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# Reconstructing cave past to manage and conserve cave present and future

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ABSTRACT

Whilst restoration and recovery of ecosystems has become a major priority, developing a baseline of what biodiversity was like prior to disturbance, and what might have driven changes in wildlife populations often remains unknown in many systems. Challenging to access ecosystems, such as subterranean ecosystems which cannot be monitored by remote sensing and frequently have very little information provide a significant challenge to understanding how biodiversity patterns may have changed, and how they might be more effectively managed. Caves represent unique ecosystems, key sites for our own human history, but with their unique conditions and stability can provide insights into their own past use as well as an index of local climate and vegetation. In addition, caves host many of the worlds over 1400 bat species, meaning that the ability to reconstruct past population trajectories may facilitate their conservation, as well as that of the many other, often undescribed cave dependant species. Here we discuss the various types of data from biological, chemical, geological and social that can be used to reconstruct the past history of cave sites across various timescales. We discuss the considerations needed for each approach as well as providing examples to guide the application of such approaches to better understand cave systems and their varying uses over time, and highlight how such data may facilitate cave management.

## 1. Introduction

Globally we are in the midst of a biodiversity crisis, with unparalleled rates of species loss and decline for many millennia (Barnosky et al., 2011; Ceballos et al., 2015). The most recent Living planet report noted an on average decrease in wildlife populations of 69 % globally (WWF, 2022). Yet whilst this figure is alarming, what is less obvious is how this figure was developed, and how representative it is of threatened species across the planet. A closer look at the data highlights that given the lack of standardised data on species, populations and regions, we only have an approximate understanding of populations of a subset of species and systems, with many species trajectories almost entirely unknown.

Under continued losses of habitat, shifting climate, and intensification of agriculture in many agrarian societies as part of urbanisation, and simultaneously the industrialisation of agriculture (Hughes et al., 2023), we can expect that these undocumented shifts and losses in biodiversity will continue, invisibly in many regions (Hughes 2017). Managing and mitigating these processes may rely on data that simply is not available for the majority of systems.

Understanding the losses and declines in neglected biodiversity is critical, as biodiversity is crucial for a multitude of services on which we depend (de Groot et al., 2012; Guerry et al., 2015; Oliver et al., 2015), and the incremental loss and decline of species and populations may have profound implications on services which we rely upon. For example, around 75 % of major crop plants rely on pollination, and thus most of the food we consume relies on pollinators (Millard et al., 2021). Much tropical pollination is dependent on native species, which may in turn rely on both intact habitats to fulfil their lifecycles and provide the services on which crops rely (Sritongchuay et al., 2019a). Multiple studies suggest the decline of insects at regional and global scales (Raven & Wagner, 2021; Wagner 2020; Wagner et al., 2021), yet like so many previous studies, drawing these trends relies on inconsistent data drawn from a variety of approaches.

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Long-term studies are the holy grail for many elements of conservation science, understanding population trajectories, shifting distributions and reasons for decline. Yet, for many species and regions we lack such studies, and have almost no knowledge of how populations may have changed. Future conservation actions may be more effective if we understand these past changes, through extending our timescale, and manage systems to reduce continued population losses and enable recovery. Given this lack of data for many systems, understanding how to reconstruct population history and changing uses of sites would provide key insights; yet how to accomplish this has rarely been discussed in detail.

Another important taxa–especially in tropical regions–are bats, providers of pollination and seed dispersal services (which are important ecologically and economically), major pest consumers, and generators of guano, which is frequently used as a valuable and potent fertiliser (Ramírez-Fráncel et al., 2022; Shapiro et al., 2021). Maintaining healthy bat populations has manifold benefits in terms of ensuring continuation of the services they provide, and sustenance of the diverse, yet little known communities of cave dependant species with entire food pyramids based on the guano they bring with them to cave systems (Ferreira et al., 2007; Phelps et al., 2016; Deharveng & Bedos 2018). Cave formation may take thousand to millions of years in the making and offer fundamentally distinct environment from the earth surfaces, creating a fragile and non-renewable environment (Neuhuber et al., 2020; Balogh et al., 2020). Yet conversely, the continued loss of key sites in karst ecosystems (Sugai et al., 2015; Tanalgo et al., 2022), and other stressors in these systems can create novel interactions between bats and other species, force them to travel further and increase ecophysiological stressors, which is frequently associated with increased risk of pathogen spillover in mammals (Becker et al., 2023; Eby et al., 2023). Thus, finding ways to maintain healthy bat populations and communities may be key to maintaining the benefits of ecosystem services, whilst avoiding various risks; and yet to do so relies on understanding what shifts in populations may have occurred, and what is responsible for these patterns and trends, enabling targeted interventions to allow population recovery into the future.

Understanding changes in conditions in these subterranean ecosystems is crucial, as karst and cave systems have unparalleled levels of endemism, with many karst systems hosting site endemic taxa (Christman et al., 2005; Nitzu et al., 2018). Caves also provide interesting sites for a multitude of fields, their isolation creating "island" ecosystems for evolutionary research. Given the lack of research in many karst systems an estimated 90 % of cave invertebrate species in some countries remain undescribed (Hughes et al., 2020). As guano forms the base of most cave food webs, understanding both the overall changes in cave conditions, and the specific trajectories for bats is likely to represent trends for diversity in these systems overall (Deharveng & Bedos 2018), and by understanding and mitigating drivers of bat decline we provide a genuine umbrella for the entire cave ecosystem. Furthermore, cave systems are overlooked Methane sinks, thus perturbing the biota of these systems could have unpredictable and unanticipated impacts on methane release, and consequently significant impacts on climate (Cheng et al., 2023).

However, even modern assessments of bat and cave populations rarely include accurate counts of individuals (i.e., laser scanning using LIDAR, thermal infrared-imaging counts, digital image analysis and roost exit counts, which are predominantly used in high-income economies) (Sabol & Hudson 1995; Azmy et al., 2012). Therefore, understanding what losses and shifts have already occurred presents unique challenges. Furthermore, caves also present interesting opportunities from another perspective. The diverse ways that people have used caves–both in recent human history and deep evolutionary time–also presents opportunities to reconstruct at least some of the anthropogenic changes in these systems (Goldberg & Sherwood, 2006; Carrión et al., 2011; Mammola 2019). By cross-referencing the ecological data with other forms of data, including accounts from those who live in and around cave systems, we can begin to understand what may have changed in these systems, and to identify what actions may be most urgent in maintaining bat populations and cave ecosystems into the future. This paper combines insights from speleology, environmental history, anthropology, and bat biology to provide a holistic understanding of human impacts on cave ecosystems and bat populations.

## 2. Ecological data

### 2.1. Understanding cave ecology and tracking changes over time

The primary data for ecologists is generally ecological surveys and inventories on the distributions of species. Unfortunately detecting trends generally relies on long term monitoring data, which rarely exists (Hughes et al., 2021). Whilst in some instances basic data on species present from previous surveys may exist, this may not be quantitative and survey effort may not be comparable. The classification of many species is challenging (Dayrat 2005; Wiens 2007; Pante et al., 2015) and may have changed, which means that interpreting historical data should be done with care. Thus, in the absence of long-term quantitative data, what data can we use to try to reconstruct at least the trajectory of change for these systems?

Bats leave three very obvious types of evidence in caves, such as the presence of guano, skeletons and ceiling marks (Fig. 1). These ceiling marks are in some ways the most interesting, as in addition to the dark or pale spots on the ceilings that can denote the roost of an individual bat (Fig. 1a), and even allow us to quantify the approximate colony size of bats, riffles and "bell-holes" in the rock itself can indicate the role of the respiration, guano, condensation and corrosion of long-dead bats in shaping the rocks themselves (Bruxelles 2021; Lundburg & McFarlane 2009). To understand if these chambers ever held populations of bats, we can look at the geological structures themselves, signs of biocorrosion from the breakdown of guano, bell-holes from roosting bats (which get hotter and drive a cycle of corrosion when bats are present), and the presence of phosphate traces on cave floors and surfaces (from the breakdown of guano, as this is not present in limestone itself). These signs will leave long-term signatures of use within a cave, and when used in combination these cues can give approximate estimates of group size as well as the length of use. However, different signals provide evidence for different periods. Whilst these geological signatures tell us if bats were ever at a site (as can bat fossils, including subfossils in some caves), they do not give information on the more recent history of use by bats. In addition, the species-specific roosting ecology (i.e. colony/sedentary/roosts in rock crevices/ or other parts of the cave) may also give different indicators of bats presence in the past (Rodríguez-Durán, 2020; Avila-Flores and Medellín, 2004).

Guano provides an index of recent cave use by bats as well as use even extending over the course of thousands of years and offers evidence of the past climate of a site (Darabad et al., 2019; Cleary et al., 2018; Bogdanowicz et al., 2020; Gallant et al., 2020). For more recent use, ceiling marks can be combined with guano (both of which can be dated to some degree, especially when both are used). Old guano becomes progressively dusty in texture (though in river-caves it will be washed out seasonally, and in wet or humid caves it will remain moist). By using cues in combination of guano and marks on the ceiling we can garner how large the colony was and if the signs represent seasonal shifts or total disuse. Closer examination of the ceiling marks for small scratches can also give an indication of whether the spot was in use recently, if not obvious from a more casual inspection (Pimentel et al., 2022; Pilo et al., 2023). Past numbers can be estimated by counting the density of these roosting marks within a set area (for example 1 $m^2$) and the area with roosting spots calculated to count past numbers (BCI, 1997). Mismatches between the number of bats present, or signs of numbers recently present (such as fresh or recent guano) and marks on the ceiling can give some indication of changes in colony size and if they represent seasonal change, or the loss of colonies from caves when they clearly have not


**Fig. 1.** A. Some indication of cave use as bat roosts in the past; erosion and coloured domes in the cave ceiling. B. fossilised bats bones. C. bat guano (including evidence of guano extraction).

been used by bats for a considerable time.

Ecological data can offer evidence of direct and indirect anthropogenic impacts on caves. In many cases our estimates of when former large colonies had disappeared tallied with other factors, such as the use of Agent Orange in Vietnam during surveys in areas where it was known to be used, as well as other war related uses (Kiernan 2021). Combining multiple kinds of data can help demonstrate the lasting legacy of large-scale anthropogenic phenomena. The dioxins present in Agent Orange can persist in the body for over a decade, and in poorly ventilated caves may still show high concentrations for many decades and may be impossible for these former colonies to recover from or recolonise (Mishra, & Trikamji, 2014; My et al., 2021). Smoke and ash from fires or mining may coat past roosting spots and also serve as evidence of long-term human impacts. Specific data points from individual caves can be understood in terms of broader anthropogenic impacts on the landscape, underground aquifers, and the atmosphere.

### 2.2. Physical signs of a changing landscape

Inside cave systems researchers may find themselves surrounded by an array of geological features, some as noted prior, from their roles as homes to bats, and others from the slow drip of calcium rich water through the cave ceiling forming various speleothems such as stalactites, helictites, stalagmites, columns as well as various other features. However, many of these features are formed from the steady drip of water, thus caves with such features, where there is no evidence of dripping or recent growth, or strange shaped crystal structures such as helictites may indicate the drying of caves, or changes in temperature increasing the rates of evaporation rather than dripping within the cave (though more research is needed) (Davis 2019). These stalactites/mites can also give a very clear indication of climate changes across longer timescales in the thousands of years (Fairchild, & McMillan 2007). Most of these geological features will show consistent annual growth unless conditions change reflecting either changes in climate or landscape governance and water use (Baker et al., 2014, 2021; Comas-Bru et al., 2020; Railsback et al., 2016). The presence of completely dry shields and pools (especially when surrounded by rock formations such as cave pearls, likely indicating constant water in the past), and when now showing signs of clearly being dry for a considerable period are likely to indicate a changing climate over time, as are dry calcite crystal flows (Tan et al., 2011) (Fig. 2). The amount of "dryer deposits" and dustiness as well as lack of drips can all be used to help indicate if the caves have become dryer, though to confirm this additional data is very useful (which can also include a variety of isotopes: Isobar Science, 2023). Thus, visual inspections can provide a reasonable index of climate changes in the cave in recent history, and more advanced analysis can provide a high resolution and accurate index of the environmental conditions; which can be cross-referenced with more recent types of data.

Changes in precipitation and temperature are likely to be the consequence of changing landcover and water use, or the diversion of rivers, or changing irrigation (Hjort et al., 2015). Tracking such changes (at least since 1985) may be possible using satellite imagery, with the Google Earth and the Google Time-Machine enabling high-resolution tracking of the landscape. The observed drying of many caves we have visited is also consistent with global data on depletion of aquifers and rivers, attributed to the expansion of agriculture, often tied to plantation systems oriented towards export (Pierrat et al., 2023; Dalin et al., 2017; de Graaf et al., 2019; Haraway 2015). Broad trends can be linked to GIS data showing changes in landscape structure.

The depletion of aquifers is expected to increase into the future, causing caves to generally get warmer and dryer, and fundamentally changing the suitability for many species dependent upon these systems (Reinecke et al., 2021; Scanlon et al., 2023). Given likely increases in the severity of drying, and the ongoing expansion of agriculture, it will be possible to cross-reference data to document changes in landcover that might be correlated with data on river levels and conditions within caves. Integrating insights from these multiple data sources could help us better understand past changes in the bat population (where sufficient evidence exists), and predict population trends into the future. Furthermore, these hydrological changes, as well as pollution of streams and groundwater (for example from agrochemicals) can impact on cave ecosystems, even causing erosion within cave systems (Guo et al., 2021; Jiménez-Sánchez et al., 2008).

Satellite data can also give us an overview of regional landscape changes, from loss of key habitats, changing of watercourses, hydroelectric projects that produce new standing water-bodies, and mining which may destroy caves. Using these satellite data, especially across time, can provide a high-resolution understanding of regional landcover

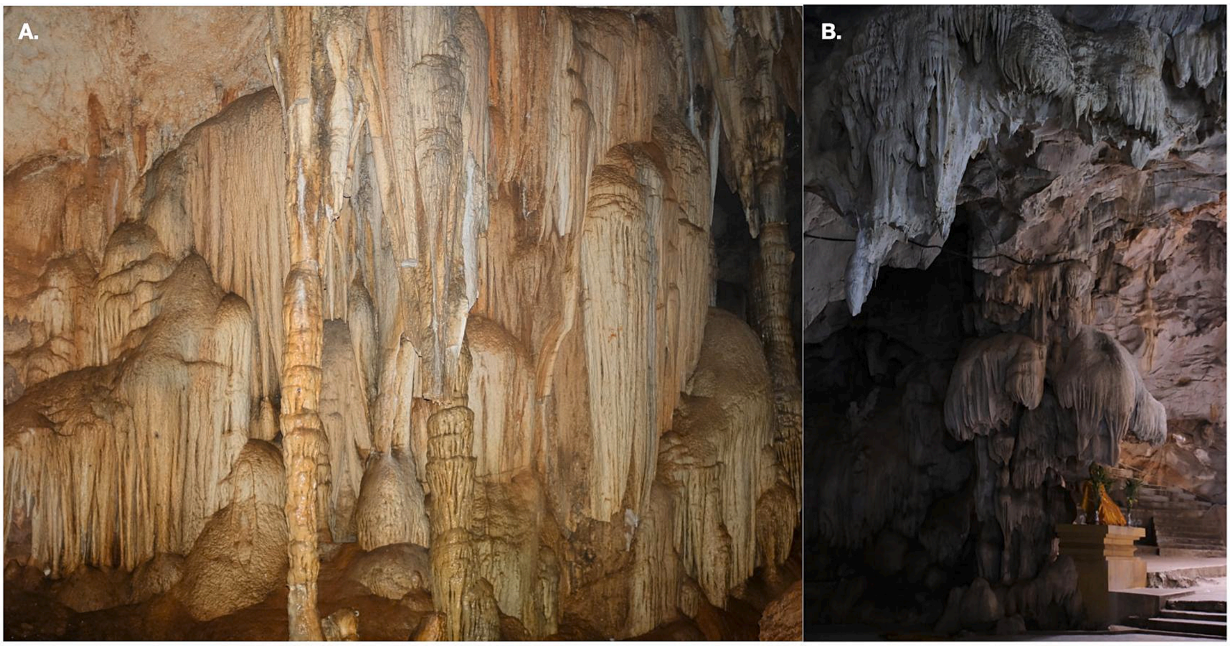


**Fig. 2.** Example of a growing speleothems with stable water drips present on surfaces (A. growing stalactites and stalagmites; B. drying stalactites, with modification, dry and dead stalactite with notable greyish colouration).

dynamics and how it may relate to landscape connectivity, and likely patterns of use. Mining (and extensive guano collection) of certain caves may drive increased displacement of bat populations to other unmined caves (leading to possibly more bats than roost spots), but also creating overcrowding, suboptimal roosting and other negative interactions (Tuttle 2013). Population shifts, driven by direct and indirect anthropogenic impacts, may increase mortality, stress, and disease transmission. However, understanding how multiple variables interact to produce shifts in bat populations needs considerable work. Future changes to conservation management practices should be driven by projects that seek to integrate these different forms of data.

From a speleological point of view, visual inspection during cave surveys, accompanied with detailed cave sketches and maps provide the description of cave passageways which provide the framework for mapping on other components of use for human and non-human species, and how these may have changed over time. Cave maps (cartographic) offers crucial information on the cave dimension, cave features, and configuration of the cave floor, walls, ceiling, sediment type (gravel, sand, clay), speleothems, detail of stream banks and other cave features (Šupinský et al., 2022). For instance, cave maps produced over different exploration periods provide essential records about the presence/absence of underground water in some parts of the caves, the vandalism of cave speleothems (i.e., broken or damaged stalactites, crystal mining sites, etc), or shifts of bat roosts along cave passages, and other important information. However, while this information can provide accurate evidence of changes within cave systems over years or decades, the existing methods still face challenges to obtain higher accuracy. The most frequently used method is still the traditional method involving manual measurements across sequences of stations inside the cave, handheld LIDAR devices and cave sketches that are rendered in 3D using computer software packages are also used, but these can be prone to human error and are time-consuming (Zlot & Bosse, 2014). These maps can be further developed through the use of dyes, and even small ballast to understand where karst aquifers go, how they connect, and to map out the network of water flows (by adding these dyes to water then assessing flow routes either visually, through chemical analysis or using fluorescence using a fluorometer) (Poulain et al., 2017). Although better cave mapping technologies has developed in recent years (e.g., Sogade et al., 2004; Zlot & Bosse, 2014; Gallay et al., 2015; Trimmis, 2018; Nováková et al., 2022), these methods are still often limited to higher income countries. Therefore, caves in tropical regions are often left unmapped and changes over the years are not well documented. This gap may be filled by training young explorers and scientists in these regions, and developing standardised cave mapping methods and disseminated to provide essential information for better karst landscape management and conservation in the future.

In addition to mapping cave features, geological investigations also provide information on the cave origins, dating, and geochronological analysis that can be linked to the palaeoenvironmental history to investigate past cave by humans and other animals, as well as providing paleoclimatic information. Some techniques including stable carbon and oxygen isotope analysis of fossil sediments extracted from cave systems (Louys et al., 2022), and sedimentation analysis from the twilight zone (around cave entrances where light is limited, but still present) are the useful approaches to understand cave use across deep-time (Goldberg & Sherwood, 2006). Furthermore, speleothems such as stalagmites can be use as archives for paleoclimatic reconstruction due to high accuracy and abundant proxies (Zeng et al., 2015). Stable Hydrogen and Oxygen isotopes (dD and d18O) analysis from stalagmites allows reconstruction of higher resolution annual and seasonal climate changes (Kano et al., 2023; Ma et al., 2018; Onac et al., 2008). Dating cave sediments (clastic and chemical sediments) is possible using radiocarbon, U/Th (Uranium/Thorium), dating of speleothems, paleomagnetic reversal and cosmogenic isotopes also provides insights to understand climatic shifts and their implications for future change (White, 2007). However, while caves clearly provide many insights into past, present and even future environmental change, most of caves globally do not fall within protected areas (~93 %) (Sanchez-Fernandez et al., 2021; Tanalgo et al., 2022). As cave ecosystems may be ecofragile, sensitive to changes in use which may impact the microclimate and community present, any activities inside the caves should be conducted with caution to ensure minimum negative impacts to the cave environment. This includes both scientific and non-scientific usage, sampling material of cave speleothems should be carefully justified, and other uses (especially more destructive use from industry, agriculture, tourism or religion) should be more sensitive to these fragile and unique ecosystems.

## 3. Unravelling cave histories using human perspectives

### 3.1. Using human accounts to reconstruct cave histories

Any speleologist or bat researcher knows that the easiest way to find caves is to ask local people. Caves have a range of uses: they are sites of religious significance (especially in Buddhist countries), destinations for tourism, places of refuge during war, and recreation sites for children and adults (who sometimes join caving clubs). People who live near caves are often knowledgeable about their history and can offer insights about bat populations and ecological interactions that can help calibrate observational data from the cave itself. When there are signs of previous use of a cave, this can serve as a prompt for interview questions about local bat population fluctuations. Furthermore, in many rural regions in tropical countries, many people will have grown up visiting cave systems, and will have their own accounts and perspectives on how the caves, or their occupants may have changed. In many instances that may include historical observations of how watercourses and wetness has changed within the cave since their childhoods, or other pertinent information. Some local rangers, tour guides, teachers, maintenance workers and monks–who have worked in caves for considerable periods of time–have become local experts of cave ecology. Building on their local knowledge can help us identify broader trends that are impacting caves regionally and world-wide.

Some caves have historical records going back for centuries (or even longer). Buddhist monks have had writing longer than any other group in Asia. Learning the long-term history of some sites may be possible (Sponsel and Natadecha-Sponsel, 2003), but historical records are often focused on human concerns, and silent on questions related to cave ecology and species population dynamics. Other caves contain surprising historical details. Some bat species are only known from the paintings or art left by long gone generations of people (Pettigrew et al., 2008; Velazco et al., 2021). Historical archives are generally anthropocentric: they may mention specific animals, or describe ecological processes, but the bulk of historical records focus on human concerns (Bonnell and Kheraj 2022). Human memory is selective, and it can also be fallible. Still, local experts can offer important vantage points for understanding the history of sites, and their bat populations. People who have lived in an area for decades, and have ventured underground, can often recount details of their caving trips. Open ended questions about the history of the region and cave ecosystems can produce evidence of historical cave use by bats. Sharing observations and expertise–for example physical signs that suggest the presence of large bat colonies several decades prior–can help elicit specific memories that may help reconstruct a local chronology of bat population fluctuation.

At one of Thailand's most popular cave destinations, Tham Luang Nang Non, we were able to combine different data sources to reconstruct local bat population dynamics. We observed physical evidence (such as ceiling marks) of very large colonies of bats that had previously roosted at the entrance of this cave, but had been abandoned. One local ranger, who was involved in early explorations of the cave in the 1990 s, reported that noxious fumes from kerosine lamps had prompted the bats to disperse. The kerosine fumes were detectable for about a week, according to the ranger, and the bats stayed away from the cave for around a week after each expedition, before the population eventually left. Such information is useful (though multiple independent accounts are preferable), but is best if supported by archival documents and physical evidence to provide a stronger and more detailed account of what may have happened.

Tham Luang Nang Non cave entered the international media spotlight in June 2018 when twelve young boys, and their coach, were trapped inside by rapidly rising waters. Following this international incident, tourism dramatically increased–from around 30 visitors a week, to around 1 million people annually. During a bat survey we conducted in March 2023 we found small numbers of *Asellicus stoliczkanus* on stalactites throughout the cave, in addition to low densities of other species in some chambers, and a few *Hipposideros armiger* were also observed flying in some larger chambers. While new lighting and high human traffic has helped make the large initial chambers unattractive to bats, combining oral history interviews with physical observations suggests that the large population of bats left the cave well before the sudden influx of tourists. Physical evidence of abandoned roosts in the cave corroborated the chronology of our interview with the local ranger at Tham Luan Nang Non cave, suggesting that a large population of bats (>1,000 individuals) left decades before the recent influx of tourists. Combining interviews with physical observations could be used to provide similar insights about long-term roosting changes in other caves.

At other sites, we found evidence that heavy hunting has contributed to the extirpation of bats. Local residents, park rangers, and vendors are often able to recall if there was past hunting at a given cave, and when hunting ceased to be viable. Bat hunting is still practiced in many regions and is contributing to species extinctions (Tanalgo et al., 2023). Physical evidence of hunting (such as nets) can be used to prompt conversations with local people or rangers to gauge if they know about hunting, and even if they know how it is done (or how bats are prepared for food) to understand local hunting practices and patterns.

Oral history interviews can also be used to understand changes to cave hydrology. We observed caves that appeared to have previously been much wetter, and are now dry with many fewer bats than the past. One local scientist who grew up near a cave in Malaysia said that when he was young a river permanently flowed through the cave, but it was no longer present. Changes in agriculture and irrigation may have driven this very visible change, as microclimate is very likely to alter the suitability of the cave to bats. Obviously concomitant changes in pesticide use, and foraging area are all associated with changes in cave climate, and all of these likely impact species to various degrees.

Satellite imagery can be used to help prompt discussions about local land-use changes, the forest loss and observed changes in bat populations over the corresponding time period. Likewise, discussions of what pesticides are used, and what impacts these may have, and how they are applied might add additional dimensions to understanding changing populations.

Buddhist temple caves are important sites in Asia that have long histories of bat-human co-existence. Monasteries frequently modify or damage natural caves with major shrine and temple construction projects. Furthermore, older temples continue to pollute them with light or smoke (from incense or candles), or with noise (especially with the now common use of loudspeakers). The relatively recent arrival of electricity in rural regions has resulted in heavy disturbance with constant lighting in some caves. Buddhist monasteries are frequently home to people who have been involved in cave management (sweeping the cave etc for human use) for many decades who can recount changes in use by bats, and in some cases how this relates to lighting, construction, and disturbance by tourists and other visitors. Similarly, people who work to maintain tourist caves may be able to provide important historical information. Given the different light intensities often present through caves it is possible to understand, with other sources of evidence like physical marks of past use from bats, how adaptations such as lighting may have impacted resident bat populations.

Monks will often hire local people to sweep or even collect guano (largely for use as fertilizer). Long-term residents, and people who work at Buddhist temples and tourist caves, are often able to note if there have been changes in the volumes of guano over time. Even if they do not know the species of bat present in these caves, they may be able to report sufficient information to reconstruct population trajectories and shifts in use of the cave by bats, such as changing positions in caves, or changes in noise (which may suggest fruit bats rather than insectivores) or even if mortality patterns have changed over time. Attending to how changes in guano production have been even (or uneven) across the cave, or vary by area, may offer clues about historical changes in different bat species that utilise different parts of the cave.

During our joint field research in Thailand we heard reports in one cave of an uneven decline in guano over the past few years, which is likely to relate directly to declines in some species using the cave. This cave was also one of few in the region to still host fruit bats which play an important role as seed dispersers. An elder Abbott stated he has stopped hunting at the cave around a decade prior, which likely explains why the species persisted there when it was lost from most caves in the region (though evidence of recent hunting of *Hipposideros armiger* exists at many other caves). We asked local sources about changes in the volume of vocalization calls by bats at this cave, and they reported that there has been little change in noise in recent years. Given the loud vocalisations of Pteropodids (fruit bats) it is likely declines in recent years are from insectivorous species that we observed in the cave.

The integration of data from site visits with local interviews also gives us a high-resolution understanding of regional cave use seasonally. For example, some of the least disturbed sites we visited were river caves with bat populations, but these sites may flood during the wet-season. Many sources at temple caves–which did not experience seasonal flooding–noted increasing bat populations during the wet-season. However, some of the persistently dry temple caves report high bat mortality during the wet-season. Understanding when high mortality rates had started may allow us to understand how this may reflect changes in habitat, diet (possibly due to increased pesticide use) or even direct pesticide exposure and bioaccumulation of chemicals. Local interviews can be combined with research in local archives, markets, and agricultural supply stores to help us understand how historical factors may have driven shifts in local bat distributions.

### 3.2. Integrating approaches from multiple disciplines

The fields of speleology, environmental history and anthropology can offer biologists methodological tools and interpretive frameworks to help understand how human activities have transformed cave ecosystems. Historians use archives, which are conventionally maintained by government agencies and public institutions, to find evidence of past environmental changes. Archival data was once limited to letters, documents, and reports which are stored in a physical form. The bulk of human history and environmental history is still stored in physical archives, even though some archives have been digitized over the past thirty years, and digital databases have become important repositories for material from recent historical periods. Locating relevant archives, and finding documents with historical information related to cave ecology, can be a challenging and time-consuming process.

While most archives are unlikely to have documents directly related to cave ecology and bat biology, the published literature in environmental history and anthropology can offer broad contextual insights for understanding how particular systems have been impacted by long-term historical and ecological processes. In particular, important studies have documented how engineering projects have impacted hydrological and ecological systems (Mitchell 2002; Whitington 2019; Carse 2012), how toxic synthetic chemical exposures are transforming human and other animal communities (Bullard 1993; Nixon 2011; Kirksey 2020), and how plantation agriculture has shaped Anthropocene landscapes (Haraway, 2015; Davis et al., 2019). In addition to ecologists, and environmental NGOs, environmental historians and anthropologists have studied how ecological communities have been impacted by human initiatives including agriculture (Scott 2017), colonialism (Crosby 1972; Crosby 1986), and large-scale landscape change (Kirksey 2015; Hughes 2017), and urban wildlife management (Rose 2022).

### 3.3. Ethical considerations and asking the right questions

Oral history interviews can produce invaluable sources of data about recent historical periods, especially in regions where there are not relevant historical archives. Many historians borrow methodological tools from cultural anthropology in approaching oral history interviews. Formal interviews usually require research ethics clearance from universities and often require a local advisory board to provide guidance and oversight. Securing informed consent for interviews usually involves securing signatures from participants on standard university forms (and in the language they speak), but in cases where participants may not be able to read or write ethics committees can approve "oral scripts" that can be used to obtain consent. Advanced training from a social scientist, or active partnerships with anthropologists or sociologists, may be needed to ensure the scope of questions and technique is consistent and rigorous. Since ethical principles and norms are not human universals, it is important to be attentive to local values and norms while conducting interviews. Informed consent is only the first step in conducting ethical research that is aligned with local values and national laws.

Clearly and openly explaining the goals of a particular research project is usually the best way to initiate a dialogue about matters of mutual interest and also help identify the best people in a given community who can serve as sources of historical information. Once participants are fully informed about the scope of a research project, and they formally elect to participate, a variety of strategies and tactics can be used during the interview to establish historical matters of fact. Open-ended prompts and questions–"Tell me about your trips inside local caves", "did you seen many bats?", "Did you visit as a child", or "Have you observed many changes since then"—can produce some of the best data related to local natural history. Following up with specific questions, like "How old were you when that happened?" or "Was that before or after President X was elected?" can help establish a detailed and accurate chronology. There are multiple ways to corroborate information. Conducting follow-up interviews with key sources, cross-checking facts during interviews with multiple sources, and using other types of data is needed to truly verify site histories.

Temporality, seasonality, and time are marked in many different ways, and calculated with many different calendars, so careful translation work may be needed to make sure that seasonal changes are not conflated with longer-term transitions, linking questions to familiar seasons like harvest or wet season can facilitate understanding of more seasonal shifts versus longer term changes. Cross checking information from one source, with other independent sources, is key to developing an accurate account of the past. Human memory is fallible, so cross-checking (asking the same question in different ways to assess consistency) and using multiple kinds of data–such as direct physical observations of abandoned roosts, analysis of guano, and printed historical records–can help establish matters of fact. As a general rule, if three independent sources report the same thing, then one might assume that it is true.

Visual data–like historical photographs and remote sensing images–can be used to prompt people's memories about specific past moments or phenomena. Taking pictures, making audio recordings, and shooting video during the course of a research project can also produce data about the intersections of nature and culture, provided people are comfortable with such recording methods, and have given informed consent. These records can help a research team reconstruct ecological dynamics in a moment of time, in the context of changing human architecture, infrastructure, and daily routines. Pictures from one site can help trigger recall from interviewees at another site. For example, gathering information about pesticide use may be difficult–in part because it is a sensitive topic, but also because of the many products available. Since pesticide labels can be difficult to read, even for people with advanced degrees, asking local experts to demonstrate how it is used can help prompt dialogue. Pictures from a local hardware store or agricultural supply store might help gardeners, farmers, and plantation managers talk about their shifting patterns of pesticide use in the past and the present–helping them become articulate about different types of herbicide, fungicide, and insecticide.

Researchers engaged in oral history interviews are generally obliged to "do no harm" to their participants (ASA 2021), even when the participants may be involved in unethical or illegal activities. Awareness of and sensitivity to divisive issues in the local context of key research sites is critical to this endeavour. If someone uses pesticides on their crops, they may suffer from reputational harm if their friends or neighbours find out. In Baan Tham village in Northern Thailand, an agricultural area with many geographically adjacent cave systems, local villagers reported to us that the use of agrochemical products in locally grown produce is a subject of community interest. The economic and social consequences of agrochemical use becoming known in the community can include reduced produce sales to chemical-averse residents in local markets and exclusion from informal produce exchange networks. It is even possible that residents will ask visiting researchers to reveal their knowledge of agrochemical use by other community members. Obtaining reliable ethnographic data on contested issues in these contexts requires the researcher to establish relationships of trust with, often vulnerable, informants who face potentially substantial and irreparable damage to their livelihoods and social standing.

The University of Oxford offers clear guidance for researchers who encounter illegal activities while conducting interviews with human participants: "criminal activity should not be revealed unless under court order" (CUREC 2022). Making research participants anonymous is one strategy that can be used to avoid harming individual interviewees by subjecting them to unwanted scrutiny from neighbours, police, park rangers, or government officials.

Sometimes the values and ethical principles of the researcher may be in direct conflict with research participants. For example, activities like hunting or poaching may be deemed unethical, according to the values of conservation ethics. In trying to understand why a given activity takes place, sometimes it is best to be reserved–to not reveal your own opinion about a subject, especially as cultural norms may vary. In many situations hunting is critical for local food security and supports livelihoods (Shostak and Nisa, 2009; Kohn 2013; Chao 2022). Even so, in some interview situations, it may be opportune to reveal your own opinions about a sensitive subject. While people may be reluctant to talk about practices that a researcher finds unethical, sometimes a respectful and courteous discussion can generate new insights about the practices in question. The dialogue that takes place during an interview can sometimes shift the beliefs of the person being interviewed, or even the researcher doing the interviewing.

### 3.4. Long term collaborations and data integration

While quick surveys may offer an overview of local cultural, ecological, and historical processes, greater depth of knowledge demands extended field research. Longer-term anthropological research relies on the method of "participant observation." This approach to ethnographic field research involves asking questions while participating in everyday activities–that may range from cooking meals, to taking part in ceremonies, to playing with children–while generating raw data in the form of fieldnotes (Spradley, 2016). Participant observation can also be used to study how humans impact cave ecosystems. A long-term study ethnographic study might involve participating in Buddhist rituals in temple caves, joining tourists groups that visit caves, observing children who play in caves, helping collect bat guano, taking part in the activities of local spelunking groups, or studying "science in action" with interdisciplinary teams that map caves (Latour 1987).

Social and natural scientists have developed new practices for integrating multiple kinds of data from ecology, geology, social sciences, economics and the natural sciences more broadly. New approaches to "multispecies ethnography" have recently been developed by cultural anthropologists to better understand how other organisms "shape and are shaped by political, economic, and cultural forces" (Kirksey and Helmreich 2010). While previous generations of ethnobotanists and ethnobiologists were concerned with local names and practices of classification (Hunn 2007), new approaches to multispecies ethnography have involved participant observation in places "where species meet" (Haraway 2008). Rather than treat "nature" and "culture" as separate domains, many anthropologists have begun to study how multispecies communities are being transformed during the accelerating changes of the Anthropocene (see van Dooren et al 2016; Tsing et al., 2021; Chao et al 2022). Some preliminary work has been done in caves by multispecies ethnographers (i.e. Kirksey et al., 2022), and future collaborations that bring anthropologists together with bat biologists and cave ecologists could generate a fruitful programme of interdisciplinary research about human impacts on subterranean multispecies communities. Perhaps these collaborations will inspire a broader programme of interdisciplinary research underground, as well as in terrestrial and marine ecosystems, and there is further opportunity to expand further on these collaborations to develop sustained interdisciplinary programs for cave research and management.

## 4. Integrating data to understand patterns and manage landscapes

The integration of human accounts with the environmental data from site inventories (and historic records) and geospatial data from remote sensing can help us reconstruct the trajectory of population changes, and in some cases both shifts in population and drivers of change. Recent accounts also provide high resolution temporal data to allow us to understand how species rely on different parts of the landscape across the course of the year. Furthermore, if spaces are regularly shared between people and bats (for example if guano collectors are present) then simple ways to monitor shifting populations (such as recording how many bags of guano are collected per week from each cave section, and recording mortality) enables a better understanding of seasonal shifts and association of mortality with weather or other temporal events. Understanding these shifts, as well as the use of space, and the drivers of change can enable strategic interventions to counteract declines. By maintaining healthy populations, it is possible to maximise ecosystem service provision from bats, minimise stress, and possible spillover. Furthermore, reducing mortality and increasing health means animals are less likely to die, and be consumed by other animals in the space, which may have closer interactions with humans and the ability to be intermediate hosts if they do become infected with pathogens. Obviously integrating this data is challenging, the structure of interviews, level of recall, and temporal landmarks to assess time can be difficult to interpret properly, especially as people can be vulnerable to suggestion if events are a long time prior. Biases, or judgments on the acceptability of certain behaviours (like hunting and consumption of bats) may also introduce biases, or alter the information interviewees are comfortable to disclose. Furthermore, as scientists from different fields rarely obtain inter-disciplinary training, the ability to collate such diverse data is challenging, despite the value of integrating such data to reconstruct past changes in cave systems and the populations of their inhabitants.

Gauging when bat population changes may have occurred using cues from the cave, and then cross-referencing this with changes in roost use, land-cover change, or other factors, can provide a clearer understanding on what may drive declines, and thus provide a basis for intervention. Other evidence, including data about when young are born, can also help provide an understanding of times when bats are vulnerable to stress and need for high calorie and protein diets. Broader biological and ecological context can feed into management practices, and disturbance should be minimised in high stress periods, thus gathering information to contextualise patterns of use in sites can facilitate management.

In addition to biodiversity assessments, caves and karst management needs to consider cultural aspects (prehistoric/historic structures, ethnographic resources), geological (speleothems, bedrock, limestones, karst), hydrology, human health and socio-economic (as mentioned in previous sections). Therefore, interdisciplinary approaches are needed. Cave and karst ecosystems are physically most at risk from quarrying, however given the role of bats as the major "bringer of nutrients" into cave ecosystems, hunting, pesticide use, defoliants, or other factors which significantly alter bat populations may also impact on the communities within cave ecosystems; yet little data exists to document these shifting communities. Given that many caves form on river systems in limestone areas, changes in water pH and pollution may also impact on cave communities, as may changes hydrology that may relate to irrigation; yet whilst such changes have been noted anecdotally (as we state) further, more standardised data is needed to better understand these patterns. Tourism activities and guano mining practices also change the faunal communities, destroy geological features (i.e., speleothems) that have taken thousands of years to form, alter the energy flows within cave ecosystems, and increase the risk of exposure to zoonotic diseases (through displacement of animals and increasing stress, both of which contribute to spill-over risk). In response to the need for cave management guidelines, multiple international conservation organization have issues caves and karst management guidelines for cave protection (i.e., IUCN, National Speleological Society (NSS)), however there has been a disproportionate focus to cave systems in higher income economies, and work is needed more broadly to better manage and conserve cave ecosystems.

## 5. Managing caves to maintain diversity

Some sites may be in particular need of restoration to improve the ability of bats to forage within an area. This broader understanding is critical for long term species survival and can help mitigate spillover risk of viruses and other pathogens. Yet long-term data may require more frequent visits than possible for scientists, and thus engagement with other site users is essential. Owing to lack of protection in the majority of karst and caves in the world (with Geoparks, where present, likely offering relatively few provisions for cave communities), a comprehensive cave biodiversity and distribution database are needed to develop management plans and developing appropriate monitoring approaches.

As well as reducing the loss of caves, especially in key sites, management is needed both of cave landscapes (i.e. to reduce contamination of waterflows in cave systems) and for visitors to caves to reduce their impacts on cave communities. Cave management guidelines should prioritize approaches which minimize damage to cave systems and encourage cave education and outreach, as well as to facilitate high-quality research across multidisciplinary scientific fields. Some tourist caves could become models of “better practices” with minimum lighting and pathways that facilitate human visits with minimal damage to the ecosystem. For example, some tourist caves use lamps which illuminate only the path, whilst providing little illumination of the ceiling, to minimise disturbance to bats, and leaving some chambers entirely dark and fenced off from visitors. Other studies have shown that some bat species have a slight preference for red light relative to other lights (Straka et al., 2020), but it still causes disturbance. Minimising lighting (and better understanding the impacts on species more widely) remains a priority. Efforts are being made to better collate such data, but few studies have been conducted in the tropics (https://www.conservationevidence.com/data/index/?synopsis_id[]=14) and more work is needed to better represent biodiversity hotspots. As cave tourism, and religious cave visits may expand in Asia in the future, trying to ensure best practice and actively assess impacts may be key to maintaining healthy bat populations. Furthermore, more work to collate data and evaluate threat to cave systems (i.e. see Tanalgo et al., 2022) are needed to genuinely understand threats to cave, and develop appropriate intervention and conservation across scales. Through the development of better baselines, and the use of better tools (such as Bat Cave Vulnerability Index/BCVI) we can finally use evidence-based approaches to guide conservation efforts in cave systems. In addition, effort to generate a comprehensive global karst distribution map has been develop as a foundation to initiate karst conservation globally, for instance in Karst Region of the World (KROW) by The Nature Conservancy (TNC) and The University of Arkansas (Kuniansky, 2008), though these maps currently lack the accuracy needed to genuinely direct research; and more work, and the development of cave databases, is needed.

Guidelines for tourists and cavers including both seasonal recommendations (for example reducing disturbance during breeding, or hibernation in key sites) and practice-based recommendations are needed to reduce the risks of negative consequences from cave visits. (such as washing field gear to reduce the risk of contamination, such as fungal pathogens between sites; Bureau for Land management, 2010). Yet, once again, such guidance has almost exclusively been developed for Nearctic caves, and whilst cave visitors can help mobilising the data needed to better understand these systems, work is needed to ensure such activities are genuinely sustainable.

### 5.1. Synthesis

Humans and bats have used caves for millennia, and as such understanding the histories of these sites has far-reaching implications both to understand the past, and better manage the future. Furthermore, with the knowledge of the role of stress and displacement on the risk of pathogen spillover, understanding how to manage caves to minimise stressors and therefore reducing risk at key periods is essential to reducing spillover risk. Our knowledge of bat populations over time remains limited, and thus through integrating diverse data to reconstruct cave histories we can better understand how to manage these systems. Using multiple methods to reconstruct past trajectories can add considerable insights into the richness of caves (see Graphical Abstract), and how species distributions may have changed over time, and what may have driven any changes and thus provide the information needed to guide interventions to reduce the impacts of such threats. In addition, increased tourism and temple-caves across Asia means developing modes of best practice for management to prevent further losses in cave bat populations are nesessary. Reassembling the mosaic of different data provides new insights which may help us better manage and conserve the systems to maintain cave diversity into the future.

Authors’ Contributions

ACH conceived the idea and wrote the first draft, AC and EK edited the first draft, all authors edited the second draft.

## 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.

## Data availability

No data was used for the research described in the article.

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