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Prioritizing underground roosts for bat conservation in Kenya

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ABSTRACT

Identifying key wildlife resources is vital for lasting conservation efforts. Bats disperse seeds, pollinate plants, consume insects, and support cave-dependent organisms. However, they face significant threats from habitat loss, fragmentation, degradation, mining, cave tourism, cave closures, evictions, and superstitious persecution. Most of Kenya's bat species roost in caves outside the country's 10% of protected areas, where cave conditions and species remain largely unknown. We employed the Scalable Bat Cave Vulnerability Index (BCVI-S) to assess the conservation priorities of bat cave roosts in Kenya, aiming to identify the most vulnerable ones and establish priorities for effective conservation. BCVI-S has two components: (1) Biotic Potential (BP), which evaluates cave's ecological value through bat species richness, abundance, and the presence of threatened and endemic species, and (2) Biotic Vulnerability (BV),which measures human disturbance. Bat assemblages in protected area caves was different than those on unprotected community lands, with *Otomops harrisoni* contributing to differences between these two groups. Bat species diversity declined near urban areas. Caves with threatened species showed moderate vulnerability, which demonstrates the importance of targeted conservation efforts. Caves in protected areas showed greater Biotic Potential and lower vulnerability scores than those on unprotected community lands. These findings justify the need to incorporate species-level data and indicators of human intrusion in conserving cave-dwelling bats. The BCVI-S is a structured tool for identifying those caves, which are vulnerable, leading to their preservation, planning, empowering local management, and supporting evidence-based policy development.

1. Introduction

Bats (Mammalia: Chiroptera) represent one of the most diverse and ecologically pivotal mammalian taxa, comprising over 1500 species globally (Simmons and Cirranello, 2024). They provide essential ecosystem services, including pollination, seed dispersal, and insect population control, that support forest regeneration, enhance agricultural productivity, and suppress pest and vector populations (Kunz et al., 2011). Despite their ecological and economic values, bats remain highly misunderstood and under-protected mammals, and are threatened by human persecution, habitat loss and degradation (Waltz, 2024).

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Bats use several roost types that can be categorized into three primary groups (Wilson, 2015): trees (using natural crevices and hollows or artificial structures within trees), built-up areas (such as buildings, bridges, and tunnels), and subterranean structures (such as caves, mines, volcanic tunnels, cliffs and talus, human built structures like bat boxes/houses). Globally, caves are indispensable roosting habitats for numerous bat species, offering stable microclimates that support key life-history processes such as breeding (Legros, 2023). However, their fixed locations and accessibility make them highly susceptible to human encroachment and disturbance with activities such as mining (e.g., limestone extraction and quarrying), unregulated cave tourism, vandalism, guano extraction, urban sprawl and agricultural expansion, and infrastructure development (Furey and Racey, 2016). These impacts have either led to loss of caves or degraded them worldwide, leading to roost abandonment and localized bat population declines (McCutchan, 2021); Tanalgo *et al.*, 2022). Additionally, pollution from litter and groundwater contamination, along with the effects of invasive species, further jeopardizes these habitats (Frick et al., 2020).

In Sub-Saharan Africa, cave-dwelling bats are diverse and many of them are endemic, threatened,and strictly dependent on cave systems for diurnal roosting and breeding (Monadjem et al., 2024). However, cave ecosystems remain poorly studied and inadequately protected, particularly outside major conservation areas, Increasing limestone extraction and the expansion of agricultural frontiers have heightened cave disturbance risks across the continent, while subterranean biodiversity remains marginal in national conservation planning (Mammola et al., 2022).

Caves in Kenya are essential for sustaining the diversity of more than 100 bat species found in the country (Patterson & Webala, 2012; Musila et al., 2019). Kenya's Bat species diversity include obligate cave roosting taxa, within the families Rhinolophidae, Hipposideridae, Miniopteridae and Emballonuridae (Patterson et al., 2020; Webala et al., 2019).The caves are found in a variety of ecosystems, ranging from the montane forests of the Rift Valley to the coral rag landscapes found in the coastal region. Most caves in Kenya are located outside of officially protected areas and are increasingly vulnerable to threats, such as limestone quarrying, unregulated cave tourism, and land conversion. The lack of systematic monitoring and the limited inclusion of cave habitats into national conservation frameworks pose significant challenges to the sustainability of bat populations.

Even though caves within protected areas, like parks and reserves, provide some refuge for bat species, their effectiveness in protecting bat populations amid various human disturbances remains unclear. Absence of standardized assessment regimes also restricts conservation on priority list as the traditional biodiversity monitoring system fails to reflect much concern on the subterranean habitats and does not tend to incorporate the ecological value with the human impact. Effective decision-making requires comprehensive approaches that incorporate both biological and landscape-level factors. It is possible to successfully solve the problem using comprehensive procedures that would involve biological and landscape level parameters. The Scalable Bat Cave Vulnerability Index

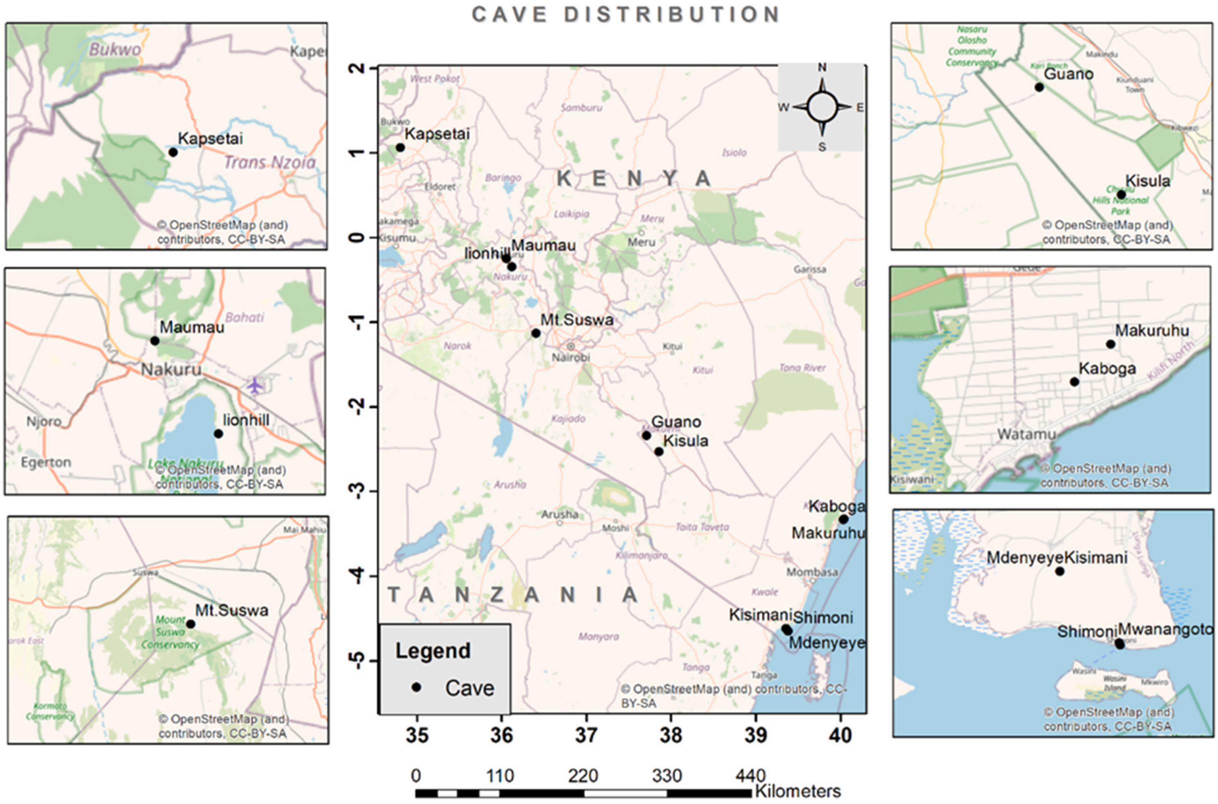

Fig. 1. Map showing spatial arrangement of study caves in Kenya. Base map derived from OpenStreetMap data (© OpenStreetMap contributors) and modified for this study.

(BCVI-S) seals this gap by incorporating species richness, endemism, IUCN threat, and spatial and observational data of human disturbance such as distance to roads, urbanization, presence of direct human threats to the cave, i.e. guano mining or cave tourism (Tanalgo and Hughes, 2025). This pilot research on caves in protected sites and those in community lands in Kenya provides baseline vulnerability ranking, and data towards evidence-based conservation and ecological assessment. We hypothesized higher biotic potential, would support larger, more diverse bat assemblages, including threatened species, while caves near altered landscapes would exhibit higher vulnerability and lower bat species diversity. Given the limited cave biodiversity data in Kenya and Africa, this work contributes to ongoing efforts to prioritize key roosts and offers a scalable approach for bat conservation in East Africa, following similar approaches applied elsewhere, such as Bulgaria (Deleva et al., 2023). The study assessed the vulnerability of sampled caves and concentrated on the effects of anthropogenic stress on bat species diversity and provided the metrics to inform conservation planning. The findings are anticipated to enhance evidence-based cave conservation and provide a scalable model for prioritizing the protection of roosts in East Africa.

2. Methods

2.1. Study area and cave selection

A purposive sampling technique was used to select cave sites for this study, based on three main criteria: accessibility, presence of bats, and variation in human disturbance levels. While limited in number, these caves were selected to capture the full gradient of ecological variation and human disturbance, across Kenya, representing sites in both protected areas and in unprotected community lands, critical for piloting BCVI-S assessments. The selected caves were distributed across three ecological regions in Kenya: Coastal/ Southeastern, Rift Valley, and Western, drawing on documented underground bat roosts reported in the literature (Musila *et al.*, 2019; (Kennedy, 1998); Wilson, 2015; Fig. 1). Caves situated within protected areas such as national parks and reserves, benefit from controlled human access whereas caves on unprotected community lands are exposed to disturbance and degradation.

Coastal caves, such as Mdenyenye and Kisimani, that are found in humid tropical climates are prone to a significant human impact such as tourism and farming activities. In the Rift Valley, Mt. Suswa and Mau Mau caves, are within community lands whereas Lion Hill (in Lake Nakuru National Park) is found in a woodland savannah and is subjected to moderate controlled disturbances such as hiking and regulated expansion of settlements. The Western region was represented solely by Kapsetai cave, selected due to its montane climate and extreme agricultural pressure resulting from subsistence farming driven by local climatic conditions. We sampled each twice in the period between September 2024 and February 2025. This purposive sampling strategy captured a comprehensive gradient of human disturbance and ecological variation, forming the basis for developing BCVI-S.

2.2. Bat species sampling

Two automatic bat detectors (Song Meter SM4BAT FS & ZC Bat Detectors: Wildlife Acoustics Inc., Massachusetts, USA) were used to record bat echolocation calls at each cave. Every cave was sampled for two consecutive nights with detectors operating from dusk to dawn. Detectors were positioned one meter above the ground and retrieved each morning to download and process data. Bat echolocation calls were analysed using, Kaleidoscope Pro software (Wildlife Acoustics; https://www.wildlifeacoustics.com/products/kaleidoscope-pro) and matched against reference libraries. However, because no published echolocation calls libraries exist for Kenyan bats and not all recorded bats could be physically captured and identified, call identifications were supported by an unpublished dataset provided by P. W. Webala, which includes species from Kenya and neighboring countries (Tanzania, DRC, Rwanda, Uganda, Ethiopia, and Djibouti). This extensive call library has been built in the course of systematic sampling of Kenya's bat fauna, supported by associated genetic and morphological analyses (Demos et al., 2019 (Scotophilus), 2019b (Nycteridae), 2020 (Miniopterus)); (Patterson et al., 2019) (Myotis), 2020 hipposiderids); Webala et al., (Webala et al., 2019) (HDC bats); Monadjem et al., (Monadjem et al., 2021) (vespers).We supplemented the library by recording released, free-flying bats at capture sites.

Bats were identified by examining call parameters such as peak frequency, duration, and bandwidth, and comparing them with Webala's unpublished library of bat vocalizations (P.W Webala, unpublished results, 2024). All acoustic identifications were verified by co-author Paul Webala. Bat capture surveys were conducted using hand nets and occasionally mist nets, and bats were released at the respective capture sites near caves. In bat research this method is commonly used to detect species that are rarely observed and challenging to capture by hand and identify by hand (Solick et al., 2024).

Bat population estimates in each cave, were collected through direct observation and quadrat sampling in accordance to Kunz et al. (Kunz et al., 2009). Abundance values were standardized by converting them into ordinal categories (Arita, 1996). This scale categorizes bat abundance into six levels: 0 (no individuals observed), 1 (1–10), 2 (11–100), 3 (101–1000), 4 (1001–10,000), and 5 (>10,000) (Phelps and Kingston, 2018). This method offers a semi-quantitative approach that is particularly useful for assessing bat populations in areas where precise counts are difficult such as complex caves with limited visibility, or caves with large species aggregation.

2.3. BCVI-S scoring and integration

The BCVI- S was calculated following the framework of Tanalgo and Hughes (2025) which combines Biotic Potential (BP) and Biotic Vulnerability (BV). BP was derived from species richness and abundance data for both total and IUCN-threatened bat species recorded at each cave.

To assess BV, both spatial and on-site data were collected. A handheld GPS device was used to georeference each cave (elevation and entrance coordinates).The habitat characteristics surrounding the cave entrance were documented as agroforest, natural forest, and shrubland among the classifications to describe the vegetation type at or close to the cave entrance.

Additionally, a Land Use/Land Cover (LULC) map was generated by clipping a recent classified raster to the study area, including

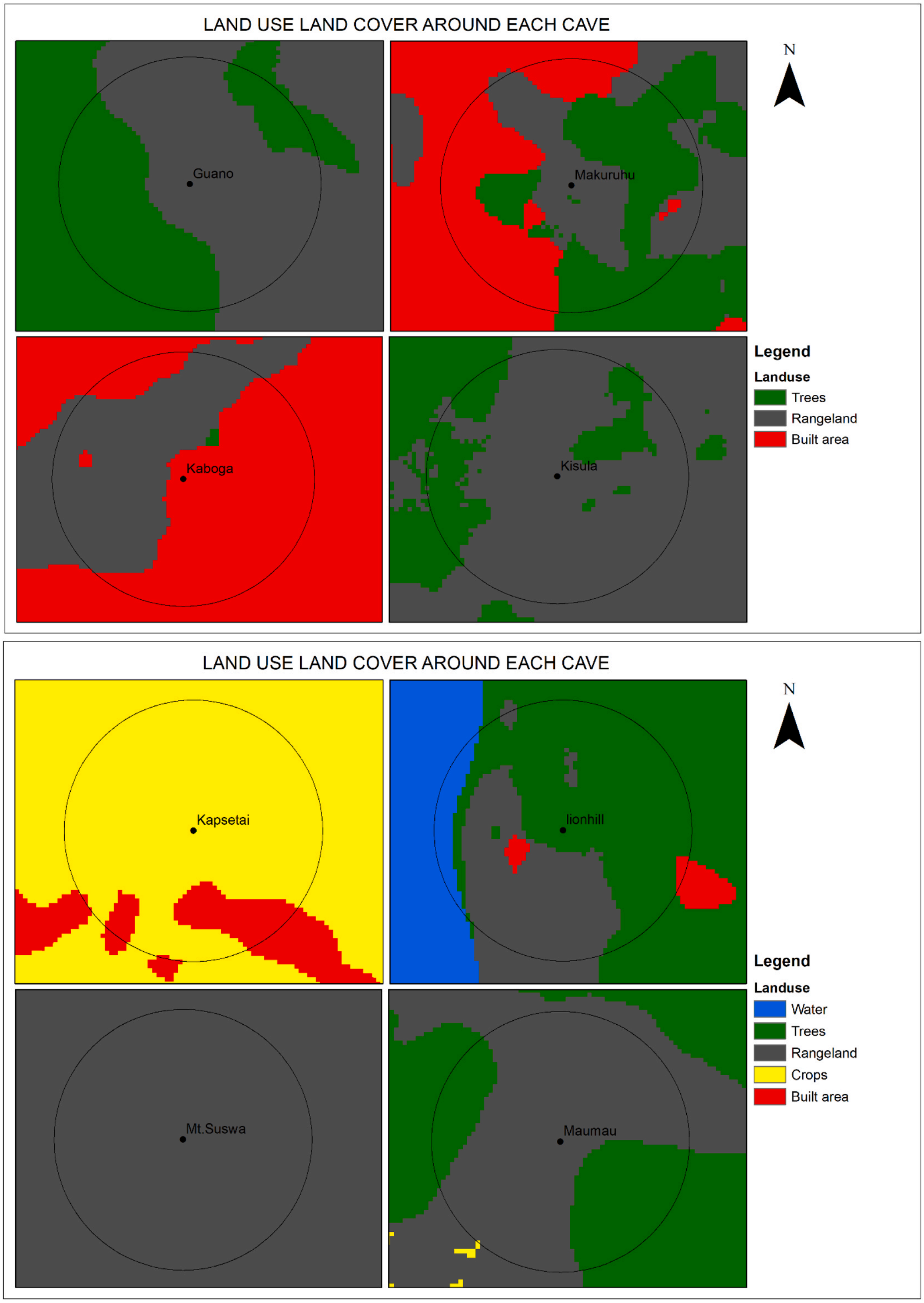

Fig. 2. Surrounding landscape context of each cave indicating adjacent land-use types.

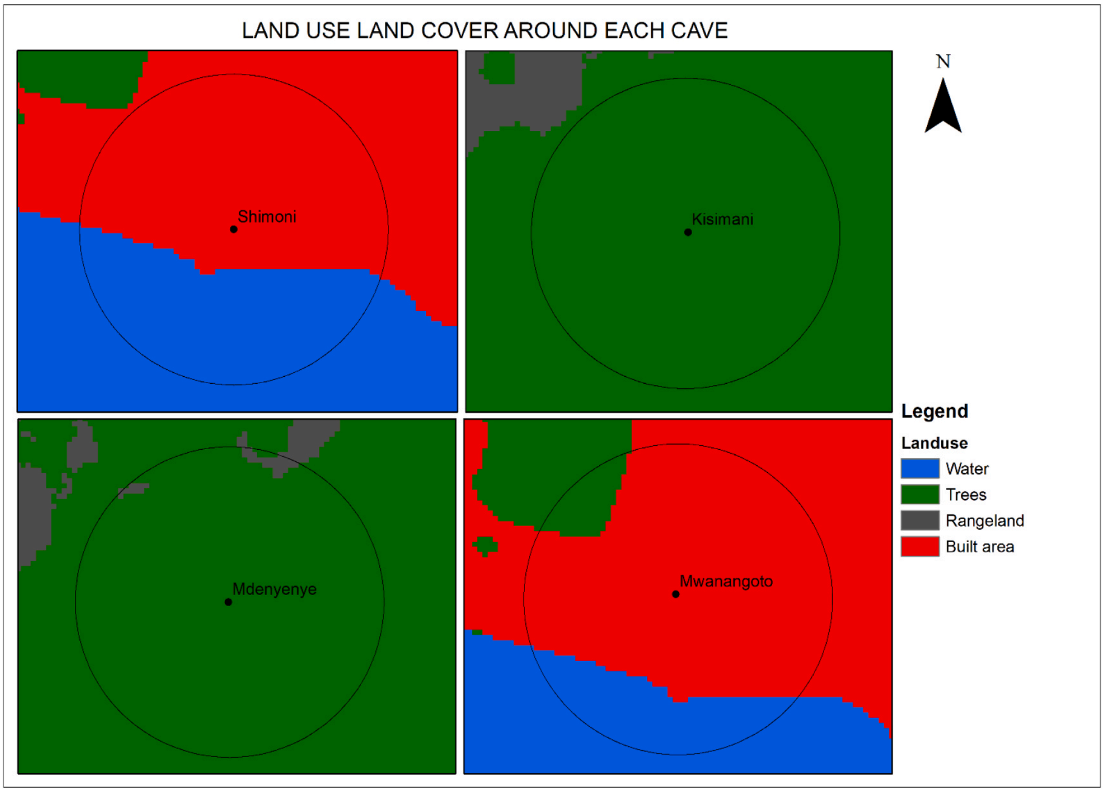

Fig. 2. (*continued*).

land use categories such as forest, shrubland, agriculture and bare land (Fig. 2). Vegetation cover around caves was assessed in terms of tree density estimates estimated from classified values of Normalized Difference Vegetation Index (NDVI) obtained from Sentinel-2 imagery *(*https://livingatlas.arcgis.com/landcover*)*.

Furthermore, spatial data, on-site assessments of human activities were recorded at each cave to capture direct human disturbance variables. Observations focused on four key disturbance categories: cave use level (e.g., guano harvesting, tourism, religious use), habitat loss (e.g., deforestation near cave entrances), pollution (e.g., litter), and structural disturbance (e.g., vegetation clearance). These activities were recorded by use of a standardized observation checklist. After verification, coded into a disturbance matrix. Each activity was scored and also depending on its intensity and frequency allowed for comparison across different sites.

A Landscape Threat Score (LandT) in accordance with the approach of Tanalgo and Hughes (2025), was calculated by analysing essential environmental variables surrounding each cave, including NDVI (vegetation cover), slope, elevation, and land use intensity. Each variable was scored on a scale from 1 to 4, where 1 indicated greater vulnerability to disturbance (e.g., degraded habitats, steep slopes, low vegetation cover), and 4 represented more intact habitat (e.g., forested areas, flat terrain, higher NDVI). The scores for all variables were summed to produce a composite LandT score, which was incorporated as a component of Biotic Vulnerability (BV) in the BCVI-S framework.

2.4. Data analyses

The Scalable Bat Cave Vulnerability Index – Species-based (BCVI-S) was calculated following the methodology of Tanalgo and Hughes (2025).

Biotic Potential (BP) was derived from species richness and abundance data and IUCN-threatened bat species recorded at each cave. First, an initial Biotic Score (Bio-S initial) was calculated by normalizing species abundance in each case against the maximum abundance across all caves. This normalized value was multiplied by species richness, and summed across all species as:

$$\text{Bio-S initial cave x} = \sum (\text{Rpops} \times \text{Spops}) + (\text{RE} \times \text{SE}) + (\text{Rcons} \times \text{Scons})\ \text{Rcons}$$

where Rpops is the relative abundance of bat species in cave x, Spops is species richness in cave x, RE is the relative abundance of bats in cave x, SE is the number of endemic bat species in cave x, and Rcons is the relative abundance, and (Scons) richness of threatened species. The Biotic Potential was then derived as:

$$\text{BP cave x} = \text{Bio-S initial cave x} \,/\, \text{Bio-S max}$$

Yielding a score between 0 and 1,with higher values indicating greater biological potential. Caves were subsequently classified into four priority levels of ecological importance following Tanalgo and Hughes (2025).

Biotic Vulnerability (BV) was assessed using spatially modeled human disturbance gradients and quantified direct observation human disturbance gradients (Tanalgo *et al.* 2018, 2025):

Spatially modeled BV: human disturbance gradients were quantified using geospatial variables including NDVI, elevation, slope, and distances to urban areas, roads, and water bodies. Each variable was normalized to a 0–1 scale then combined to produce a composite landscape score (Land Score T).

$$\text{BV cave x} = \Sigma\ \text{LandT}/\text{N}\circ\text{T}$$

where LandT is the average score for each threat and N∘T is the number of threats assessed

resulting in a value ranging between 0 and 4, with higher scores indicating greater vulnerability.

Onsite BV: Field observations recorded anthropogenic activities such as guano harvesting, tourism, habitat degradation, pollution, and structural disturbance. Each threat was scored based on intensity and frequency using a standardized checklist modified by Tanalgo *et al.* (2018).The final Biotic Vulnerability index integrated both spatial and onsite BV measures to provide a comprehensive assessment of human pressures. Caves were then grouped into four categories of Vulnerability each reflecting levels of disturbance as interpreted from Tanalgo *et al.* (2025).

2.5. *The BCVI-S calculation*

The BCVI-S was calculated as a product of Biotic Potential and Biotic Vulnerability:

$$\text{BCVI-S} = \text{BP} \times \text{BV}$$

where BCVI-S is the combined effect of ecological importance and vulnerability of each cave.

To facilitate interpretation, BCVI-S values were grouped into four priority levels derived from combinations of Biotic potential scores and Biotic Vulnerability scores, following the classification scheme of Tanalgo and Hughes (2025).

2.6. *Statistical analyses*

Spearman rank correlations were used to examine the relationship between BP, BV and bat community metrics including total species richness, total abundance, threatened species richness and abundance. Prior to analyses, data normality was tested using the Shapiro-Wilk test confirming the suitability of using non-parametric methods. All statistical procedures were performed in R-studio (R Core (Team, 2023).

3. Results

We surveyed a total of 12 caves, of which 3 caves were in protected areas, and 9 in community lands. Spatially, caves were distributed across three regions: Coastal/Southeastern (8 caves), Rift Valley (3 caves), and Western (1 cave). These sites supported 24 bat species from 11 families.

3.1. *Biotic potential (BP)*

Biotic Potential (BP) index varied significantly in the twelve caves, with differences in values ranging between 0.00009 in Kapsetai Cave up to 1.0000 in Makuruhu Cave. Based on the BP, most caves were categorized as Level 4, classification thresholds (Tanalgo *et al.* 2018; 2022), indicating low species richness and few threatened species (Table 1). Notably, Mdenyenye and Makuruhu recorded the

Table 1
Biotic potential scores with level 1denoting highest biotic potential and level 4 lowest biotic potential.

Cave	Biotic potential (BP)	BP level
Makuruhu	1	Level 1
Mdenyenye	0.7825	Level 1
Mt. Suswa	0.5531	Level 3
Guano	0.1493	Level 4
Kaboga	0.0070	Level 4
Kapsetai	0.0001	Level 4
Kisimani	0.0947	Level 4
Kisula	0.0307	Level 4
Lion Hill	0.0016	Level 4
Mau Mau	0.0041	Level 4
Mwanangoto	0.0013	Level 4
Shimoni	0.0015	Level 4

highest BP scores of 0.7472 and 1.0000, respectively, thereby qualifying them as Level 1 caves. These caves exhibited high bat species richness and abundance, including the occurrence of endangered species, and thus the highest priorities of conservation intervention (Table 1).

3.2. Biotic vulnerability (BV)

Spatially modeled data exhibited variation in Biotic Vulnerability (BV) scores among the surveyed caves, ranging from 0.049 to 0.686. Based on the classification thresholds on Tanalgo and Hughes (2025), three caves had the lowest BV scores, including Kapsetai (BV = 0.135), Lion Hill (BV = 0.049), and Mau Mau (BV = 0.162), were assigned to Level A. In contrast, Guano (BV = 0.686) and Kisula (BV = 0.658) were classified as Level D, indicating low vulnerability (Table 2).

3.3. Biotic vulnerability based on onsite observations

BV scores derived from direct field observations varied among caves, reflecting differing levels of exposure to onsite anthropogenic and environmental threats. Shimoni cave recorded the highest vulnerability score of 0.833, which places it in Level A (high vulnerability). In contrast, the lowest BV scores at Lion Hill (0.208), Kisula (0.167), and Guano caves (0.083), which were classified under Level D (low vulnerability, Table 3).

3.4. Comparison of biotic vulnerability scores based on spatial data and onsite observations

Shimoni had the highest BV score based on onsite observations, while Kaboga and Mwanangoto caves showed higher BV scores in on-site observations compared to their spatial BV scores. Lion Hill and Kisula caves were consistently ranked as low vulnerability across both approaches (Tables 2 and 3).

3.5. Land use context within cave surrounding

The 300-meter buffer zone maps depicted the land use types surrounding each surveyed cave. (Fig. 2). Coastal/Southeastern caves were largely bordered by a mix of range land, trees, and built-up areas. Rift Valley caves were adjacent to range land, trees, while the western region cave was surrounded by cropland.

3.6. BCVI-S scores

The BCVI-S scores for the twelve surveyed caves showed variation in conservation priority levels. Mt. Suswa was classified as a Yellow Priority site, indicating moderate diversity under high threat (Table 4).

3.7. Spearman rank correlation analysis between biotic potential, biotic vulnerability, and bat assemblage metrics

The Spearman correlation analysis revealed robust positive associations among the BCVI-S, BP, and total bat abundance. BCVI-S and BP exhibited a near-perfect correlation ($\rho = 0.964$, $p < 0.001$), while the total bat abundance was also strongly and positively correlated with both BP ($\rho = 0.964$, $p < 0.001$) and BCVI-S ($\rho = 0.927$, $p < 0.001$, Table 5).

3.8. Spearman rank correlations between biotic vulnerability and patterns by protection status

The Spearman correlation analysis revealed no statistically significant relationships between the BV and both total species richness ($\rho = -0.140$, $p = 0.665$) and total bat abundance ($\rho = -0.350$, $p = 0.264$). In contrast, BV showed a positive but non-significant

Table 2
Biotic vulnerability scores with level A indicating highest level of biotic vulnerability and D lowest level.

Cave	BV_index	BV_Level
Guano	0.6864	D
Kaboga	0.3745	B
Kapsetai	0.1358	A
Kisimani	0.2094	B
Kisula	0.6578	D
Lion Hill	0.0491	A
Makuruhu	0.3968	B
Mau Mau	0.1622	A
Mdenyeye	0.2091	B
Mt. Suswa	0.2296	B
Mwanangoto	0.2209	B
Shimoni	0.2222	B

Table 3

Biotic vulnerability (BV) results derived from onsite observations, with A denoting the highest level of biotic vulnerability and D indicating the lowest level.

Cave	Total score	BV status
Shimoni	0.833	A
Kaboga	0.708	B
Mwanangoto	0.525	B
Kapsetai	0.433	C
Mt. Suswa	0.392	C
Mdenyenye	0.342	C
Mau Mau	0.308	C
Kisimani	0.267	C
Makuruhu	0.267	C
Lion Hill	0.208	D
Kisula	0.167	D
Guano	0.083	D

Table 4

Scalable bat cave vulnerability index scores (Blue color = high to low threat with low diversity; Green = high diversity with low threat; Yellow =moderate diversity under high threat).

Cave	BCVI_S	Priority color
Guano	0.0124	Blue
Kaboga	0.0050	Blue
Kapsetai	0.0001	Blue
Kisimani	0.0253	Blue
Kisula	0.0051	Blue
Lion Hill	0.0003	Blue
Makuruhu	0.2670	Green
Mau Mau	0.0013	Blue
Mdenyenye	0.2676	Green
Mt. Suswa	0.2168	Yellow
Mwanangoto	0.0007	Blue
Shimoni	0.00126	Blue

Table 5

Spearman rank correlation results comparing BP, BV and bat assemblage metrics.

Var1	Var2	Correlation	P_value
BCVI_S	BP	0.964	< 0.001
Total abundance	BP	0.964	< 0.001
BP	BCVI_S	0.964	< 0.001
Total abundance	BCVI_S	0.927	< 0.001
BP	Total Abundance	0.964	< 0.001
BCVI_S	Total Abundance	0.927	< 0.001

correlation with threatened species richness ($\rho = 0.308$, $p = 0.330$) and threatened species abundance ($\rho = -0.064$, $p = 0.844$). Further, total bat abundance was moderately correlated with threatened species abundance ($\rho = 0.655$, $p = 0.012$) and threatened species abundance was strongly and significantly associated with threatened species richness ($\rho = 0.902$, $p = 0.0007$).

A significant positive correlation was observed between total bat abundance and threatened species abundance in protected caves ($\rho = 0.89$, $p = 0.04$), and threatened species abundance was strongly correlated with threatened species richness ($\rho = 0.97$, $p = 0.007$, Table 6)

A significant positive relationship was observed between Shannon diversity and the BV score in unprotected caves ($\rho = 0.83$, $p = 0.02$).The Shannon Diversity Index increases alongside BV scores, with orange points representing unprotected caves (e.g.,

Table 6

Spearman rank correlation results by protection status of caves, showing relationship between bat abundance, threatened species abundance, threatened species richness, Shannon diversity index and Bat Vulnerability score.

Cave protection status	Variable 1	Variable 2	Spearman's rho	p-value
Protected	Total abundance	Threatened species abundance	0.894	0.041
Protected	Threatened species abundance	Threatened species richness	0.968	0.007
Unprotected	Shannon Diversity index	Bat Vulnerability Score	0.829	0.021

Shimoni) clustering at higher BV scores, while protected caves represented by blue points (e.g., Lion Hill) cluster at lower vulnerability levels (BV < 0.4, Fig. 3).

Having caves classified by their protection status, distinct patterns emerged: caves in protected areas (Kisula, Guano and Lion Hill) showed lower BV scores, whereas caves in unprotected community lands (e.g., Shimoni, Makuruhu) exhibited higher BV scores (Fig. 4).

4. Discussion

This study marks the inaugural application of the BCVI-S in Kenya to evaluate conservation priorities for bat caves. The study revealed that bat species diversity declined closer to urban areas. Caves like Mt. Suswa, Mdenyenye, and Shimoni, despite being on unprotected community lands, harbored threatened species, underscoring the importance of unprotected caves on community lands as roost sites of threatened bat species such as *Taphozous hildegardeae* and requiring targeted conservation measures (Furey and Racey, 2016).

Its success as a unifying measure of anthropogenic influence on the vulnerability of caves is shown by the strong positive correlations between BV scores and disturbance pressures, and the negative linkage with bat species proves that anthropogenic stressors negatively affect the quality of roosts and diminish ecological heterogeneity (Erasmy, 2022).

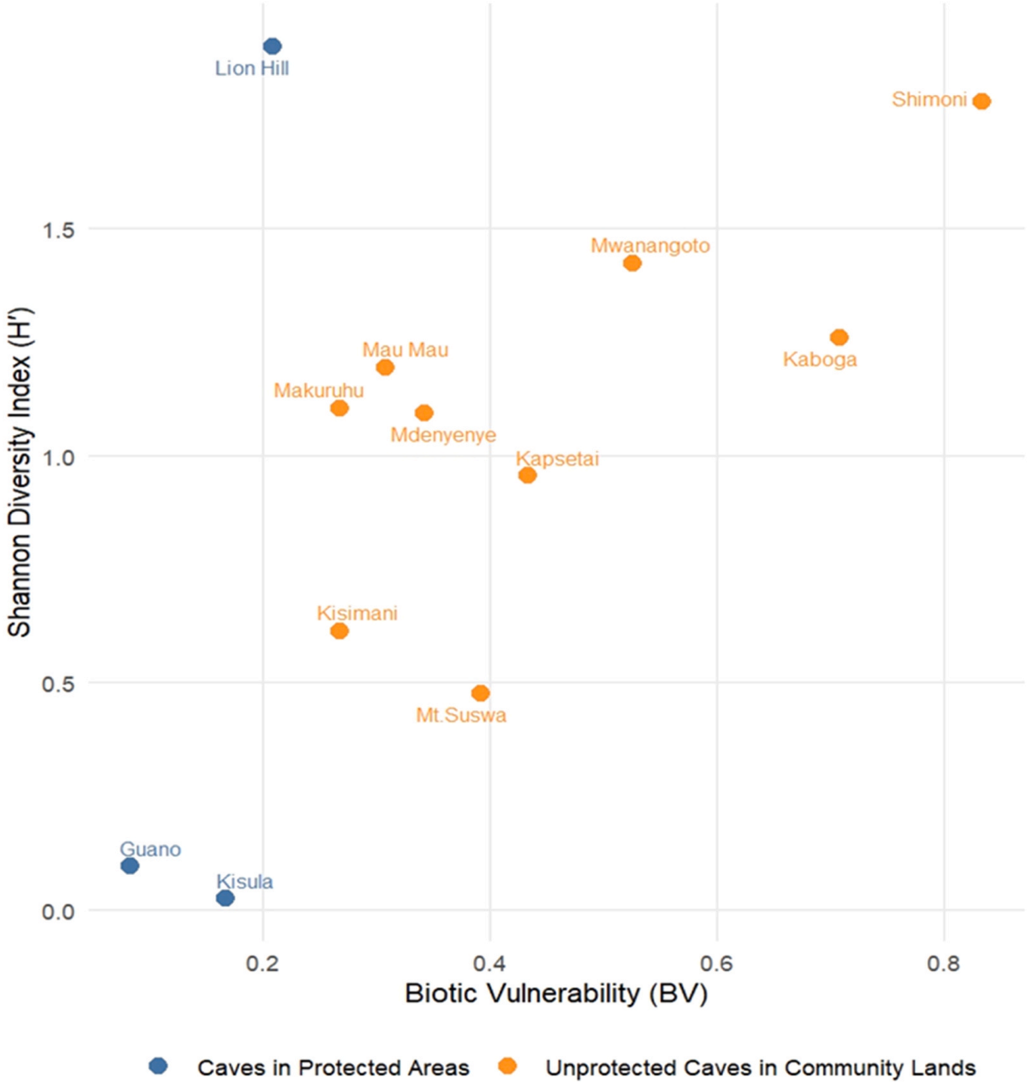

Fig. 3. Scatter plot shows relationship between Shannon diversity index and Biotic Vulnerability (BV) scores.

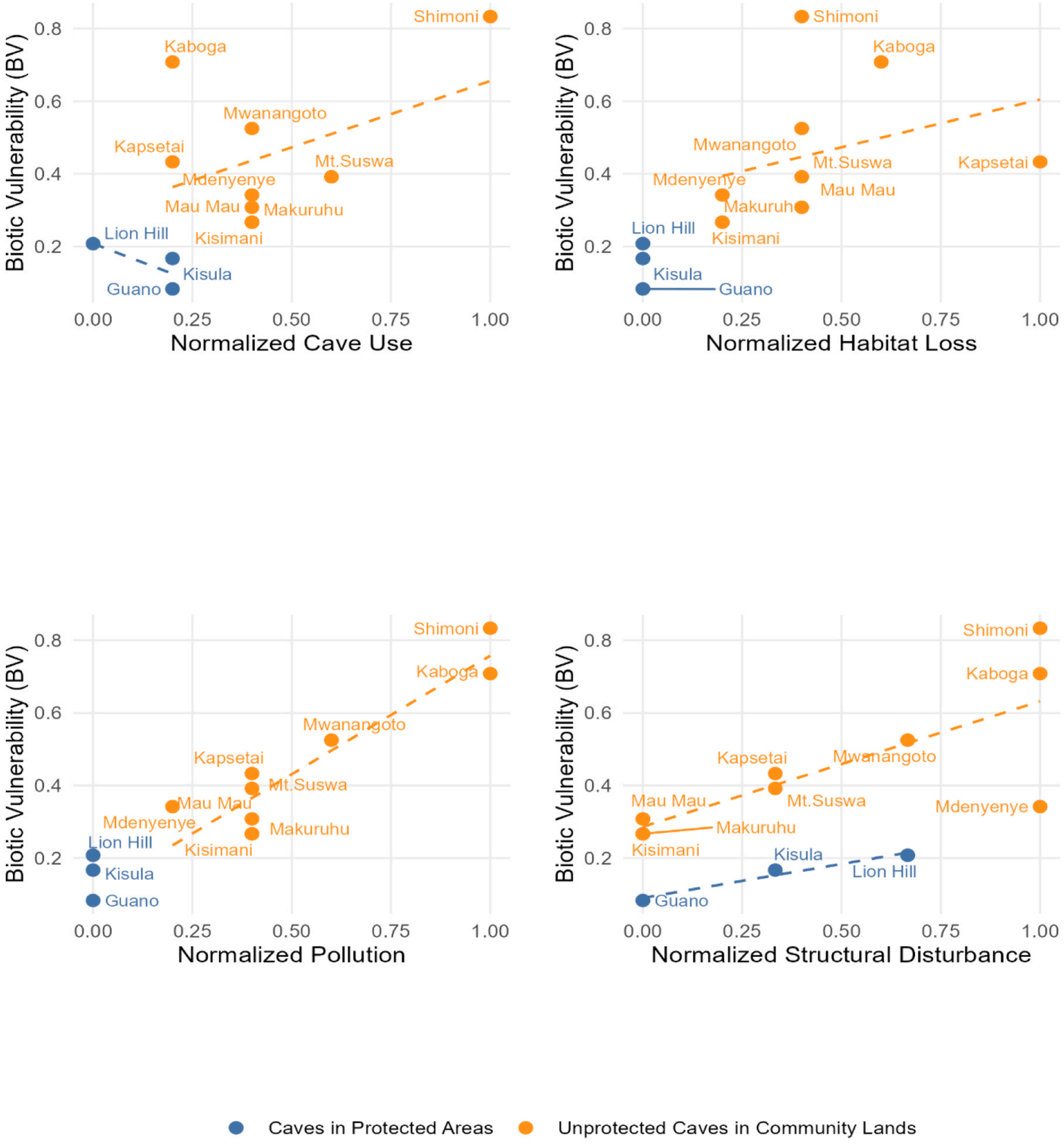

Fig. 4. Scatterplot showing relationship between Onsite Human Disturbance Variables (cave use, habitat loss, pollution and structural disturbance and Biotic Vulnerability (BV) Scores. Caves in protected areas (Blue) show lower BV compared to caves in unprotected areas (Orange).

4.1. *Extensive protection status: comparison of vulnerability patterns in caves*

Although it was anticipated that there would be a higher bat species diversity in caves within protected areas in Kenya due to reduced level of human disturbance, our findings showed a complex scenario. Caves in unprotected community lands, such as Mdenyenye and Makuruhu, scored high BP values comparable to those in formally protected areas, reflecting their significance as key roosting habitats despite lacking formal protection (Frick et al., 2020). Lion Hill cave, located within the protected Lake Nakuru National Park, scored an unexpectedly high BV score, highlighting that designation of protection status alone may not necessarily mitigate human disturbance for bats (Tanalgo and Hughes, 2025). Moreover, low Bat species diversity in some caves in protected areas may reflect ecological and historical constraints rather than current management failure, including limited cave structural complexity, naturally low regional species pools or effects of past disturbance prior to gazettement (Furey and Racey, 2016; Mammola et al., 2022)

Spearman Rank Correlation analyses highlighted distinct patterns between caves located in protected areas and those in unprotected community lands. In protected sites, a strong positive association was observed between total abundance and the number of threatened species, underscoring the importance of protected sites refuges for sensitive taxa. In contrast, caves in unprotected areas showed a positive correlation between Bat species diversity and vulnerability,reflecting the influence of human activities, whereas caves in protected areas showed lower vulnerability and no corresponding increase in diversity. Similar patterns have been reported elsewhere, where legal protection has not prevented pressures from tourism, guano extraction and quarrying (Furey and Racey, 2016); Tanalgo *et al.,* 2022). These findings suggest that effective cave conservation requires more than legal designation; it must also include enforcement, site-specific management, and community participation to safeguard bat populations.

4.2. Biotic potential (BP) and biotic vulnerability as an indicators of cave ecological value and conservation priority

We found that BP, total bat abundance, and BCVI-S had positive relations, which suggest that caves with higher biotic potential harbor larger and more diverse bat assemblages, including species of conservation interest. This is in line with the previous research that emphasize on the importance of key roosts in maintaining viable bat populations and biodiversity (Kingston et al., 2013; Mammola et al., 2022). High BP caves like Mdenyenye and Makuruhu play a vital part in the crucial life stages of breeding, that indicates ecological value as well as adaptation to moderate levels of anthropogenic pressures. However, Mt. Suswa, a yellow priority site, had a moderate BP despite elevated BV, suggesting persistence of bat communities under human influence, but these observations are to be interpreted with care since the study was conducted on a short-term basis. This observation is in line with global evaluations that support the need to focus on caves based on biodiversity and exposure to threats to determine resilient systems (Tanalgo *et al.*, 2022; 2025). Nevertheless, the relationship can fluctuate across regions, which is why long-term monitoring is necessary to identify early signs of biodiversity loss (Frick et al., 2020). The use of endemic and threatened species in the BP calculation is one of the conservation priorities advocated by the IUCN and the latest ecological frameworks which emphasize the importance of conserving the endangered habitats.

The strong relationship between BP and bat abundance is similar to other karst landscapes, in which roost complexity and habitat quality shape bat community structure (Struebig et al., 2009). This underscores the importance of habitat heterogeneity and stable microclimates in maintaining bat populations (de Sousa Barros et al., 2020). High BP scores may also identify caves that support multiple foraging guilds, thereby enhancing ecosystem services such as insect pest control and pollination (Kunz et al., 2011).

Our findings further suggest that BP may serve as a proxy for ecological resilience. Green-priority caves (Makuruhu and Mdenyenye) showed high BP scores with low BV scores, reflecting stable bat assemblages buffered against human disturbance.

Consequently, BP offers a useful measure of ecological significance of bat caves and provides a foundation for conservation prioritization. Protecting and enhancing biotic potential in cave habitats is essential for sustaining Bat species diversity and the ecosystem services they provide in Kenya’s landscapes.

The Biotic Vulnerability (BV) scores varied widely reflecting differences in both landscape level and onsite human pressures. High BV caves including Shimoni, Kaboga, were associated with intensive land use, habitat loss, and pollution, which limit roosting alternatives and fragment foraging habitats, affecting cave microclimates critical for bat persistence (Webala et al., 2019): Browning *et al.,* 2021). In addition, these threats reduce habitat quality and particularly for species that have narrow ecological niches or specialized roosting requirements (Frick et al., 2020). Differences in BV between protected caves and unprotected caves further illustrate the buffering effect of legal protection and active management (Gillieson et al., 2022).

Our results highlight the need for conservation strategies that integrate land use planning with site-specific anthropogenic pressures. Effective approaches should reduce habitat loss and pollution, promote habitat restoration, and regulate human activities within and around critical roosts (Tanalgo and Hughes, 2025).

4.3. Implications for conservation planning

BCVI-S is a useful decision-support tool that helps to guide allocation of resources and conservation prioritization. Even though certain BCVI-S categories (e.g., Blue-priority sites) have a broad threat gradient, they support low bat species diversity and, thus, have lower conservation priority, in comparison with those sites with higher BCVI-S scores (e.g., yellow priority site), should be given priority for immediate intervention, e.g., by restricting access during sensitive breeding period, regulating guano harvesting, as well as by involving local communities stewardship of roosts. Bat Conservation International (2026) has shown that caves inhabited by *Taphozous hildegardeae* can be managed by communities with the intention of conserving these caves (in coastal Kenya) reduces human disturbance and helps maintain stable populations, illustrating how targeted interventions can mitigate the impacts of habitat degradation and human activities on bat roosts. Conservation projects focussing on the vulnerable *Otomops harrisoni* at Mt.Suswa have identified expanding eco-tourism, guano harvesting and deforestation as threats to bat maternity colonies (Wechuli, 2023), motivating community-led protection and forest restoration to maintain habitat quality and bat persistence.

Low BP–high BV sites may warrant targeted disturbance mitigation to prevent further biodiversity loss, while high BP–low BV sites represent conservation strongholds that require ongoing protection and monitoring. Importantly, the scalable nature of BCVI-S means that it can be adapted to other caves in-country and other East African contexts where data availability and conservation capacity vary.

4.4. Caveats and prospects of BCVI-S applications

Although our study marks the first application of BCVI-S in Kenya, we must acknowledge several limitations. While BP reflects ecological richness and BV captures exposure to threats, considering either alone can be misleading; BCVI-S integrates both to provide robust conservation prioritization. Limited long-term monitoring restricted our ability to capture seasonal and interannual variations in bat assemblages, which may influence conservation priorities. Secondly, not all potential caves within study areas were surveyed due to logistical constraints; hence the BCVI-S assessment done does not fully represent the entire cave network in Kenya.

Therefore, future research should prioritize long-term monitoring to detect bat population trends and associated threats. Lastly, it may be necessary to expand the application of BCVI-S to a wider range of caves in Kenya and East Africa for comparative analyses and to highlight opportunities for strengthening transboundary conservation.

While BCVI-S provides a robust integrative framework, its performance depends on data quality and sampling scope. In data-poor contexts or where bat assemblages are highly seasonal, BCVI-S may underestimate vulnerability or biotic value, particularly when short- term surveys fail to capture migratory dynamics. Additionally, strong correlation of BCVI-S and its components reflect internal index structure and should be interpreted as validation of index coherence rather than independent ecological relationships.

4.5. Conclusion

The Scalable Bat Cave Vulnerability Index (BCVI-S) identified critical underground roosts in Kenya requiring conservation attention. Caves hosting endangered species, such as *Taphozous hildegardeae* and *Otomops harrisoni*, exhibited elevated vulnerability scores largely associated with human disturbance. Roosts located near urban areas showed reduced Bat species diversity, consistent with higher BV and BCVI-S scores, underscoring the influence of anthropogenic pressures on cave-dwelling bat assemblages. These findings demonstrate the utility of BCVI-S as a decision support tool for prioritizing bat roost conservation.

4.6. Recommendations

First we recommend applying the BCVI-S framework to additional caves in Kenya to validate its robustness across ecological regions and disturbance gradients. Secondly, long-term monitoring of seasonal bat population dynamics is needed to capture temporal variation in cave use and refine vulnerability assessments. Lastly, caves identified as yellow-priority should be integrated into national conservation frameworks, with strengthened protection measures and community -based management strategies to mitigate human disturbance.

CRediT authorship contribution statement

Kimanzi Johnstone: Writing – review & editing, Validation, Supervision, Methodology. **Patterson Bruce:** Writing – review & editing, Validation, Supervision, Resources, Methodology. **Tieleman Irene:** Writing – review & editing, Validation, Software. **Bungei Millicent:** Writing – original draft, Visualization, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Sospeter Kibiwot:** Writing – review & editing, Visualization, Formal analysis. **Webala Paul:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Methodology, Funding acquisition.

Declaration of Competing 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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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.gecco.2026.e04180.

Data availability

Data will be made available on request.

References

Arita, H.T., 1996. The conservation of cave-roosting bats in Yucatan, Mexico. Biol. Conserv. 76 (2), 177–185.

Bat Conservation International. Saving Hildegarde's tomb bat in Kenya. Bat Conservation International. Retrieved January 20, 2026, from ⟨https://www.batcon.org/our-work/endangered-species-interventions/saving-hildegardes-tomb-bat-in-kenya/⟩.

Deleva, S., Toshkova, N., Kolev, M., Tanalgo, K.C., 2023. Important underground roosts for bats in Bulgaria: current state and priorities for conservation. Biodivers. Data J. 11, e98734.

Demos, T.C., Webala, P.W., Goodman, S.M., Kerbis Peterhans, J.C., Bartonjo, M., Patterson, B.D., 2019. Molecular phylogenetics of the African horseshoe bats (Chiroptera: Rhinolophidae): expanded geographic and taxonomic sampling of the Afrotropics. BMC Evolut. Biol. 19, 166. https://doi.org/10.1186/s12862-019-1485-1.

Demos, T.C., Webala, P.W., Kerbis Peterhans, J.C., Goodman, S.M., Bartonjo, M., Patterson, B.D., 2019. Molecular phylogenetics of slit-faced bats (Chiroptera: Nycteridae) reveals deeply divergent African lineages. J. Zool. Syst. Evolut. Res. 57 (4), 1019–1038. https://doi.org/10.1111/jzs.12313.

Demos, T.C., Webala, P.W., Lutz, H.L., Peterhans, J.C.K., Goodman, S.M., Cortés-Delgado, N., Bartonjo, M., Patterson, B.D., 2020. Multilocus phylogeny of a cryptic radiation of Afrotropical long-fingered bats (Chiroptera, Miniopteridae). Zool. Scr. 49 (1), 1–13. https://doi.org/10.1111/zsc.12388.

Erasmy, M. 2022. Bat activity and diversity in a temperate old-growth forest-Influence of horizontal and vertical structural heterogeneity on the bat assemblage of the Belovezhskaya Pushcha, Belarus.

Frick, W.F., Kingston, T., Flanders, J., 2020. A review of the major threats and challenges to global bat conservation. Ann. N. Y. Acad. Sci. 1469 (1), 5–25.

Furey, N.M., Racey, P.A., 2016. Conservation ecology of cave bats. Bats in the Anthropocene: Conservation of Bats in a Changing World, pp. 463–500..

Furey, N.M., Racey, P.A., 2016. Conservation ecology of cave bats. Bats in the Anthropocene: Conservation of Bats in a Changing World, pp. 463–500.

Gillieson, D., Gunn, J., Auler, A., Bolger, T., 2022. Guidelines for cave and karst protection. In: Postojna, Slovenia: International Union of Speleology and Gland, 112. IUCN, *Switzerland*, p. 2.

Kennedy, M.D., 1998. The cave exploration group of East Africa and volcanic caves in Kenya. Int. J. Speleol. 27 (1), 3.

Kingston, T., 2013. Response of bat diversity to forest disturbance in Southeast Asia: Insights from long-term research in Malaysia. In: *Bat evolution, ecology, and conservation*. Springer, pp. 169–185.

Kunz, T.H., Betke, M., Hristov, N.I., Vonhof, M.J., 2009. Methods for assessing colony size, population size, and relative abundance of bats. Ecol. Behav. Methods Study Bats 133, 157.

Kunz, T.H., Braun de Torrez, E., Bauer, D., Lobova, T., Fleming, T.H., 2011. Ecosystem services provided by bats. Ann. N. Y. Acad. Sci. 1223 (1), 1–38.

Legros, J., 2023. Habitat Selection of Temperate Bats at Different Temporal and Spatial Scales. McGill University, Canada.

Mammola, S., Meierhofer, M.B., Borges, P.A., Colado, R., Culver, D.C., Deharveng, L., Delić, T., Di Lorenzo, T., Dražina, T., Ferreira, R.L., 2022. Towards evidence-based conservation of subterranean ecosystems. Biol. Rev. 97 (4), 1476–1510.

McCutchan, J.L., 2021. Fijian bats: Interactions between people and bats and a preliminary investigation into zoonotic pathogens: a thesis. Presented in partial fulfilment of the requirements for the degree of Masters of Veterinary Science in Wildlife and Zoo Animal Health at Massey University. Manawatū, New Zealand. Massey University, *Palmerston North*.

Monadjem, A., Demos, T.C., Dalton, D.L., Webala, P.W., Musila, S., Peterhans, J.C.K., Patterson, B.D., 2021. A revision of pipistrelle-like bats (Mammalia: Chiroptera: Vespertilionidae) in East Africa with the description of new genera and species. Zool. J. Linn. Soc. 191 (4), 1114–1146. https://doi.org/10.1093/zoolinnean/zlaa087.

Monadjem, A., Montauban, C., Webala, P.W., Laverty, T.M., Bakwo-Fils, E.M., Torrent, L., Tanshi, I., Kane, A., Rutrough, A.L., Waldien, D.L., 2024. African bat database: curated data of occurrences, distributions and conservation metrics for sub-Saharan bats. Sci. Data 11 (1), 1309.

Musila, S., Monadjem, A., Webala, P.W., Patterson, B.D., Hutterer, R., De Jong, Butynski, T.M., Mwangi, G., Chen, Z.Z., Jiang, X.L., 2019. An annotated checklist of mammals of Kenya. Zool. Res. 40 (1), 3–52. https://doi.org/10.24272/j.issn.2095-8137.2018.059.

Patterson, B.D., Webala, P.W., Kerbis Peterhans, J.C., Goodman, S.M., Bartonjo, M., Demos, T.C., 2019. Genetic variation and relationships among Afrotropical species of Myotis (Chiroptera: Vespertilionidae). J. Mammal. 100 (4), 1130–1143. https://doi.org/10.1093/jmammal/gyz087.

Patterson, B.D., Webala, P.W., Lavery, T., Peterhans, J.C.K., Goodman, S.M., Agwanda, B.R., Demos, T.C., 2020. Evolutionary relationships and population genetics of the Afrotropical leaf-nosed bats (Chiroptera: Hipposideridae). ZooKeys 929, 117–161. https://doi.org/10.3897/zookeys.929.50240.

Phelps, K.L., Kingston, T., 2018. Environmental and biological context modulates the physiological stress response of bats to human disturbance. Oecologia 188 (1), 41–52.

Simmons, N.B., Cirranello, A.L., 2024Bat Species of the World: A taxonomic and geographic database. Version 1.4. Accessedon 02/02/2024 . Org.⟨Https:// Batnames⟩..

de Sousa Barros, J., Bernard, E., Ferreira, R.L., 2020. Ecological preferences of neotropical cave bats in roost site selection and their implications for conservation. Basic Appl. Ecol. 45, 31–41.

Solick, D.I., Hopp, B.H., Chenger, J., Newman, C.M., 2024. Automated echolocation classifiers vary in accuracy for northeastern US bat species. Plos one 19 (6), e0300664.

Struebig, M.J., Kingston, T., Zubaid, A., Le Comber, S.C., Mohd-Adnan, A., Turner, A., Kelly, J., Bożek, M., Rossiter, S.J., 2009. Conservation importance of limestone karst outcrops for Palaeotropical bats in a fragmented landscape. Biol. Conserv. 142 (10), 2089–2096.

Tanalgo, K.C., Hughes, A.C., 2025. Bat Cave Vulnerability Index 3.0 (BCVI-S): An integrative and scalable tool to prioritise bat caves for conservation. Glob. Ecol. Conserv. 57, e03396.

Team, R.C., 2023. R: A language and environment for statistical computing (Version Version 4.3. 1)[Computer software]. R. Found. Stat. Comput.

Waltz, T., 2024. Bats, fear, and ecological ethics: pragmatically changing perceptions to improve the environment. North. Plains Ethics J. 12 (1), 59–102.

Webala, P.W., Rydell, J., Dick, C.W., Musila, S., Patterson, B.D., 2019. Echolocation calls of high duty-cycle bats (Hipposideridae and Rhinonycteridae) from Kenya. J. Bat Res. & Conserv. 12 (1), 10–20. ⟨http://hdl.handle.net/123456789/8945⟩.

Wechuli, D.W.B., 2023. Conservation of Threatened Harrison's Giant Mastiff Bat at Mt Suswa Conservancy. Conservation Leadership Programme. ⟨https://www.conservationleadershipprogramme.org/project/conservation-of-threatened-harrisons-giant-mastiff-bat-at-mt-suswa-conservancy-kenya/⟩.

Wilson, D.E., 2015. Bats in Question: The Smithsonian Answer Book. Smithsonian Institution.