risk level for industrial fishing than in the High-risk level for artisanal fishing. *Rodentia*, after an opportunistic peak in the Medium risk level for artisanal fishing (2.2), collapse to 0.05, compared to remaining at 1.55 in the High-risk level for industrial fishing.

Finally, the error bars confirm the precariousness of the artisanal approach: uncertainty is highest in Medium and High zones, making survival random. Conversely, the stability of the data in Very High industrial zones, particularly for *Proboscidea*, attests to their guaranteed survi*val.* In short, the imminent danger posed by industrial inclusion is less detrimental than fragmentation by artisanal sites, which systematically pushes species toward critical extinction.

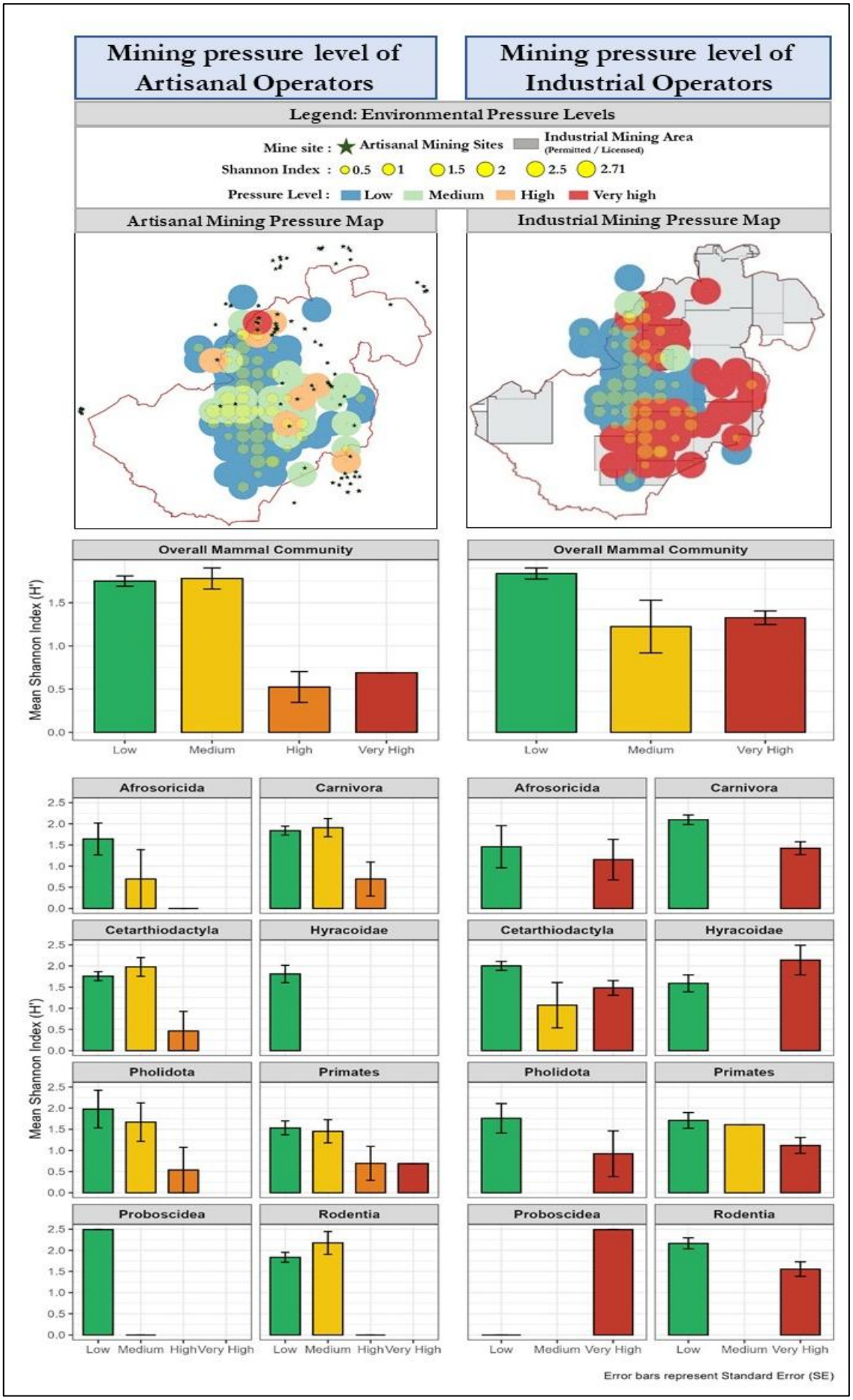


Figure 3. Shannon index and spatial distribution of mammalian diversity under mining pressures

3.3. Analysis of the spatial response of mammalian diversity via GAM modeling

This analysis quantifies the impact of distance from mining sites on mammalian diversity (H') by superimposing the initial state (T_0) onto landscape evolution simulations (Figure 4). The model reveals a spatial response dictated by critical thresholds, distinguishing between artisanal mining, where the "noise" of points saturates the space, and industrial mining, where surface pressure shifts ecological balances.

Across all simulations, a zone of chaos extends from 0 to 5 km. In the immediate vicinity of mining sites, the H' index drops sharply and fluctuates erratically, demonstrating that human-induced disturbances structurally disrupt communities within the species' usual range of movement. The "5 km Threshold" acts as a universal statistical tipping point: it is the physical boundary where wildlife begins to break free from mining influence and start its recovery towards a stable equilibrium.

i. *The Expansion (EXP)* scenario shows that increasing the mining footprint to 25%, 50% and 100% gradually pushes the diversity curves below the reference line T0. At 100% expansion, the degradation halo expands massively, pushing the recovery zone well beyond the initial threshold.
ii. Conversely, *the Restoration scenario (REST)* demonstrates that a reduction in pressures of 25%, 50%, and even 100% allows the curves to rise above T0. This restoration dynamic triggers a vigorous recovery that peaks between 8 and 15 km, stabilizing diversity at values close to 2.0.

Modeling demonstrates that the impact of mining follows a strict threshold logic. Whether it is an artisanal or industrial block, each site generates a degradation halo of 5,000 meters. Below this limit, corresponding to the zone of disturbed mobility, the balance of mammal populations is structurally compromised, while above it, the resilience of the ecosystem allows a return to intact forest function.

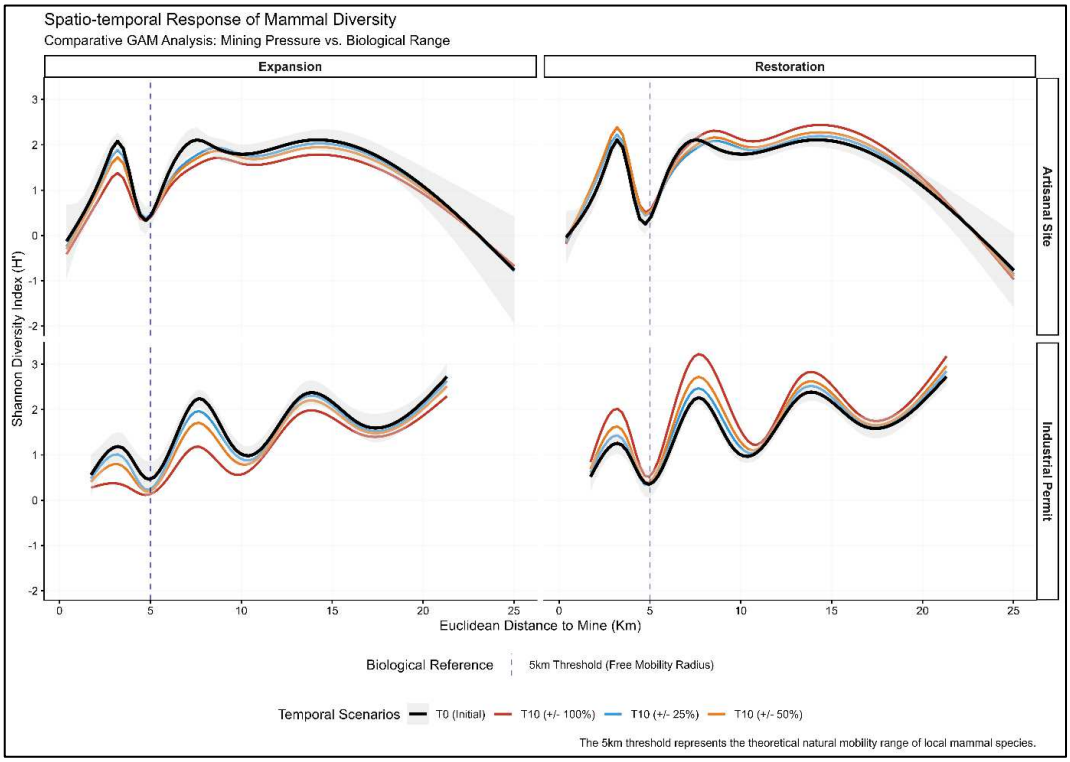


Figure 4. Dynamics of disruption and resilience of mammalian fauna in the face of the halo of mining degradation.

3.4. Bayesian trajectories of biodiversity: Inference of the tipping point between degradation and restoration in Itombwe.

This in-depth analysis uses the BGLMM (Bayesian Generalized Linear Mixed Model) to project the biodiversity trajectories of mammalian wildlife in the Itombwe reserve by 2036, based on the distribution of data collected since 2023. She uses Figure 5 (vulnerability matrix) to transform these probabilities into visual evidence. Table 2 (BGLMM Parameters) locks these observations with precise coefficients, setting the reference level at $\boldsymbol{\beta_0}$= 1.68.

The initial state, or Current baseline, is clearly identified on the left of Figure 5 and serves as a strategic anchor point representing a healthy forest balance. As detailed in Table 1 (Synthetic Graph), this reference displays a Shannon index of 1.68 and a taxonomic richness of 7.51. Dominance is maintained at a low level of 0.31, reflecting a balanced community structure prior to any additional mining pressure.

Under the *Expansion scenario* (red boxes), the decline of wildlife is brutal and systematicA major difference in trajectory appears between the sectors: while Artisanal mining shows a gradual erosion, Industrial mining causes a much deeper collapse.This degradation is statistically confirmed by the interaction $\boldsymbol{\beta_6}$= -0.01. Table 1 shows that at 100% industrial intensity, the predicted mean $(\boldsymbol{\mu_i})$ Shannon index falls to 1.12 and taxonomic richness drops to 5.05.At the same time, dominance climbs towards a critical peak, validated by the coefficient $\boldsymbol{\beta_{13}}$ =+0.01, proving the saturation of the environment by opportunistic species..

Conversely, the *Restoration scenario* (blue boxes) creates a striking mirror effect. This lever makes it possible to break the monopoly of opportunistic species $\boldsymbol{\beta_{Int4}}$= -3.55 in the template, associated with $\boldsymbol{\beta_{10}}$ in the summary data and to ensure the effective return of mammals. While artisanal restoration stabilizes the indices, industrial restoration generates a massive gain, bringing the specific wealth $\boldsymbol{\mu_i}$ to 10.02 according to Table 2. However, it should be noted that the industrial impact exhibits greater instability, with very stretched box plots. This variability is captured by $\boldsymbol{\sigma}$ $(sigma)$ a value of 7.05, reflecting a complex recovery trajectory on large industrial concessions.

The robustness of these results is guaranteed by a high Log-posterior of 141.25. The credibility intervals in Table 1, widening to 24 for richness in industrial restoration, underscore that while the survival of mammalian fauna is possible, it requires intensive intervention to compensate for the depth of industrial degradation.

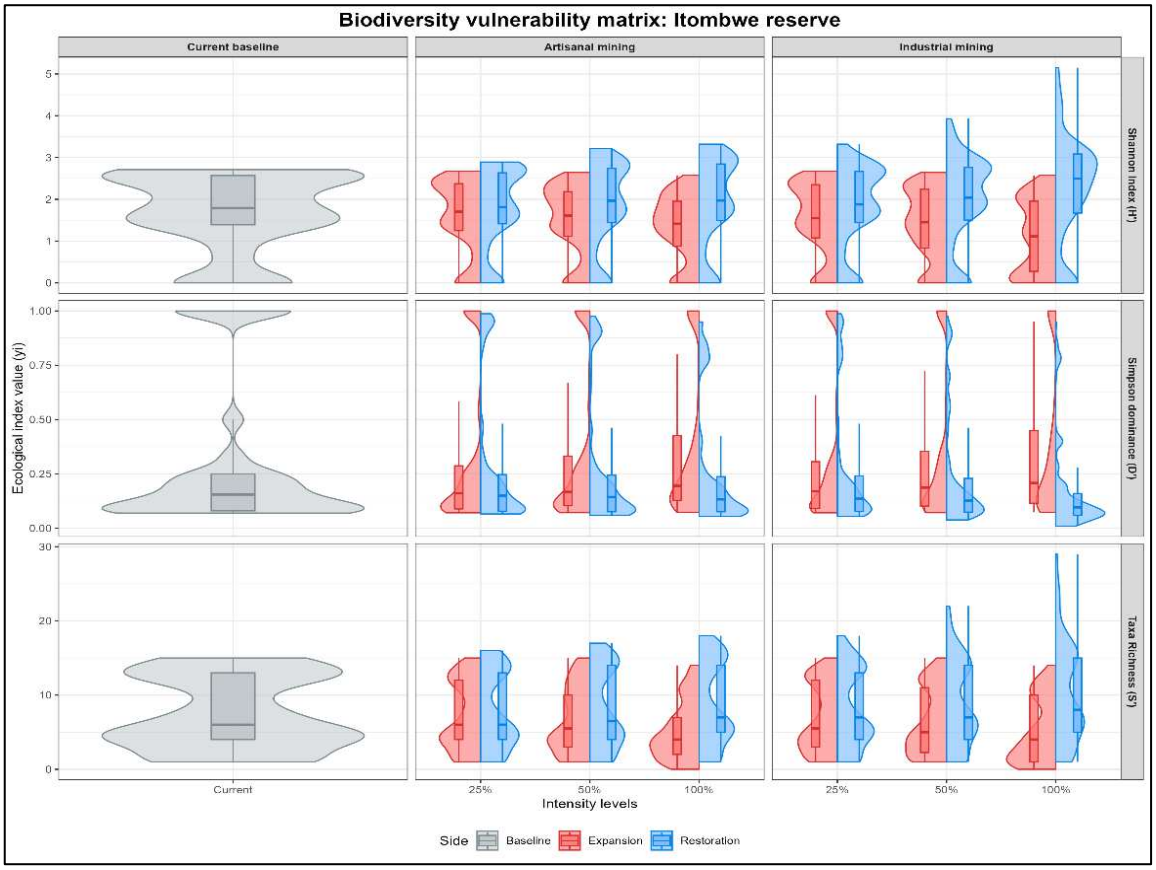


Figure 5:10-year mammalian biodiversity vulnerability matrix: Projections of Shannon, Simpson and Taxa indices under EXP and RST scenarios.

Table 1. Summary of Predicted Values ($\boldsymbol{\mu_i}$) and Credibility Thresholds

Index	Group	Side	Scenarios	μi	Credibility_Low	Credibility_High
Shannon Index (H')	Current baseline	Baseline	Current	1.68	0	2.71
σ (sigma) fixed= 7.05	Artisanal mining	Expansion	25%	1.57	0	2.68
			50%	1.49	0	2.64
			100%	1.32	0	2.57
		Restoration	25%	1.74	0	2.86
			50%	1.83	0	3.15
			100%	1.91	0	3.25
	Industrial mining	Expansion	25%	1.52	0	2.61
			50%	1.39	0	2.51
			100%	1.12	0	2.44
		Restoration	25%	1.79	0	3.12
			50%	1.93	0	3.53
			100%	2.2	0	4.5
Simpson dominance (D')	Current baseline	Baseline	Current	0.31	0.07	1
σ (sigma) fixed= 7.05	Artisanal mining	Expansion	25%	0.32	0.07	1
			50%	0.33	0.07	1
			100%	0.35	0.08	1
		Restoration	25%	0.29	0.07	0.96
			50%	0.27	0.06	0.93
			100%	0.26	0.06	0.95
	Industrial mining	Expansion	25%	0.32	0.07	1
			50%	0.33	0.08	1

			100%	0.36	0.08	1
		Restoration	25%	0.27	0.06	0.95
			50%	0.24	0.05	0.9
			100%	0.17	0.01	0.8
Taxa Richness (S')	Current baseline	Baseline	Current	7.51	1	15
σ (sigma) fixed= 7.05	Artisanal mining	Expansion	25%	7.19	1	15
			50%	6.63	1	15
			100%	5.2	0	14
		Restoration	25%	7.79	1	16
			50%	8.15	1	17
			100%	8.67	1	18
	Industrial mining	Expansion	25%	6.96	1	14
			50%	6.39	1	14
			100%	5.05	0	13
		Restoration	25%	8.06	1	17
			50%	8.73	1	20
			100%	10.02	1	24

Table 2. Coefficients and Parameters of the BGLMM Model

Family	Parameter	Symbol	Mean	SD	Lower CI: 2.5	Upper CI: 97.5	Status
Initial state	(Intercept)	β_0	1.68	0.18	1.33	2.03	Certain
Direct impacts	Intensity	β_1	0	0	0	0	Uncertain
	SideExpansion	β_2	-0.02	0.23	-0.47	0.43	Uncertain
	SideRestoration	β_3	0	0.23	-0.45	0.45	Uncertain
Index weights	IndexSimpson dominance (D')	β_4	-1.37	0.25	-1.86	-0.88	Certain
	IndexTaxa Richness (S')	β_5	5.83	0.25	5.34	6.32	Certain
Interactions	Intensity:SideExpansion	β_6	-0.01	0	-0.01	-0.01	Certain
	Intensity:IndexSimpson dominance (D')	β_7	0	0	0	0	Uncertain
	Intensity:IndexTaxa Richness (S')	β_8	0.01	0	0.01	0.01	Certain
	SideExpansion:IndexSimpson dominance (D')	β_9	0.02	0.33	-0.63	0.67	Uncertain
	SideRestoration:IndexSimpson dominance (D')	β_{10}	0	0.33	-0.65	0.65	Uncertain
	SideExpansion:IndexTaxa Richness (S')	β_{11}	0.28	0.33	-0.37	0.93	Uncertain
	SideRestoration:IndexTaxa Richness (S')	β_{12}	-0.03	0.33	-0.68	0.62	Uncertain
	Intensity:SideExpansion:IndexSimpson dominance (D')	β_{13}	0.01	0	0.01	0.01	Certain
	Intensity:SideExpansion:IndexTaxa Richness (S')	β_{14}	-0.04	0	-0.04	-0.04	Certain
Error	Residual sigma (σ)	σ	7.05	0.91	5.27	8.83	Certain
Validation	Mean PPD	**PPD**	0.13	0.55	-0.95	1.21	Uncertain
Validation	Log-posterior	**lp**	141.25	3.73	133.94	148.56	Certain

4. DISCUSSION

4.1. The Itombwe Dilemma: "Song of the Shovels" and technological signature

The title of this work, "The Song of Shovels at the Heart of Biodiversity," highlights the governance conflict between human survival and ecological integrity. Our results show that the impact on mammalian fauna varies according to the extraction technology:

i. ***Impact of Fragmentation (Craftsmanship):*** It acts through diffuse fragmentation. The use of motor pumps, shovels and picks does not only attack the soil; it saturates the sensory space. The constant "ecological noise" from motor pumps and the proliferation of wells saturates the soundscape, leading to the exclusion of sensitive taxa. Our results show a near-total disappearance of *Proboscidea (Loxodonta cyclotis)* and *Hyracoidea* in areas of high artisanal activity. This finding corroborates the work of Cowan et *al.*, (2024); Kenedy-Siqueira et *al.*,

(2025); Tchatchou et *al.* (2015) on the collapse of forest elephants in the face of the density of micro-human activities in the Congo Basin.

ii. ***Impact of Surface Area (Industrial):*** The use of heavy machinery (bulldozers, excavators) completely strips the habitat. Although surface area encroachment strips habitat, our BGLMM models paradoxically reveal a relative stability of diversity in some concessions. This observation aligns with Kleinschroth et *al.* (2019); Lawer et *al.* (2021), suggesting that centralized management of industrial access routes can limit poaching, unlike the uncontrolled nature of artisanal trails.

4.2. Scenario Analysis (GAM & BGLMM) and Breakdown Threshold Dynamics

The major innovation of this work lies in the mathematical modeling of tipping points, allowing us to anticipate the future of mammalian fauna in Itombwe according to two opposing trajectories: mining expansion and ecological restoration.

i. The 5km Critical Threshold and Connectivity: Our models prove that a distance of 5 km constitutes a safe biological boundary. Below this threshold, we observe a breakdown of mammal communities. This result corroborates the conclusions of Deere et *al.* (2020); Michielsen et *al.* (2023); Tam et *al.* (2021). Mining infrastructure creates a boundary effect that disrupts animal mobility far beyond the visible footprint of the site. For orders such as *Proboscidea (Loxodontata africana)* and *Cetarthiodactyla (Syncerus caffer, Tragelaphus spekei, Neotragus batesi)*, this reduction of safe mobility space leads to population fragmentation, increasing the risk of inbreeding and local extinction.

ii. Expansion Scenarios (25%, 50%, 100%): Our projections using GAM models show an alarming non-linear response. At a 100% expansion stage, species richness collapses to 5.05 species, compared to 7.51 in the baseline state. This shift towards a state of permanent degradation confirms the theory of Gutiérrez-Santillán et *al.* (2019); Mubin, (2025); Short & Darimont (2021) on the loss of resilience. Slow-growing species, including *Primates* (*Gorilla gorille, Pan troglodytes*) and *Pholidotes* (*Manis gigantea*), display critical resilience scores (1-2), which mathematically condemns them to extinction in a landscape saturated by the "*song of shovels*".

iii. Restoration Scenario (Specific Gain Lever): Conversely, restoration modeling shows that an active rehabilitation policy can increase taxonomic richness to more than 10 species per grid cell. This gain is possible thanks to recolonization by generalist species initially, followed by the gradual return of specialists if the 5 km threshold is restored. Our BGLMM models suggest that industrial restoration, although technically complex, offers a more structured recovery potential than abandoned industrial areas, which are often subject to persistent residual degradation (Brancalion et *al.*, 2025; Indrajaya et *al.*, 2022).

4.3. Defaunation and the Realities of the "Sociology of Emergency"

The comparison of our results with the concept of "Defaunation de Dirzo et *al.* (2014) The conclusion is inescapable: the Itombwe Nature Reserve risks becoming an "*empty forest*".

i. Taxonomic vulnerability: Analysis of the orders shows that Carnivora and Artiodactyla are under unsustainable pressure from mechanized mining and associated subsistence hunting. According to Van Vliet (2010) and Xie et *al.* (2025), specialist species lack the biological flexibility to compensate for fragmentation-induced mortality.

ii. ***Biotic Homogenization:*** Without restoration, we are witnessing the replacement of endemic and rare taxa by opportunistic and resilient species. This loss of functional diversity threatens all ecosystem services of the INR, leaving human survival trapped in a "*sociology of emergency*" that destroys its own long-term natural capital (Santos et *al.*, 2022).

5. CONCLUSION AND RECOMMENDATIONS

5.1. General Conclusion

This work, entitled “The Song of Shovels at the Heart of Biodiversity: A Dilemma Between Mining and Mammal Conservation in Itombwe,” highlights the precarious balance of a unique ecosystem in the face of anthropogenic pressures. The combined use of Generalized Additive Models (GAMs) and Bayesian Generalized Linear Mixed Models (BGLMMs) made it possible to scientifically quantify what field observations suggested: mining activity is the primary driver of the disruption of mammal communities in the Itombwe National Reserve.

Our results confirm the existence of a critical threshold at 5 km. Below this distance, species mobility is severely compromised, leading to a collapse in species richness. The predictive scenarios are unequivocal: unregulated mining expansion (100% scenario) would lead to near-total defaunation, reducing diversity to only 5.05 species and promoting biotic homogenization in favor of opportunistic species. Conversely, our models demonstrate that an active restoration policy could reverse this trend, allowing for the recovery of 10 species per grid cell.

Finally, this study highlights that the problem is not merely technical but profoundly sociologic*al.* The "sociology of urgency," driven by structural poverty, transforms small-scale miners into unwitting agents of ecological destruction. The "sound of shovels" can only be stopped if conservation offers a viable economic alternative, capable of resolving the dilemma between starving today and losing their natural heritage tomorrow.

5.2. Recommendations

To guarantee the survival of iconic taxa (Gorillas, Forest Elephants, Pangolins) by 2036, the following measures are recommended:

5.2.1. In terms of spatial and scientific management:

i. *Protecting critical areas:* Impose a moratorium on all mining activity and movement of heavy machinery within a minimum radius of 5 km around identified habitat areas of large mammals.
ii. *Mandatory catering plan:* Make the granting of industrial concessions conditional on an immediate ecological rehabilitation plan, financed by the operators, to restore the connectivity of stripped habitats.
iii. *Monitoring of "ecological noise":* Regulate the use of motor pumps and dynamite in industrial areas to reduce noise pollution that fragments the vital habitats of wildlife.

5.2.2. In terms of policy and governance:

i. *Economic transition:* Develop microcredit programs and income-generating activities (IGAs) as alternatives to mining for local communities, in order to reduce dependence on the "sociology of emergency".

ii. *Collaborative governance:* Create joint management committees (ICCN, local communities and mining operators) to ensure transparent and respected zoning of conservation areas.
iii. *Legislative strengthening:* Integrate mammalian resilience thresholds (scores 1-2) into the national Mining Code as criteria for suspending activities in the event of a critical threat to protected species.

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Data Availability
The datasets generated and/or analyzed during the current study are available from the corresponding author upon reasonable request.

Conflict of Interest
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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