

Ecotourism Pressure and Conservation Gaps in Cave-Dwelling Bat Habitats of Southern Africa: A Policy and Biodiversity Perspective

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Abstract Cave ecosystems are biologically rich yet ecologically fragile environments that host specialised fauna, notably cave-dwelling bats. These species provide critical ecosystem services, including pollination, seed dispersal, and insect regulation. However, the expansion of cave-based tourism across Southern Africa poses growing threats to subterranean biodiversity, particularly through habitat degradation and behavioural disruption of bat populations. This review synthesizes current knowledge on the ecological roles of cave bats and evaluates the impacts of tourism-related activities on species richness, abundance, and roost fidelity. Drawing on regional data and comparative international case studies, it identifies patterns of vulnerability and resilience among bat communities, and highlights conservation strategies that integrate scientific monitoring with community engagement. The review underscores the importance of policy-driven cave management, emphasizing the need for regulatory frameworks, ecological baselines, and public awareness to mitigate anthropogenic pressures. Key challenges include insufficient monitoring, fragmented governance, and limited integration of cultural values into conservation planning. By proposing a science-based, socially inclusive approach to cave-tourism development, this review contributes to the discourse on sustainable tourism and biodiversity protection. The findings aim to inform policymakers, conservation practitioners, and tourism stakeholders on best practices for safeguarding cave

ecosystems while enhancing socio-economic benefits in biodiversity-rich regions.

Keywords Cave-Dwelling Bats, Cave-Ecosystems, Ecotourism, Biodiversity Conservation, Habitat Disturbance

1. Introduction

Cave ecosystems, particularly those hosting bat colonies, represent biologically unique and ecologically fragile environments. These subterranean habitats support specialised fauna and flora, many of which are endemic and highly adapted to low-light, nutrient-poor conditions. Cave-dwelling bats play a pivotal role in maintaining ecosystem functionality through pollination, seed dispersal, insect population control, and guano deposition, which sustains cave trophic networks [1].

Simultaneously, caves have emerged as popular tourist destinations, attracting millions of visitors annually due to their representation of nature's beauty, geological formations, cultural significance, and biodiversity. This dual role, as biodiversity hotspots and tourism assets, creates tension between conservation imperatives and economic interests. The challenge lies in developing sustainable tourism models that safeguard ecological

integrity while supporting local livelihoods [2].

The planet is currently experiencing an unprecedented biodiversity crisis, with extinction rates estimated to be 100 to 1,000 times higher than natural background levels [3]. Anthropogenic activities such as deforestation, urban expansion, mining, and unregulated tourism have accelerated habitat degradation, particularly in sensitive karst landscapes [4]. Cave ecosystems are disproportionately affected due to their limited spatial extent, specialised species assemblages, and vulnerability to microclimatic changes [5].

Recent assessments, such as the IUCN Red List, highlight that over 9,300 vertebrate species remain threatened by human-induced stressors [6]. Bats, despite their ecological importance, are often overlooked in conservation planning and suffer from negative public perceptions, persecution, and habitat loss. Their low reproductive rates and high roost fidelity further exacerbate vulnerability to disturbance [7].

In response to the escalating biodiversity loss, the Kunming-Montreal Global Biodiversity Framework (GBF) was adopted at the 15th Conference of the Parties (COP15) in December 2022. The GBF sets ambitious targets to halt biodiversity decline by 2030 and achieve harmony with nature by 2050 [8]. Key goals include conserving 30% of terrestrial and marine areas, restoring degraded ecosystems, and integrating biodiversity into national development strategies. The GBF emphasizes ecosystem services and recognizes the role of local communities, indigenous knowledge, and sustainable tourism in achieving conservation outcomes [9]. Cave ecosystems, though not explicitly mentioned, fall within the broader mandate of protecting ecologically significant habitats and species.

Globally, there are over 1,400 bat species, with approximately 40% utilizing caves as primary roosting sites. Cave-dwelling bats contribute to ecosystem resilience by regulating insect populations, most of which are insectivorous microbats, and bringing associated benefits to the ecosystems. While some bat species are vital for pollination and seed dispersal services, these roles are mainly performed by nectar-feeding microbats and frugivorous megabats, rather than by most cave-roosting insectivorous species [10].

Caves function as natural laboratories that preserve paleoclimatic records, host endemic species, and offer insights into subterranean biodiversity. Yet only an estimated 10% of the world's caves have been documented, and fewer still are included in formal conservation frameworks. The transformation of wild caves into show caves often involves irreversible ecological modifications, including Lampenflora proliferation, CO₂ accumulation, and speleothem degradation [5].

Cave tourism often involves artificial lighting, and, in some instances, there is also the use of polluting light such as petrol lamps, flame torches, which further pollute caves. Additionally, infrastructure development and high visitor

volumes can disrupt bat behaviour, alter microclimates, and lead to roost abandonment. The ecological consequences are cascading, affecting not only bats but also the invertebrate communities and microbial assemblages dependent on guano inputs [11].

The Dupnisa Cave System in Türkiye is an archetypal initiative that highlights the need for responsible cave development, ecological restoration, and real-time environmental monitoring. The cave management for Dupnisa has successfully implemented seasonal access restrictions to safeguard bat populations during critical reproductive periods, a model of conservation-positive tourism that blends ecological science with regulatory enforcement [12].

The review therefore, synthesizes current knowledge on the impacts of tourism on cave-dwelling bats, identifies key threats and stressors, and evaluates mitigation strategies within the context of sustainable cave management. By examining global case studies and policy frameworks, the paper aims to highlight the ecological roles and vulnerabilities of cave-dwelling bats, assess the direct and indirect impacts of tourism on cave ecosystems, and explore successful conservation models and adaptive management practices, as well as advocate for integrated approaches that align biodiversity protection with ecotourism development. Inferences and findings from this review are particularly useful and timely as Southern Africa evolves its cave tourism sector, taking into consideration the intersection with the rich bat biodiversity and community-based conservation opportunities.

2. Cave Ecosystems and the Ecology of Cave-Dwelling Bats

2.1. Cave Ecosystems as Subterranean Biodiversity Reservoirs

Caves are truncated ecosystems characterized by permanent darkness, high humidity, and thermally stable microclimates. These conditions foster highly specialised biota, including troglobionts, troglaphiles, and troglonexes, many of which exhibit extreme morphological adaptations such as depigmentation, elongated appendages, and reduced eyesight [12]. Guano deposits from cave-dwelling bats serve as the primary energy source for invertebrate communities, sustaining guanophilic arthropods and microbial assemblages [13].

Despite their ecological significance, cave ecosystems remain underrepresented in conservation frameworks, particularly in Africa [14]. In Southern Africa, caves are often valued for archaeological or geological features, while their biological importance is overlooked [15]. The insular nature of caves and limited gene flow between populations contribute to high levels of endemism and vulnerability to disturbance [16].

2.2. Roosting Ecology and Species Assemblages

Globally, over 1,400 bat species are known, with approximately 40% utilizing caves as primary roosts [10]. In South Africa, at least 18% of the 60 reported bat species are cave-dependent, including *Miniopterus natalensis* and *Rousettus aegyptiacus*, which are ecologically dominant and widely distributed [17]. These species often co-roost, increasing the potential for cross-species viral transmission and ecological interactions [18].

Roost selection is influenced by cave morphology, entrance size, elevation, and microclimatic stability [13]. Seasonal use patterns vary: *M. natalensis* migrates between maternity roosts and hibernacula, while *R. aegyptiacus* exhibits year-round cave residency. Roost fidelity is high, and disturbance during reproductive periods can lead to colony abandonment [19].

Studies in the De Hoop Guano Cave and Gatkop Cave have documented multi-species assemblages, with temporal and spatial partitioning of airspace and prey resources [20]. These dynamics are shaped by wing morphology, echolocation traits, and foraging strategies, enabling niche differentiation and coexistence.

2.3. Foraging Strategies and Ecosystem Services

Cave-dwelling bats are central-place foragers, often concentrating feeding activities within a few kilometres of their roosts. Insectivorous species such as *M. natalensis* and *Myotis tricolor* regulate pest populations, while frugivorous bats like *R. aegyptiacus* contribute to seed dispersal and pollination [1]. In Thailand, *Chaerephon plicatus* consumes rice pests, and *Eonycteris spelaea* pollinates durian and *Parkia* species [21].

In South Africa, guano harvesting from caves is minimal compared to that in Southeast Asia, but the ecological role of guano remains critical. It supports microbial and invertebrate communities, including endemic guanobionts [22]. Foraging behaviour is influenced by landscape composition; bats avoid pesticide-intensive croplands and prefer natural vegetation [16]. Recently, telemetry and acoustic monitoring have revealed seasonal shifts in

foraging zones, with increased activity during spring and summer [23, 24, 25]. These patterns align with insect biomass peaks and reproductive cycles, underscoring the need for habitat connectivity and pesticide regulation.

2.4. Threats and Conservation Imperatives

Cave-dwelling bats face multifaceted threats: habitat loss, tourism disturbance, mining, guano overharvesting, and climate change [26]. In Southern Africa, land-cover change around roosts has led to a 4–10% decline in natural woody vegetation and increased proximity to urban settlements [16]. A significant proportion of roosts occur outside designated protected areas, exposing them to escalating risks of vandalism.

The Bat Cave Vulnerability Index (BCVI) offers a rapid assessment tool to prioritize caves for conservation based on species richness, disturbance levels, and ecological significance. Passive monitoring technologies, such as cable reader systems and acoustic sensors, are being piloted to track bat movements without disturbance [27]. Other advanced monitoring technologies are increasingly used to track bat responses to disturbance, as will be discussed in section 4.2 of this review.

Policy integration remains limited. Caves are not formally recognized as ecosystems in South Africa's biodiversity assessments, hindering their inclusion in protected area expansion [28]. Sacred natural sites like Motouleng and Mautse offer opportunities for culturally embedded stewardship and could be designated as Other Effective Area-Based Conservation Measures (OECMs) under the Kunming-Montreal Global Biodiversity Framework [29]. However, factors such as ecological pressures, socio-economic realities shape conservation effectiveness. Moreover, limited livelihood alternatives, weak governance, and inequitable tourism revenue distribution often undermine community-based stewardship of caves [30]. Addressing these socio-economic drivers is essential to ensure that conservation strategies are both ecologically and socially sustainable. Table 1 shows some notable examples of cave-associated bat species in Southern Africa.

Table 1. Notable Examples of Cave-Associated Bat Species in Southern Africa and Their Ecological Roles







Miniopterus natalensis	Rousettus aegyptiacus	Myotis tricolor
		
<p>Image Source: [31]</p> <p>Common Name: Natal long-fingered bat</p> <p>Ecological Role: Insectivorous; pest control</p> <p>Roosting and Behaviour: Migratory; high roost fidelity; uses caves seasonally for maternity and hibernation; key bioindicator</p> <p>Distribution: Widespread across eastern and southern Africa, including South Africa, Eswatini, Zimbabwe, and Mozambique [34].</p>	<p>Image Source: [32]</p> <p>Common Name: Egyptian fruit bat</p> <p>Ecological Role: Frugivorous; seed dispersal</p> <p>Roosting and Behaviour: Year-round cave resident; prefers warm, humid caves; zoonotic relevance</p> <p>Distribution: Northeastern and southern Africa, including confirmed populations in Limpopo, Mpumalanga, and KwaZulu-Natal [34].</p>	<p>Image Source: [33]</p> <p>Common Name: Cape hairy bat</p> <p>Ecological Role: Insectivorous; cave forager</p> <p>Roosting and Behaviour: Caves, rock crevices, and hollow trees; sensitive to disturbance</p> <p>Distribution: Patchy across southern Africa; prefers moist savanna and forest edges [34]. Other less common species include Myotis bocagii, which has been found at the Gatkop Caves.</p>

Table 1 continued

Hipposideros caffer	Rhinolophus spp.	Nycteris thebaica
		
<p>Image Source: [35]</p> <p>Common Name: Sundevall's leaf-nosed bat</p> <p>Ecological Role: Insectivorous; clutter-edge forager</p> <p>Roosting and Behaviour: Caves, hollow trees, and mine shafts; sensitive to disturbance.</p> <p>Distribution: Confirmed presence at Sudwala caves and its environs; broadly distributed across sub-Saharan Africa and other karst caves [36].</p>	<p>Image Source: [37] (Picture showing <i>R. landeri</i>)</p> <p>Common Name: Horseshoe bats</p> <p>Ecological Role: Insectivorous; echolocation specialists</p> <p>Roosting and Behaviour: Communal roosting in caves and abandoned structures; often co-roost with <i>Miniopterus</i> spp.; can tolerate human activities to an extent.</p> <p>Distribution: Multiple species across South Africa, including <i>R. clivosus</i> and <i>R. simulator</i> at the Gatkop Caves and <i>R. landeri</i> and <i>R. hildebrandtii</i> at Sudwala Caves. Several species present in varied locations, including Mpumalanga, the Cape, and KwaZulu-Natal, are also present in Mozambique [38, 39].</p>	<p>Image Source: [40]</p> <p>Common Name: Egyptian slit-faced bat</p> <p>Ecological Role: Insectivorous; edge forager; echolocation specialists</p> <p>Roosting and Behaviour: Communal roosting in caves and abandoned structures; prefers humid cave roosting, can tolerate human activities to an extent.</p> <p>Distribution: found in a variety of tropical and temperate habitats throughout Africa and the Arabian Peninsula [41].</p>

3. Impacts of Tourism on Caves and Cave-Dwelling Bats

Cave tourism has grown substantially across Southern Africa, offering economic and educational benefits while posing significant ecological risks. Due to the vulnerability of cave ecosystems, their largely unchanging microclimates, and limited nutrition supply, they are particularly susceptible to anthropogenic disturbances [42]. The development of show caves often involves artificial lighting, infrastructure modifications, and increased human traffic, which can disrupt cave microclimates, introduce pollutants, and disturb resident fauna, particularly bats [16].

In South Africa, caves such as Sudwala, Cango, and Wonderwerk are popular tourist destinations, yet few are formally protected under conservation frameworks [16, 43]. Cave-dwelling bats, including *Miniopterus natalensis*, *Rousettus aegyptiacus*, and *Hipposideros caffer*, rely on these habitats for roosting, breeding, and hibernation. Disturbance during critical life stages can lead to colony abandonment, reduced reproductive success, and increased mortality [44].

3.1. Physical and Ecological Impacts of Tourism

Tourism infrastructure, such as walkways, lighting systems, and ventilation, tends to alter cave temperature, humidity, and CO₂ levels, affecting both geological formations and biological communities. Artificial lighting promotes lampenflora growth, which can degrade speleothems and alter cave aesthetics. Increased foot traffic compacts sediment layers and disrupts guano-based nutrient cycles essential for cave invertebrates [11]. Since microclimatic changes and behavioral disruptions can be subtle yet cumulative, non-invasive monitoring is essential to detect early signs of ecological stress.

Bats are particularly vulnerable to light, noise, and human proximity. Studies in Bulgaria's Devetashka Cave and India's Gupteswar Cave show that tourist presence correlates with increased bat mortality and reduced colony size, especially during the reproductive season [44, 45]. In South Africa, researchers have observed that high light intensity and visitor noise significantly altered bat flight behaviour and roosting patterns in maternity colonies [46].

Pertinently, the socio-economic context of tourism development also determines ecological outcomes. In regions where cave tourism generates local employment and equitable revenue-sharing, communities are more likely to enforce visitor regulations and protect bat colonies. Where benefits are captured externally, however, local resistance and unsanctioned cave use increase, exacerbating ecological stress [47].

4. Southern Africa Regional Trends in Cave-dwelling Bats' Biodiversity Changes

Recent research in South Africa revealed a 4–10% decline in natural woody vegetation around bat-inhabited caves between 2014–2018, with increased proximity to urban settlements [16]. This landscape change exacerbates tourism pressure and increases the likelihood of human-bat interactions, raising concerns about zoonotic spillover and long-term population viability [18]. Cave ecosystems across Southern Africa represent biologically rich yet underexplored conservation frontiers. These subterranean habitats host specialised fauna, including cave-dwelling bats, invertebrates, and microbial communities adapted to low-light, nutrient-limited conditions. Despite their ecological importance, caves remain largely absent from national conservation frameworks and biodiversity assessments [15].

A comparative bibliometric study by Mazebedi et al. [15] revealed that Africa has a disproportionately low cave biodiversity research output, with Southern Africa relatively well represented, though almost exclusively driven by South Africa. However, the regional focus remains skewed toward vertebrates, particularly bats, while invertebrate and microbial cave fauna are vastly understudied. Botswana and Namibia, despite hosting ecologically significant karst systems, lag in ecological documentation and conservation planning.

South Africa is home to over 60 bat species, with at least 18% relying on caves for roosting [48]. Two species, *Miniopterus natalensis* and *Rousettus aegyptiacus*, are of particular interest due to their ecological roles and potential as zoonotic hosts. A study by Pretorius et al. [16] showed that land-cover changes around 47 bat roosts between 2014–2018 resulted in a 4–10% decrease in natural vegetation and an increase in proximity to urban settlements. Alarmingly, 72% of these roosts fall outside protected areas, exposing them to unregulated tourism, mining, and vandalism.

Table 2 shows some of the cave conservation efforts being undertaken within the Southern African region. A significant number of the caves in focus in Southern Africa lack standardized approaches to visitor monitoring; the visitors' numbers are either undocumented or only anecdotal, which further demonstrates the data gap in tourism monitoring. Given the desire for ecological and cave tourism as economic drivers in Southern Africa, a thorough examination of conservation initiatives reveals the lack of documentation as one of the significant challenges. Additionally, caves are not officially acknowledged as ecosystems in South Africa's national biodiversity evaluations [29]. This exclusion illustrates policy 'blind spots' and obstructs their inclusion in the expansion of protected areas and climate resilience planning.

Table 2. Some Examples of Cave Conservation Strategies in Southern Africa


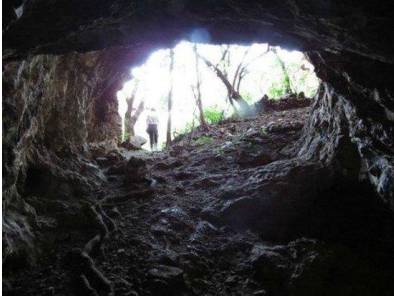





Cave System / Region	Country	Approximate Cave Size	Annual Visitors	Image	Conservation Strategy	Key Species Present	Challenges / Gaps	References
Sudwala Caves	South Africa	~30 km system; 600 m accessible	Not documented (popular tourist site)		Tourism under review; ecological monitoring	<i>Miniopterus natalensis</i> , others	Tourism pressure; limited legal protection	[16].
Hoogland Health Hydro Caves	South Africa	Not documented (fossil-bearing cave)	Not documented		Passive monitoring by AfricanBats NPC	<i>Rousettus aegyptiacus</i> , <i>M. natalensis</i>	Outside protected areas; land-use change	[24].
Motouleng & Mautse Caves	South Africa	Large sandstone cave, ~2 km hike access	Not documented (spiritual pilgrimage site)		Sacred site stewardship (OECM potential)	Unknown bat diversity	Lack of formal recognition; access rights	[29].
Wynberg Cave System	South Africa	Multiple caves; significant troglobitic fauna	Not documented (visited, but no official counts)		Proposed hotspot; endemic invertebrates	19 troglobitic species, bats	Graffiti, trampling, bat colony decline	[49].

Table 2 continued

Aigamas Cave	Namibia	Vertical cave with a subterranean lake	Not documented (specialist tourism, cave diving)		Limited ecological data; endemic catfish	<i>Clarias cavernicola</i> , several species of bats	Mining threats; no conservation framework	[15].
Gcwihaba Cave	Botswana	Large labyrinth; Drotzky's Cavern ~10 m high chambers	Not documented (limited tourism)		UNESCO tentative list; cultural significance	Invertebrates, <i>Hipposideros commersoni</i> , and <i>Nycteris thebaica</i>	Sparse ecological research; tourism plans	[50].
Sterkfontein Caves	South Africa	Extensive limestone caves; ~40 km NW of Johannesburg	80,000–100,000 annually		Archaeological focus; limited biodiversity data	Fossil hominids, and bat presence noted but not characterised	Conservation centred on heritage, not ecology	[51].

Show caves such as Sudwala and Cango draw thousands of visitors each year, yet they do not implement standardized environmental impact assessments or seasonal access limitations to save vulnerable wildlife. Masilela and Beckedahl [52] assert that karst systems in Namibia and Botswana are put at risk by limestone extraction and infrastructural expansion, frequently lacking ecological supervision. Recently, Sinthumule [53] contends that there exists a deficiency in cultural stewardship and an absence of national guidelines for cave maintenance. The author referenced sacred caves like Motouleng as prospects for conservation via Indigenous knowledge systems, although they necessitate formal acknowledgment within the scope of 'Other Effective Area-Based Conservation Measures' (OECMs).

4.1. Opportunities for Integrated Conservation for South African Regions

The Southern African Development Community (SADC) will benefit from transboundary collaboration, especially as it relates to biodiversity data collection and collation. A regional cave biodiversity network across SADC countries could facilitate data harmonisation, capacity building, and joint conservation planning. Such collaboration aligns with the SADC Transfrontier Conservation Areas (TFCAs) framework and supports cross-border species management [54]. Furthermore, community-based stewardship, which will involve engaging local communities in cave monitoring, tourism management, and cultural preservation, fosters long-term ecological resilience. Models such as the Amboni Caves initiative in Tanzania demonstrate the value of participatory governance in heritage-rich subterranean landscapes [55]. This study highlights how local communities around the Amboni Caves have shown interest in tourism and conservation but are often sidelined in formal management processes. It advocates for collaborative governance to ensure sustainable development and ecological resilience in heritage-rich subterranean landscapes.

Approaches to improving cave biodiversity endeavours should include policy reform, which integrates cave ecosystems into national biodiversity strategies and protected area frameworks, as this is essential for safeguarding subterranean biodiversity. Currently, none of SADC member states has legislation dedicated solely to caves' protection. Cave ecosystems are generally covered by broader environmental, biodiversity, mining, or heritage laws, rather than by cave-specific statutes. For example, South Africa does not have legislation dedicated solely to caves, while the constitutional framework provides a strong foundation for their protection. Section 24 of the Constitution of the Republic of South Africa guarantees the right to an environment that is not harmful to health or

well-being and obliges the state to secure ecologically sustainable development. This mandate is operationalized through the National Environmental Management Act (NEMA), the National Environmental Management: Biodiversity Act (NEMBA, 2004), and the National Heritage Resources Act, all of which apply to cave ecosystems. Importantly, these laws embed societal inclusion by requiring public participation in environmental decision-making, recognizing indigenous knowledge systems, and mandating equitable access to natural and cultural heritage. Thus, cave protection in South Africa is constitutionally grounded and linked to broader frameworks of biodiversity conservation and community stewardship. Both documents outline mechanisms for expanding protected areas and integrating biodiversity priorities, including subterranean habitats, into national planning. In Namibia, caves fall under the Environmental Management Act (2007) and heritage provisions. The Aigamas Cave and other karst systems are recognized for biodiversity and heritage, but there is no cave-diversity protection law. Mining legislation (Minerals Act, 1992) governs limestone extraction risks. In Botswana, caves such as Gwihaba are listed on the UNESCO tentative list for cultural/natural heritage (Table 2). They are managed under the Monuments and Relics Act (2001) and general environmental laws, not cave-specific legislation. Caves in Zimbabwe, Eswatini, Mozambique and Tanzania are protected under general heritage acts or environmental management laws. For example, Zimbabwe's National Museums and Monuments Act (1972) covers archaeological caves, while Tanzania's Amboni Caves are managed under heritage and tourism frameworks.

The SADC Mining Protocol (1997) and related guidelines harmonize mining and environmental practices across member states. However, this protocol addresses karst and limestone extraction risks only in the context of mining, not cave-specific conservation. Therefore, in the absence of direct protection laws for caves in the region, they are subsumed under mining, biodiversity, or heritage frameworks. The implications of this gap in governance are that caves are ecologically unique but legally invisible in most SADC countries. This jeopardizes most cave conservation efforts as they must rely on broader legal frameworks such as general biodiversity, heritage, or mining laws. Nonetheless, this gap is open to reflection, and it is an opportunity for regional policy harmonization that can be achieved through the embedding of cave-specific provisions that explicitly recognize caves in national biodiversity frameworks and protected area expansion strategies that can be integrated into the SADC biodiversity strategies or Transfrontier Conservation Areas.

The keen participation of transdisciplinary research groups within universities and research institutions will be pivotal in driving any initiatives. In South Africa, initiatives led by African Bats NPC and the University of Pretoria are advancing long-term monitoring and public engagement. Other Universities should follow suit and adopt caves in their proximity as part of their community engagement initiatives, fostering the development of long-term studies. The gap in governance around cave conservation illustrates the important role that universities and researchers in the SADC region could play by collecting long-term ecological data and shaping future policy decisions.

Further proof of the necessary support of research institutions in conservation efforts is evidenced in recent transformative advances by cave ecology and subterranean biodiversity monitoring with the introduction of novel tools and frameworks that support evidence-based conservation planning. For example, the Bat Cave Vulnerability Index (BCVI), developed by [27], offers a rapid means of identifying high-risk caves based on bat diversity, roost fidelity, and human disturbance, while pilot studies in Southeast Asia validate its zoning applications. Complementing this, African Bats NPC and the University of Pretoria have introduced passive technologies—including cable reader systems and acoustic sensors—to track bat movements longitudinally without interference [24]. Microbial and algal surveys in South African caves further underscore the ecological complexity of cave environments, revealing significant seasonal variation linked to light and humidity [49]. When combined, the derived datasets enable spatially explicit roost mapping and inform adaptive zoning to protect vulnerable cave habitats.

4.2. Integrated Monitoring Approaches for Cave-Dwelling Bats and Tourism Management

Effective conservation of cave ecosystems requires

robust, non-invasive monitoring frameworks that provide ecological baselines and track tourism impacts. Traditional methods such as telemetry and guano surveys have offered insights into bat foraging and nutrient cycles, but recent advances now enable continuous, disturbance-free monitoring. Passive acoustic networks, using distributed recorders and curated call libraries, quantify nightly activity, emergence timing, and colony dynamics [56, 57]

Airborne environmental DNA (eDNA) sampling complements acoustic monitoring by detecting both vocal and non-vocal taxa from genetic material suspended in cave air, thereby providing presence–absence data across vertebrate communities [58, 59, 60]. To capture the full spectrum of ecological change, these biological indicators should be integrated with physical monitoring of cave microclimates, including temperature, humidity, CO₂ levels, and Lampenflora growth [25]. Passive acoustic arrays yield quantitative measures of bat colony activity, while airborne eDNA surveys identify species that may not be acoustically active, bridging the gap between environmental conditions and biodiversity outcomes. Together, these datasets support adaptive management strategies such as seasonal closures during maternity periods, visitor quota adjustments, and compliance auditing under frameworks like the Bat Cave Vulnerability Index [27]. Crucially, monitoring must also incorporate socio-economic dimensions—engaging communities in data collection and ensuring transparent reporting—to enhance legitimacy and foster long-term stewardship [30].

Table 3 shows the strengths and limitations of the individual approaches for monitoring highlighted in this section of this review. Consolidating these approaches into a unified monitoring protocol and its implementation routine, strengthens both scientific rigour and policy relevance, aligning cave management with the Kunming-Montreal Global Biodiversity Framework’s evidence-based conservation targets.

Table 3. Integrated monitoring approaches for cave ecosystems

Monitoring type	Method	Output	Strengths	Limitations
Acoustic networks	Passive recorders, call libraries	Activity indices, colony dynamics	Non-invasive, scalable, continuous	Limited to vocal species
Airborne eDNA	Air samplers, DNA sequencing	Species presence/absence	Detects cryptic/non-vocal taxa	Requires lab processing, reference databases
Physical sensors	Temperature, humidity, CO ₂ loggers	Microclimate trends	Early warning of stress	Does not capture biodiversity directly
BCVI	Rapid assessment index	Risk zoning	Policy-ready, provides comparative data sets	Needs local calibration
Community monitoring	Local guides, participatory surveys	Socio-economic & ecological data	Builds stewardship, legitimacy	Requires training, equitable benefit-sharing

5. Overview of Some Internationally Accepted Conservation and Management Strategies

5.1. Sustainable Practices in Cave Tourism

Cave tourism, or speleotourism, has grown into a lucrative global industry, with over 25 million visitors annually frequenting more than 800 show caves worldwide [26]. While this expansion offers economic benefits and educational opportunities, it also poses significant ecological risks to subterranean biodiversity, particularly cave-dwelling bats and troglobitic invertebrates [61, 62]. To mitigate the impacts of visitors, sustainable cave tourism must prioritize ecological integrity through adaptive management. Some places, such as the Dupnisa Cave in Türkiye, impose visitor influx regulation by limiting access during sensitive periods, such as bat breeding seasons that has proven effective in reducing disturbance [26]. Changes in infrastructure design, such as raised walkways and low-impact lighting systems, are presumed to minimize physical and photic disruption to cave microclimates and fauna [63]. The inclusion of environmental monitoring regimes through continuous assessment of temperature, humidity, and CO₂ levels enables responsive management and early detection of ecological stress (Integrating community engagement by training local guides and integrating ecotourism into regional development fosters stewardship and aligns conservation with livelihoods [64]. However, community-based conservation succeeds when socio-economic incentives align with ecological goals. Transparent benefit-sharing, training of local guides, and integration of cultural values into tourism design foster stewardship and reduce conflict [65]. These socio-economic factors must be embedded alongside ecological monitoring to ensure long-term sustainability.

The Škocjan Caves in Slovenia exemplify best practice, combining UNESCO designation with strict visitor quotas and microclimate monitoring to balance tourism and conservation [66]. Table 4 shows some cases of cave sites that have employed varied approaches and have been successful in integrating conservation models of biodiversity conservation and tourism through collaborative governance, scientific oversight, and community participation. Although these case studies are sparse, they underscore the importance of interdisciplinary approaches that combine ecological science, policy frameworks, and socio-economic incentives to achieve long-term sustainability in cave ecosystems.

5.2. Management and Mitigation Strategies




Effective cave tourism management presents a complex

challenge: it must reconcile the imperative of ecological preservation with the growing demand for immersive visitor experiences. This dual mandate requires a nuanced, evidence-based approach that integrates ecological science, infrastructure design, education, and policy reform. Seasonal access restrictions are among the most direct and effective tools for minimizing disturbance to bat populations, particularly during sensitive maternity and hibernation periods. Studies from Turkey and India have demonstrated that limiting human entry during these windows significantly reduces mortality and behavioural disruption among cave-dwelling bats [12, 45]. However, access restrictions alone are insufficient without complementary infrastructure adaptations. Low-impact design features such as red-filtered lighting, elevated walkways, and controlled ventilation, help to maintain cave microclimates and reduce anthropogenic stressors, preserving both speleothem integrity and faunal stability [26].

Visitor education plays a pivotal role in shaping public attitudes and behaviours. Interpretive signage and guided tours not only enhance the visitor experience but also foster stewardship by contextualizing caves as fragile ecosystems rather than mere recreational spaces [44]. Yet education must be underpinned by robust monitoring systems. Passive acoustic monitoring and tools like the Bat Cave Vulnerability Index (BCVI) offer scalable, non-invasive methods for assessing roost fidelity, species richness, and anthropogenic pressures [26, 27]. These data-driven insights support adaptive zoning policies that restrict access to high-risk areas while allowing sustainable tourism elsewhere. Beyond these classic methods, new technologies like virtual reality (VR) headsets, 3D replica caves and remote cameras systems provide exciting new ways to educate people about caves. Such strategies are in line with global best practices for sustainable tourism and aid in ensuring long-term conservation success [68, 69].

Finally, long-term conservation hinges on policy integration. Caves must be formally recognized within national biodiversity assessments and protected area frameworks to ensure legal protection and resource allocation. South Africa's revised National Biodiversity Framework (2022) and Protected Areas Expansion Strategy (2020) exemplify how subterranean habitats can be embedded into broader conservation planning [26]. In summary, effective cave tourism management is not a singular intervention but a constellation of interdependent strategies, each reinforcing the others to balance ecological integrity with meaningful human engagement. Figure 1 summarizes a holistic recommended integrated cave management and risk mitigation strategy that attempts to balance ecological integrity with visitor experience.

Table 4. Cave Sites using Integrated Conservation Models

Cave and Location	Integrated Conservation Models	Cave size	Annual number of visitors	Image	Reference
Gupteswar Cave, India	<ul style="list-style-type: none"> • This sacred site employs zoning, seasonal closures, and awareness campaigns to protect bat populations while accommodating religious tourism. • Conservationists conduct regular biodiversity assessments, and local communities are engaged as guides and monitors. 	Limestone cave shrine; entrance ~3 m wide	Thousands annually during festivals (esp. Mahashivaratri)		[45]
Dupnisa Cave, Türkiye	<ul style="list-style-type: none"> • Seasonal cave closures during bat hibernation, coupled with eco-sensitive infrastructure and visitor education, have preserved rich bat assemblages. • Partnerships with universities support ongoing research and adaptive management. 	3,200 m long; 500 m accessible	~120,000		[25]
Škocjan Caves, Slovenia	<ul style="list-style-type: none"> • A model of conservation-led tourism, the site enforces strict access controls, and uses specialised lighting to reduce ecological disruption. • They reinvest tourism revenue into local development and conservation research. 	~6,200m	150,000–190,000		[2].
Togenra Caves, Indonesia	<ul style="list-style-type: none"> • Initially threatened by mining and unregulated tourism, these caves now benefit from integrated management plans developed with NGOs, scientists, and local stakeholders. • Zoning regulations, guide-only access, and biological monitoring have reversed ecological degradation. 	Located in Tonasa Karst Formation; size not documented	Not documented	Not available	[67]

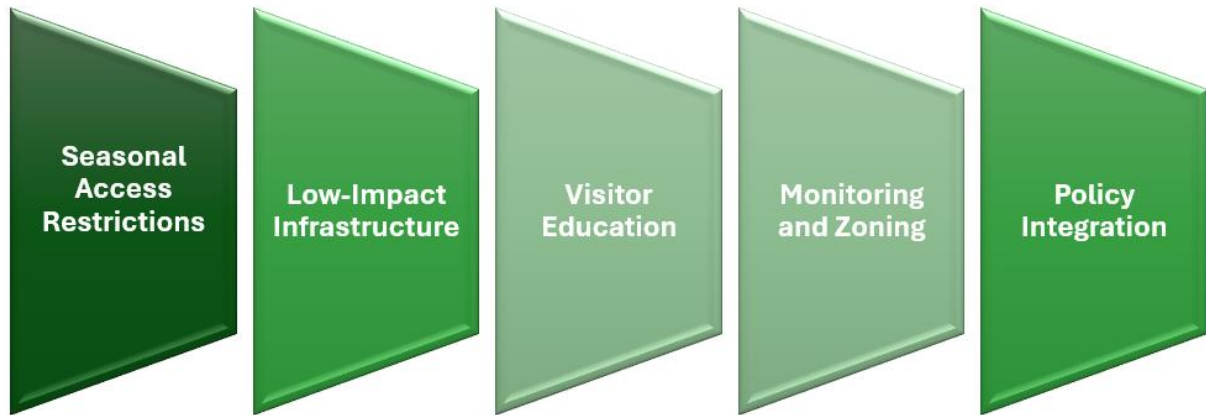


Figure 1. A holistic cave management and risk mitigation strategy to protect biodiversity, including bats (adapted from [5, 26, 27, 28, 45, 46])

6. Challenges and Future Visions

Despite growing recognition of cave ecosystems as biodiversity hotspots, significant challenges persist in aligning conservation with tourism development. These challenges are multifaceted, spanning ecological, socio-cultural, and policy domains.

6.1. Ecological Vulnerability and Anthropogenic Pressures

Cave ecosystems are inherently fragile, with species highly sensitive to microclimatic shifts, light pollution, and physical disturbance. Tourism-related modifications—such as artificial lighting, paved walkways, and increased human traffic—can disrupt bat roosting behaviour, alter humidity and CO₂ levels, and degrade speleothem formations [70]. In South Africa, land-use change around bat-inhabited caves has led to a 4% decline in woody vegetation and increased proximity to urban settlements, exacerbating human-wildlife conflict and zoonotic risk [16].

6.2. Cultural Perceptions and Human Behaviour

Bats remain misunderstood and stigmatized in many regions, often associated with disease or superstition. These perceptions hinder conservation efforts and contribute to persecution, particularly in areas where bats are hunted for food or displaced due to tourism infrastructure. Conservation strategies must address these socio-cultural dimensions through targeted education and community engagement [64].

6.3. Policy Gaps and Enforcement Limitations

Although frameworks such as the Kunming-Montreal Global Biodiversity Framework advocate for inclusive conservation, cave ecosystems are underrepresented in national biodiversity strategies and protected area

networks [8]. In South Africa, most bat roosts fall outside formally protected zones, and cave-specific conservation plans remain absent [16]. Enforcement challenges—particularly around visitor behaviour and informal cave access—further undermine ecological integrity.

6.4. Research and Monitoring Deficiencies

There is a paucity of standardized global data on cave biodiversity, roost dynamics, and tourism impacts. Emerging tools such as the Bat Cave Vulnerability Index (BCVI) and passive acoustic monitoring offer promise but require broader implementation and integration into policy frameworks [26, 27].

6.5. Socio-Economic Factors Shaping Community-Based Cave Conservation

The success or failure of community-based cave conservation initiatives is strongly influenced by socio-economic conditions. Key determinants include livelihood diversification, equitable benefit-sharing, governance structures, and cultural valuation of caves [30]. Where tourism revenues or conservation incentives are transparently distributed, communities demonstrate higher stewardship and compliance. Conversely, inequitable benefit allocation or exclusion of local stakeholders often leads to conflict, unsanctioned access, and biodiversity decline [47]. Education and capacity-building are equally critical, as local guides and monitors provide both ecological data and cultural interpretation, strengthening legitimacy and resilience of conservation programs [65]. Integrating socio-economic baselines into cave management plans ensures that conservation outcomes are not undermined by poverty, unemployment, or lack of institutional support. Table 5 summarizes how the varied factors can determine the success and/or failures community-based cave conservation.

Table 5. Socio-economic factors influencing success or failure of community-based cave conservation

Factor	Success conditions	Failure conditions
Livelihood diversification	Tourism revenues supplement agriculture/mining; reduced dependence on extractive practices	Lack of alternatives drives unsanctioned cave use
Benefit-sharing	Transparent, equitable distribution of tourism income	Elite capture, external appropriation of revenues
Governance structures	Local councils and community trusts manage access and monitoring	Weak institutions, fragmented authority
Cultural valuation	Recognition of caves as sacred/heritage sites strengthens stewardship	Cultural marginalization reduces legitimacy of conservation
Capacity-building	Training of local guides, monitors, and researchers	Lack of skills and exclusion from decision-making

7. Towards a Sustainable Future for Cave Tourism and Bat Conservation

Achieving sustainability in cave tourism and bat conservation demands a paradigm shift from reactive protection to proactive, integrated management. Sustainable cave tourism must prioritize ecological thresholds. This includes: (1) Seasonal Access Restrictions during maternity and hibernation periods [45]; (2) Low-Impact Infrastructure such as red-filtered lighting and elevated walkways [26]; and (3) Visitor Education through interpretive signage and guided tours [44]. These measures reduce disturbance while enhancing public appreciation of subterranean biodiversity.

7.1. Community Stewardship and Cultural Integration

Local communities play a pivotal role in cave conservation. Initiatives such as the Amboni Caves in Tanzania demonstrate how participatory governance can foster ecological resilience and cultural preservation [55]. Recognizing sacred caves as Other Effective Area-Based Conservation Measures (OECMs) could be a great way to secure formal protection while honouring Indigenous knowledge systems [53]. However, OECMs should not be regarded as a *one size fits all* solution. The evidence around their effectiveness varies around the world, and there are only a few documented cases that focus specifically on cave-ecosystems, especially in Southern Africa. While sites governed by Indigenous communities offer a chance for OECMs recognition, their success hinges on having a clear governance structure, ongoing community support, and realistic expectations about what these measures can actually achieve. Although OECMs show promise, they are still a work in progress rather than a definite way to ensure conservation [53].

7.2. Policy Reform and Regional Collaboration

Integrating cave ecosystems into national biodiversity frameworks such as South Africa's Protected Areas Expansion Strategy [61] and SANBI's policy roadmap [62] is essential. A transboundary cave biodiversity network

across SADC countries could facilitate data sharing, capacity building, and joint conservation planning.

7.3. Adaptive Management and Research Integration

Long-term sustainability requires adaptive management informed by robust ecological data. Tools like BCVI, microbial monitoring, and acoustic sensors should be embedded into conservation protocols. Climate change, zoonotic risk, and land-use dynamics must be factored into future cave management strategies [16, 70].

8. Conclusions

This review demonstrates that cave-dwelling bats in Southern Africa occupy a critical ecological niche, providing indispensable services such as insect regulation, seed dispersal, and nutrient cycling through guano deposition. Yet, the rapid expansion of cave-based tourism, coupled with fragmented governance and insufficient ecological monitoring, has intensified pressures on these fragile subterranean ecosystems. Evidence from regional and international case studies underscores that tourism-related disturbances—particularly artificial lighting, noise, and infrastructure modification—can disrupt roost fidelity, reproductive success, and long-term population viability.

The study's key contribution lies in synthesizing ecological, socio-economic, and policy perspectives to highlight conservation gaps and propose integrated strategies. By situating cave ecosystems within broader biodiversity frameworks such as the Kunming-Montreal Global Biodiversity Framework, the review emphasizes the need for regulatory recognition of caves as distinct ecological units. It also identifies opportunities for culturally embedded stewardship, community engagement, and transboundary collaboration under the Southern African Development Community (SADC) framework. These approaches can strengthen resilience by aligning ecological science with local livelihoods and heritage values.

Future research should prioritize three directions: (1)

expanding ecological baselines through systematic monitoring of bat populations, invertebrate assemblages, and microclimatic dynamics; (2) documenting and evaluating community-based conservation models, particularly those rooted in indigenous knowledge and sacred site stewardship; and (3) advancing policy innovation by embedding cave-specific provisions into national biodiversity strategies and protected area expansion. Addressing these gaps will not only safeguard subterranean biodiversity but also ensure that cave tourism evolves as a genuinely sustainable enterprise—balancing ecological integrity with socio-economic benefits across Southern Africa.

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