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Using Bat Cave Vulnerability Index (BCVI) to determine cave conservation priorities in the Tuban Karst Area, East Java, Indonesia

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Abstract. *Prakarsa TBP, Suhartini, Putri RA, Nugroho FA. 2025. Using Bat Cave Vulnerability Index (BCVI) to determine cave conservation priorities in the Tuban Karst Area, East Java, Indonesia. Biodiversitas 26: 5040-5048.* Bats are keystone species in cave ecosystems, acting as major providers of energy that sustain diverse cave-dependent communities. Their presence and diversity make caves crucial habitats for broader ecosystem stability. In the Tuban Karst Area, East Java, Indonesia, where caves host high species diversity and endemism, bats play a central role in maintaining ecological balance. However, this ecosystem faces severe threats from ongoing habitat destruction. Identifying caves that should be prioritized for conservation requires an understanding of bat diversity, endemism, behavior, and conservation status, as well as a standardized mechanism for risk evaluation. This study aimed to determine cave conservation priorities in the Tuban Karst Area through a holistic rapid assessment using the Bat Cave Vulnerability Index (BCVI) with an index ranging from high to low conservation priority: 1A, 1B, 1C, 1D, 2A, 2B, ..., 4D. Sampling was conducted purposively in five caves: Lawa Belik, Srunggo, Jingkat, Ngerong, and Akbar. Data were analyzed using the BCVI method, which integrates biotic potential and vulnerability, represented primarily by bat species diversity and cave exposure to threats. The caves were ranked from highest to lowest conservation priority as follows: Ngerong (1A), Lawa Belik (2B), Akbar (3A), Srunggo (3B), and Jingkat (3C). This study demonstrates the significance of caves as bat roosting habitats. These findings highlight the critical role of bats in guiding cave conservation strategies and provide an evidence-based framework for prioritizing management actions in caves with the highest BCVI scores.

Keywords: Bat ecology, biospeleology, ecosystem services, sustainable development, wildlife

INTRODUCTION

Today, Earth is undergoing its sixth mass extinction, with species loss occurring at an unprecedented rate, estimated to be up to 100 times faster than natural background levels due to human exploitation (Pievani 2014; Ceballos et al. 2015). Overexploitation and ecosystem degradation demand the urgent protection of critical habitats to safeguard biodiversity (Şeren and Çelekli 2024). Effective conservation strategies depend on identifying areas with high biodiversity or endemism to optimize the design of protected areas and maximize the efficiency of conservation resources (Hughes 2017; Liu et al. 2024). Determining such priorities requires systematic strategies that evaluate habitat vulnerability to threats and disturbances. These assessments are often based on representative or keystone taxa that serve as indicators of ecosystem health (O'Reilly et al. 2022). While keystone species have been widely applied in ecological assessments, their use in specialized ecosystems, such as caves, remains limited despite their high vulnerability and ecological significance (Sætersdal and Gjerde 2011; Vaccarelli et al. 2023).

Cave ecosystems are globally significant biodiversity reservoirs, characterized by high levels of endemism. Yet, they remain poorly documented, with up to 90% of cave-dwelling species estimated to be undescribed and highly vulnerable to disturbance (Hughes et al. 2023). These fragile ecosystems face multiple threats, including limestone extraction for cement production, which can result in complete destruction of cave systems (Liew et al. 2016). Additional pressures arise from tourism development and land-use change in surrounding areas (Prakarsa et al. 2021). Among cave fauna, bats represent ideal indicators of ecosystem health, functioning as keystone species and primary energy providers that sustain entire cave food webs (Prakarsa et al. 2021, 2023). Their roosting activity also influences microclimatic conditions, such as increasing oxygen content in inhabited chambers compared to non-bat passages (Prakarsa et al. 2024). Bats are relatively easy to survey compared to other cave taxa, making them both ecologically and practically suitable for conservation assessments.

Southeast Asia and South China contain more than 800,000 km² of karst landscapes, yet only 13% are formally protected (Yang et al. 2015). In Southeast Asia alone, approximately 178 million metric tons of karst limestone are quarried annually (Hughes 2017). This demand is largely driven by global cement production, which increased from 1.39 billion tons in 1995 to 4.2 billion tons in 2022 (Cembureau 2021). China is the largest producer, contributing 57.2% of global cement output (USGS 2021). In Indonesia, cement production more than doubled from 51.7 million tons in 2010 to 107.9 million tons in 2017

(ASI 2022), fueling the expansion of limestone extraction in karst regions (Parise 2016). Beyond biodiversity loss, such extraction threatens critical ecosystem services, including water storage and carbon sequestration.

Assessing cave conservation priorities requires an approach that integrates the ecological role of bats with habitat vulnerability. The Bat Cave Vulnerability Index (BCVI) provides such a framework, offering a rapid and holistic method to evaluate both biotic potential and anthropogenic threats in karst ecosystems (Tanalgoa et al. 2018). BCVI assessments provide the conservation status of caves as a foundation for prioritizing management strategies that are both effective and efficient.

The Tuban Karst Area in East Java, Indonesia, presents an important case study for this approach. It represents a tropical karst ecosystem of global relevance but faces severe threats from large-scale mining (Cahyadi et al. 2014; Prakarsa et al. 2021). Uniquely, the Tuban karst differs from other karst formations in Java due to its geological history, formed when the northeastern part of Java was connected with Borneo, resulting in distinct cave landscapes and habitats. Comprehensive assessments of its caves are urgently needed to inform conservation priorities, particularly as habitat loss accelerates. This study, therefore, applies the BCVI to determine conservation priorities among Tuban's caves, using bats as keystone indicators in a rapid yet holistic assessment framework. To our knowledge, this represents the first application of the BCVI in the Tuban karst, contributing novel insights into cave-based conservation prioritization in Southeast Asian karst ecosystems.

MATERIALS AND METHODS

Study area

This research was conducted from August 2024 to January 2025. Sampling was carried out purposively in five caves in the Tuban Karst Area, East Java, Indonesia, including Lawa Belik Cave, Jingkat Cave, Srunggo Cave, Ngerong Cave, and Akbar Cave (Figure 1). These caves are located in Tuban Regency, East Java, Indonesia. The main considerations were the distribution of caves, representation of visits to caves, threats, and biodiversity.

Procedures

Data collection consisted of biotic data and landscape features and human impacts in caves. Biotic data represents the population of cave-dwelling bats. Data collection is carried out every month in all caves, with sampling twice a month. Bats were captured using mist nets 3x6 m and 3x9 m (single ply, mesh 20mm) and hand nets (diameter 40 cm) at each cave sampling location. The installation of mist nets was carried out from 17:00-20:00 with checks carried out every 15 minutes.

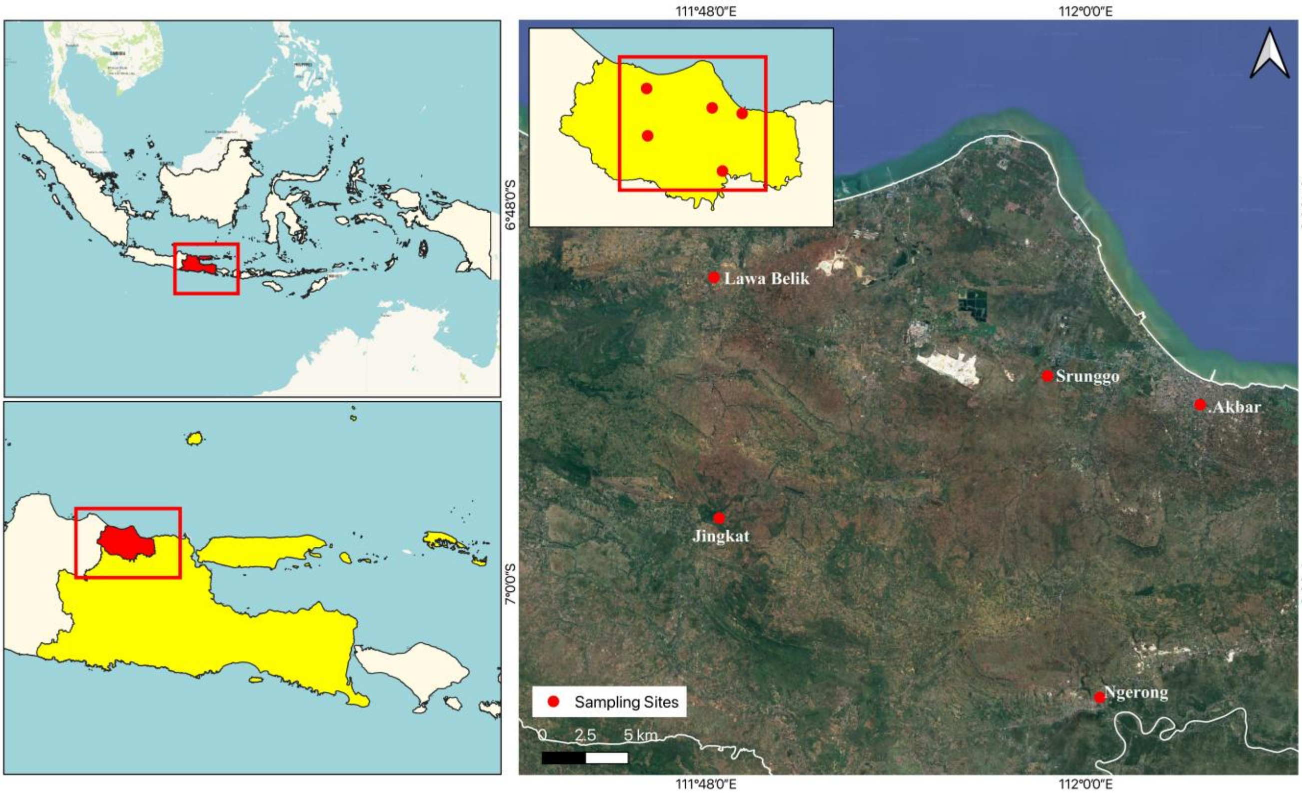

Figure 1. Sampling locations in Tuban Karst Area, East Java, Indonesia

Bats that were captured were immediately released from the mist net carefully to reduce stress and avoid injuries to the fingers and skin. Bat capture and handling followed the safety handling protocol from the guidelines recommended by the American Society of Mammalogists (Sikes 2016). Captured bats were then morphometry and identified, then released again. Identification followed the guidelines recommended by the American Society of Mammalogists (Sikes 2016). Bats were identified by their echolocation calls (using Batsound Petterson U256) (Hasibuan et al. 2021; Prakarsa et al. 2023), and morphometric measurements (Russ 2012) including: body mass (W), head and body (HB), ear (E), forearm (FA), tibia (Tib), hindfoot (HF), and tail length (T). The data to be collected in morphometric measurements is shown in Figure 2. Population data was collected using roost counts and evening emerging counts following Prakarsa et al. (2025). The roost-count method counts bats at the roosting site during the day, while the evening emerging count counts in front of the cave when the bats come out of the cave. Data on landscape features and human impacts in caves was collected by observing the landscape, access, and visitation activities to the caves, following Tanalgo et al. (2018).

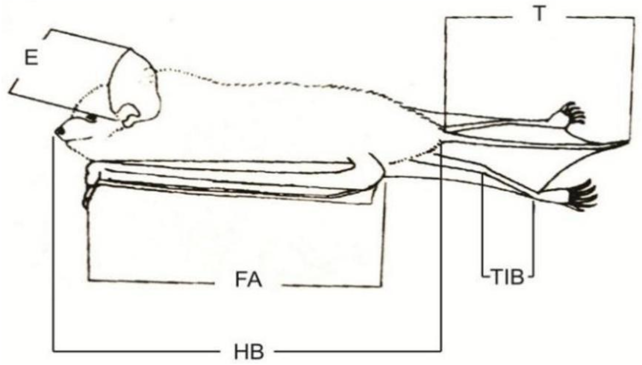

Figure 2. Measurement of bat body parts as a reference for morphometric identification. E: Ear, T: Tail, FA: Forearm, HB: Head-body, TIB: Tibia (modification from Russ et al. (2012) and Sikes (2016))

Table 1. Scoring of species attributes based on endemicity (E) and conservation status (cons) (modified from Tanalgo et al. (2018))

Species attributes	Code	Score
Species endemism E scale		
Widespread	NE	2
Regional endemic (i.e., Southeast Asia)	RE	3
Country endemic	CE	4
Restricted only to a single or few localities/Faunal region/Data Deficient	RES	5
Conservation status cons scale		
Least concern	LC	2
Least concern (decreasing population)	LCD	3
Near threatened	NT	3
Vulnerable	VU	4
Endangered	EN	5
Critically endangered	CR	6

Table 2. Priority level for caves based on biotic potential (modified from Tanalgo et al. (2018))

BP Score	BP level value	Description
>100,000	1	Cave habitats have the highest species richness, the largest populations, with many threatened and endemic species, and with rarest species also represented
60,000-100,000	2	Cave habitat tends to have high species richness (>1 number of species), the population is relatively large, may contain a number of endangered and endemic species with several rare species
20,000-59,999	3	Cave habitat tends to have few species, relatively low populations, lesser threatened and endemic species is present. Most are common species
<20,000	4	Cave habitats have the lowest species, relatively with the lowest population and most species are least concern, non-endemic species and are common in all cave sites

Data analysis

The data were analyzed using the Bat Cave Vulnerability Index (BCVI) statistical method following Tanalgo et al. (2018). The formulation of the index is as follows:

$$BCVI = (BP)(BV)$$

Where, BCVI: Bat Cave Vulnerability Index; BP: Biotic Potential Index; BV: Biotic Vulnerability Index. Formulation of Biotic Potential Index (BP):

$$BP = \Sigma \text{ Species 1 } [(A*Ar*E*cons*site) + \text{Species 2 } (A*Ar*E*cons*site)\ldots\text{Species nth}(A*Ar*E*cons*site)]\ (S),$$

$$BP = \Sigma \text{ individual species score } (S)$$

Where, BP: Cave Biotic potential index; A: Cave bat species abundance; Ar: Relative species abundance; S: Species richness per cave; E: Species endemicity (Table 1); cons: Species conservation status (Table 1); site: Species-Site commonness. Formulation of Biotic Vulnerability Index (BV):

$$BV = \Sigma N/No$$

Where, BV: Biotic Vulnerability Index; N: Threats assessed; No: Number of threats assessed/present/.

In using BCVI as a holistic rapid assessment is by making a index based on the BP and BV score (modified from Tanalgo et al. (2018)) (Tables 2 and 3). Then, in the conservation priority assessment, the two tables (Tables 2 and 4) are combined to obtain the following categories (Figure 3).

Table 3. Scoring of cave site based from the Biotic Vulnerability (BV) (modified from Tanalgo et al. (2018))

Geophysical and human activity features	Codes	Score	Scenario
Accessibility to cave sites	Acc	1	Easily accessible with no permit needed. The caves are very near to human settlements; easily accessible by a vehicle, motorcycle or easy walking distance
		2	No permit needed. Accessible with a motorcycle or two-wheeled vehicle
		3	Difficult to access, needs permission to enter, far from human settlements, with human trail Requires trekking for under 8 h from the motorized vehicle accessible area
		4	Permit enter/explore is needed, no roads, no tracks, and trails, can be reached by trekking at least one day
Cave openings	Co	1	Main openings are around 2 m tall and a meter wide. Two or more people can enter at the same time
		2	Anyone can enter, with more than 1 entrance but only one person at a time can pass through squat/crawl
		3	Difficult to enter, narrow openings but wide on the interior (needs to crawl and clamber)
		4	Very difficult to pass, narrow entrance and narrow inside; needs special equipment to pass cave openings on vertical wall/vertical openings. Effort of exploration Eff 1 Easy to explore, no Obst
Tourism activity	Tour	1	Tourism activity is very high. Frequent (at least 4× a month) visitation of large volume of visitors (more than 10 persons per group) per annum
		2	Tourism activity is very high but only outside the cave. Visits to the cave are only occasional (less than 4× a month) from a small number of visitors (less than 10) per year
		3	Intermittent (less than a 4× month) visitation of large volume (more than 10 persons) of tourists per year
		4	Occasional (less than 4× a month) visitation of small volume of the visitor (less than 10) per year
Cave use	CavUs	1	Intense cave use and exploitation. All of these disturbances are present in the cave: regular hunting of bats for bush meat and trade; high volumes of noise occur inside the cave; evidence of lighting or electric cables; mining of minerals; guano collection
		2	Two of the listed cave use mentioned above are present
		3	Only single cave use and activity mentioned above is present in the cave
		4	All cave use mentioned above is absent
Land-use change activities within cave vicinity	Land Us	1	All of these land use activities are present near the cave openings; multiple land-use activities are present nearby; monoculture plantations are present; forest conversion and mining/quarrying are also present
		2	Land-use is minimal; some land has been converted for small-scale agriculture, mining/quarrying is present
		3	Land-use mentioned above is present but too far; the forest is intercropped with small-scale agriculture; mining is absent
		4	Land-uses mentioned above are absent. Cave is located in a pristine forest
Caves as sacred sites	CavS	1	Not sacred
		2	Tends not to be sacred
		3	Tends to be sacred
		4	Most sacred

Table 4. Biotic Vulnerability Index (BV) scale (modified from Tanalgo et al. (2018))

BV Score	BV Index	Description
1-1.99	A	Greater accessibility and highly prone to human disturbance and activities
2-2.99	B	Lesser accessibility but disturbance is/may be present in distance
3-3.99	C	Less accessibility, less prone to human disturbance
4	D	No disturbance, far from localities and difficult to pass

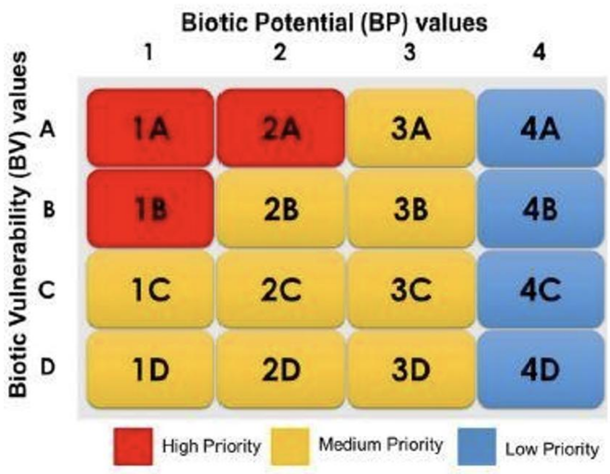

Figure 3. Bat Cave Vulnerable Index (BCVI) priority scale based on Tanalgo et al. (2018)

In this study, the cave conservation priority scale is determined based on the combined value of BP (1, 2, 3, 4) and BV (A, B, C, D) (Figure 3). Biotic Potential (the presence and diversity of bat species) remains a key component of the BCVI, supported by data on the vulnerability of cave (BV) as strategic bat roosting habitat. Based on this combination, the Vulnerability Index (BCVI) has index values ranging from high to low conservation priority 1A, 1B, 1C, 1D, 2A, 2B, 2C, 2D, 3A, 3B, 3C, 3D, 4A, 4B, 4C, and 4D. Caves classified as 1A, 1B, and 2A have high priority and are highly vulnerable to population decline and habitat destruction, thus requiring urgent conservation intervention. Caves categorized as 1C, 1D, 2B, 2C, 2D, 3A, 3B, 3C, and 3D are moderately vulnerable to population decline and species loss due to their low exposure to human activities and disturbances. Meanwhile, caves classified as 4A, 4B, 4C and 4D are less vulnerable (low priority) due to minimal disturbance or a stable cave bat population.

RESULTS AND DISCUSSION

Result

Cave biotic potential (BP): Bat species diversity

Based on this study, a total of 13 bat species were recorded across the five cave habitats (Table 5). Among these, one species is both endemic and vulnerable status (*Nycteris javanica*) (Waldien and Wiantoro 2021), one species is classified as vulnerable (*Miniopterus fuliginosus*), if referring to the original species *M. schreibersii* (Cistrone et al. 2023), one is near threatened (*Rousettus leschenaultii*) (Bouillard et al. 2021), and two have declining population trends: *Hipposideros diadema* (Aguilar and Waldien 2021) and *Eonycteris spelaea* (Waldien et al. 2020). Among the five caves, the highest species richness was found in Ngerong Cave with 9 species, followed by Lawa Belik Cave with 6 species, Akbar Cave with 3 species, and the lowest were Srunggo and Jingkat Caves with 2 species each. The cave with the most threatened species and declining population trends was Ngerong. Meanwhile, Lawa Belik cave contained one endemic species and 1 species with a declining population trend. Srunggo Cave had no endemic or threatened species. A detailed summary of species richness and threatened species are presented in Table 5.

Caves as bat roosting habitats with the most threatened conservation status will be the highest priority compared to other caves. This is used to calculate the BP of each cave. Ngerong Cave was classified as 'Level 1', Lawa Belik Cave as 'Level 2', and Srunggo, Jingkat, and Akbar Caves as 'Level 3' (Table 6).

Cave Biotic Vulnerability (BV): Landscape features and human impacts in caves

Information on the physical characteristics of the caves and the presence of anthropogenic threats was used to assess their Biotic Vulnerability (BV) of the caves. This study found that two caves (40%) (Ngerong and Akbar) had high accessibility to human activities and threats, and were therefore classified as 'Status A'. The other two caves (40%) (Lawa Belik and Srunggo) were classified as 'Status B', facing fairly high threats but lower accessibility than the two previous caves. One cave (Jingkat) was assigned 'Status C' with minimal accessibility and disturbance (Table 7).

Cave priority status

The priority status of the caves using BCVI integrated with Biotic Potential (BP) and Biotic Vulnerability (BV), while Cave Grading was based on the population and conservation status of bats. The results from the BCVI equation showed that one cave is classified as 'High Priority' (Ngerong), and four caves as 'Medium Priority' (Lawa Belik, Akbar, Srunggo, and Jingkat) (Table 8).

Table 5. Species population of cave bats from Tuban Karst Area, East Java, Indonesia

Species	Cave site				
	Lawa Belik	Srunggo	Jingkat	Ngerong	Akbar
Rousettus amplexicaudatus (E.Geoffroy, 1810)	-	-	-	9,643	-
Rousettus leschenaultii (Desmarest, 1820)***	-	-	-	6,051	-
Eonycteris spelaea (Dobson, 1871)*	-	-	-	3,608	-
Nycteris javanica (É. Geoffroy, 1813)****	235	-	-	-	-
Megaderma spasma (Linnaeus, 1758)	-	-	-	11,065	-
Rhinolophus pusillus (Temminck, 1834)	614	-	-	12,472	-
Hipposideros diadema (É.Geoffroy Saint-Hilaire, 1813)*	547	-	-	18,270	393
Hipposideros larvatus (Horsfield, 1823)	890	-	-	15,536	-
Hipposideros ater (Templeton, 1848)	805	-	-	-	-
Miniopterus fuliginosus (Hodgson, 1835)**	-	-	182	19,760	168
Miniopterus australis (Tomes, 1858)	725	-	275	25,264	226
Taphozous melanopogon (Temminck, 1841)	-	1,254	-	-	-
Mops plicatus (Buchanan, 1800)	-	472	-	-	-
Endemic species	1	0	0	0	0
Threatened species	1	0	0	3	1

Note: ****: Endemic and vulnerable (VU), ***: Vulnerable (VU), **: Near Threatened (NT) and decreasing population, *: Decreasing population

Table 6. The Biotic Potential (BP) of cave sites assessed from Tuban Karst Area, East Java, Indonesia

Cave	Pop	Sp. Rich	BP Score	BP Index
Lawa Belik	3,816	6	90,745*	2
Srunggo	1,726	2	60,931	3
Jingkat	457	2	60,026	3
Ngerong	121,669	9	131,129*	1
Akbar	787	3	60,580	3

Notes: Pop: Estimated population, Sp. Rich: Species Richness, *: Indicates number of endemic and threatened species

Table 7. Assessed Biotic Vulnerability (BV) of cave sites using cave geophysical and human disturbance parameters

Cave	Geophysical features						BV Score	BV Index
	Acc	Co	Tour	CavUs	LandUs	CavS		
Lawa Belik	2	1	3	2	2	2	2	B
Srunggo	2	1	3	2	2	2	2.2	B
Jingkat	1	1	3	3	3	3	3	C
Ngerong	1	1	2	3	2	4	1.5	A
Akbar	1	1	1	1	1	1	1	A

Notes: Acc: Accessibility to cave sites, Co: Cave openings, Tour: Tourism activity, CavUs: Cave use, LandUs: Land-use change activities within cave vicinity, CavS: Caves as sacred sites

Table 8. Priority level of five cave models using Bat Cave Vulnerability Index indicating the suggested conservation needed

Cave	Bat Cave Vulnerable Index					
	BP Score	BP Index	BV Score	BV Index	BCVI	Priority/Suggested action needed
Lawa Belik	90,745	2	2	B	2B	High-medium population; high site accessibility
Srunggo	60,931	3	2.2	B	3B	Medium-low population, high site accessibility
Jingkat	60,026	3	3	C	3C	Medium-low population, medium site accessibility
Ngerong	131,129	1	1.5	A	1A	High-high population, high site accessibility, highly disturbed
Akbar	60,580	3	1	A	3A	Medium-medium population, high site accessibility

Discussion

BCVI as a holistic rapid assessment

Previous conservation priority assessments have employed diverse methodologies (Macdonald et al. 2015; Colléony et al. 2017; Tanalgo et al. 2018). However, many of these approaches had limitations: they often emphasized caves with the largest bat populations or prioritized based solely on population size, while overlooking cave vulnerability to anthropogenic disturbances (Tanalgo et al. 2018). Data deficiencies in many taxonomic groups further restrict comprehensive threat assessments, hindering effective conservation planning (Orr et al. 2022). Moreover, indicators-based conservation assessments have disproportionately focused on ecosystems such as forests, leaving other critical systems, including caves, relatively neglected (Wynne et al. 2021). The Bat Cave Vulnerability Index (BCVI) addresses these shortcomings by providing a holistic assessment framework that integrates both bat diversity and anthropogenic pressures. By combining biotic potential with biotic vulnerability, the BCVI is specifically designed to guide management decisions and prioritize caves requiring urgent protection (Tanalgo et al. 2018).

In this study, the BCVI results ranked the five caves in Tuban karst from highest to lowest conservation priority as follows: Ngerong Cave (1A, high priority), Lawa Belik Cave (2B, medium priority), Akbar Cave (3A, medium priority), Srunggo Cave (3B, medium priority), and Jingkat Cave (3C, medium priority) (Table 8; Figure 4). These rankings reflect distinct ecological and anthropogenic dynamics. For example, Ngerong Cave exhibited the highest biotic potential due to its bat species richness, placing it in the highest conservation category. However, the Biotic Vulnerability index revealed different patterns: Ngerong and Akbar showed high accessibility and susceptibility to human disturbance, while Jingkat had low accessibility and thus lower immediate vulnerability. If assessed solely by vulnerability, Jingkat would not warrant priority, yet the integrated BCVI framework balanced its limited diversity against reduced threats, resulting in a medium-priority classification.

Bat populations and species vary across the caves in Tuban Karst Area. According to Prakarsa (2013), the number of bat species and populations in Ngerong is the largest in the Tuban Karst. Most of the populations are insectivorous species. Insectivorous bats play a significant role in controlling populations of agricultural insect pests (Taylor et al. 2018). In the Tuban Karst, these insectivorous bats can consume approximately 45% of their body weight, and some pregnant *Hipposideros ater* individuals can consume up to 2.5 times their body weight (Prakarsa 2013).

With a flight radius of 20 km and an average cave population reaching thousands (estimated to be hundreds of thousands in Ngerong Cave), their role as insect population controllers is highly significant. Likewise, nectar-eating species will help pollinate durian fruit (Sheherazade et al. 2019). In cave ecosystems with minimal energy supplies, bats provide the primary energy supply through their guano. This guano largely replaces the role of producers in cave ecosystems (Ferreira 2019). Furthermore, according to Misra et al. (2019), elements in bat guano are a source of nutrients for the growth of microbiota in cave ecosystems. This impacts the maintenance of the balance of the cave ecosystem.

These results highlight a key insight: caves with high species richness may become especially vulnerable when exposed to intense human activity, as in Ngerong (BCVI: 1A), while some caves under heavy pressure but with lower species richness, such as Akbar (BCVI: 3A), receive lower priority scores. Thus, species diversity alone is insufficient as a criterion for conservation prioritization, as it neglects endemism, rarity, and conservation status (Colléony et al. 2017; Veach et al. 2017; Srivathsa et al. 2022). In this study, the inclusion of endemic and threatened taxa—such as *N. javanica* in Lawa Belik Cave, listed as Vulnerable by the IUCN (Waldien and Wiantoro 2021)—altered the relative ranking of caves with only moderate diversity. Similarly, large populations of generalist species, such as *Rousettus amplexicaudatus*, influenced conservation status despite their ubiquity.

The management implications differ by site. Ngerong and Akbar are heavily impacted by mass tourism, with human access concentrated at cave mouths and underground rivers, altering microclimatic conditions and directly affecting cave biodiversity (Kurniawan and Rahmadi 2017; Kurniawan et al. 2022; Prakarsa et al. 2025). For Ngerong in particular, enhanced management strategies are required to reconcile conservation with local socio-economic needs. Developing specialized religious tourism and educational ecotourism may provide sustainable alternatives, provided community welfare is safeguarded. In contrast, Lawa Belik Cave faces less tourism pressure but is directly threatened by phosphate mining, which could irreversibly alter cave structure and habitat integrity (Jaffé et al. 2016). Here, conservation urgency is justified by the presence of endemic and threatened species.

These findings reinforce the need for conservation frameworks that move beyond species richness as the sole metric. By integrating multiple biotic and anthropogenic variables, the BCVI provides a more comprehensive basis for conservation prioritization, ensuring that caves of ecological significance are not overlooked (Figure 5). Comparable studies in Mindanao, Philippines, also demonstrated the utility of the BCVI in generating site-specific conservation priorities (Tanalgo et al. 2022). However, conservation planning must extend beyond initial prioritization. Regular monitoring is essential to update vulnerability assessments and ensure effective long-term management (Deleva et al. 2023). Standardized and comparable frameworks, such as the BCVI and DarkCideS (https://darkcides.wordpress.com/), are therefore critical for translating cave biodiversity data into actionable conservation policy (Tanalgo et al. 2022).

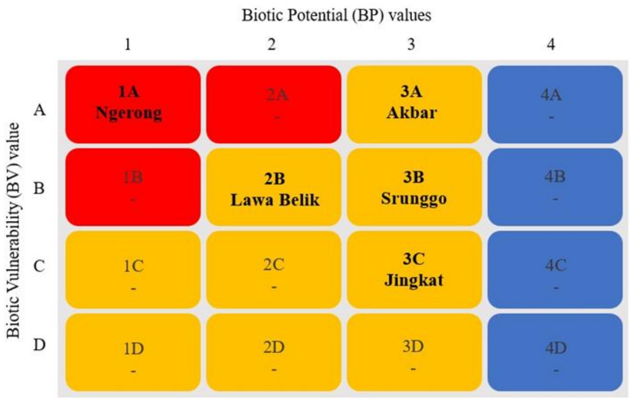

Figure 4. Bat Cave Vulnerable Index (BCVI) priority scale in Tuban Karst Area, East Java, Indonesia

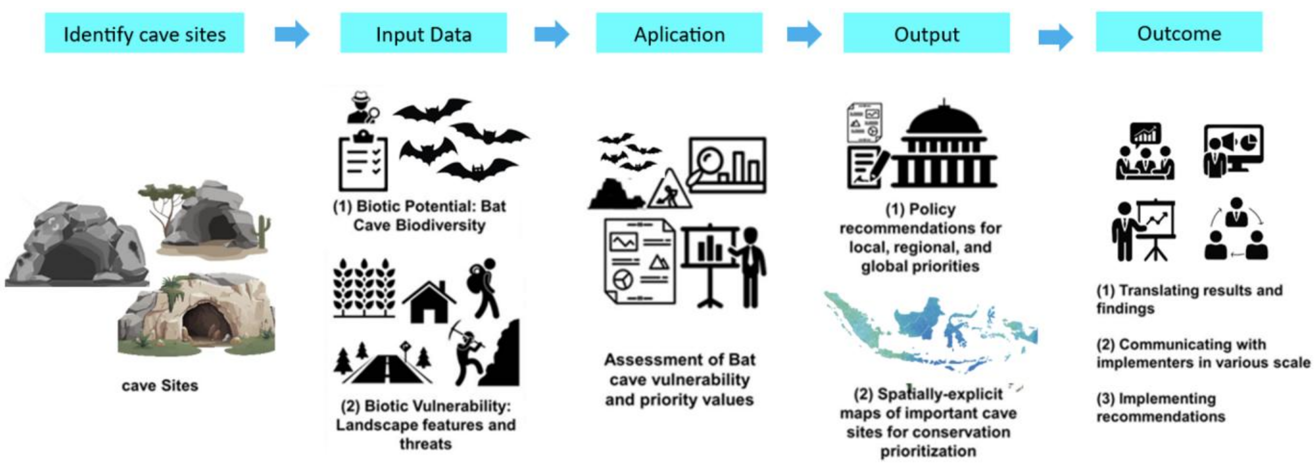

Figure 5. The schematic diagram of the application of BCVI in prioritising bat caves for conservation (modified from Tanalgo et al. (2018))

The process begins by identifying cave sites to evaluate their conservation importance. Key input data for this comprehensive assessment include bat species diversity and existing threats within the caves, which reflect their and BV. The BCVI framework is then applied to determine priority levels, which are subsequently translated into spatial maps highlighting critical areas and guiding policy recommendations. These outputs can be tailored and implemented at regional, national, or global levels.

Future perspectives

Globally, very few regions have established strong legal frameworks for the protection of karst and cave ecosystems. Where such laws exist, they are often weak in scope and lack effective monitoring mechanisms (Prakarsa et al. 2021). For example, in the Philippines, the National Cave Management Act provides a legal basis for cave protection, yet many sites remain poorly surveyed and inadequately protected (BCI 2013). In Indonesia, regulations typically frame karst formations as landscapes rather than ecosystems, which limits their conservation effectiveness. Even when biodiversity protection is addressed, policies often treat species in isolation rather than considering the integrity of the entire ecosystem (Prakarsa et al. 2021).

Bats represent key indicators of biodiversity in caves and subterranean ecosystems (Deleva et al. 2023; Meierhofer et al. 2024). The Bat Cave Vulnerability Index (BCVI) fills a critical gap by providing a systematic framework to prioritize cave and karst habitats for conservation. As a rapid assessment tool, the BCVI enables evidence-based decision-making for resource allocation, research priorities, restoration planning, and sustainable use. However, challenges remain in its broader application. In temperate regions with distinct seasons, bat populations undergo hibernation or migration, complicating year-round assessments. Furthermore, the highly mobile and seasonal use of caves by bats across different life stages (van Harten et al. 2022) may result in single-time surveys failing to capture long-term ecological dynamics (Llaven-Macías et al. 2021). Addressing these challenges will require standardized monitoring protocols and repeated surveys across seasons to ensure robust and reliable conservation prioritization.

In conclusion, the Bat Cave Vulnerability Index (BCVI) proved to be an effective rapid and holistic tool for assessing cave conservation priorities by integrating bat diversity with vulnerability to anthropogenic impacts. Applied in the Tuban karst, the BCVI identified Ngerong Cave as the highest priority for conservation, while Lawa Belik, Srunggo, Akbar, and Jingkat were classified as medium priorities. Based on these findings, we recommend stricter access control to Ngerong Cave, including permits for entry and improved management of surrounding mass tourism to ensure habitat sustainability. For Lawa Belik, closing phosphate mining activities is critical, with visits limited to research purposes. Srunggo and Jingkat should remain under special-permit access, while Akbar may continue as a general tourist attraction, provided visits are confined to designated routes with professional guides.

Given the limited temporal and spatial scope of this study, broader-scale assessments are needed to strengthen generalization and ensure robust conservation strategies. Regular re-evaluation of the BCVI, ideally on an annual basis, will be essential for adaptive management. Extending this approach to other karst regions will provide a standardized framework for prioritizing cave and karst habitat conservation across Southeast Asia and beyond.

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