A literature-based database of the natural heritage, the ecological status and tourism-related impacts in show caves worldwide

Nature Conservation 50: 159–174 (2022)
doi: 10.3897/natureconservation.50.80505
https://natureconservation.pensoft.net

DATA PAPER

A peer-reviewed open-access journal
Nature Conservation
Launched to accelerate biodiversity conservation

A literature-based database of the natural heritage, the ecological status and tourism-related impacts in show caves worldwide

Elena Piano[1], Giuseppe Nicolosi[1], Stefano Mammola[2,3], Valentina Balestra[4], Benedetta Baroni[1], Rossana Bellopede[4], Elena Cumino[1], Nicola Muzzulini[1], Anna Piquet[1], Marco Isaia[1]

1 *Department of Life Sciences and System Biology, University of Torino, Via Accademia Albertina 13, 10123 Torino, Italy* **2** *Laboratory for Integrative Biodiversity Research (LIBRe), Finnish Museum of Natural History (Luomus), University of Helsinki, Pohjoinen Rautatiekatu 13, 00100 Helsinki, Finland* **3** *Molecular Ecology Group (MEG), Water Research Institute (IRSA), National Research Council of Italy (CNR), Corso Tonolli 50, 28922 Verbania, Italy* **4** *Department of Environment, Land and Infrastructure Engineering, Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129 Torino, Italy*

Corresponding author: Elena Piano (elena.piano@unito.it)

Academic editor: Cyrus Samimi | Received 13 January 2022 | Accepted 16 September 2022 | Published 10 November 2022

https://zoobank.org/89A4A1BD-A638-42B6-8533-9D75F5450474

Citation: Piano E, Nicolosi G, Mammola S, Balestra V, Baroni B, Bellopede R, Cumino E, Muzzulini N, Piquet A, Isaia M (2022) A literature-based database of the natural heritage, the ecological status and tourism-related impacts in show caves worldwide. Nature Conservation 50: 159–174. https://doi.org/10.3897/natureconservation.50.80505

Abstract

The touristic use of caves causes multiple environmental alterations to the subterranean ecosystem, having potential effects on all components, from the atmosphere to lithosphere, hydrosphere, and biosphere. Setting a baseline on the current knowledge of the ecological status of world show caves is pivotal to implement monitoring and management programs aiming at their conservation. However, information on this topic is scattered throughout several publications, making it difficult to access data and ultimately delaying advances towards a sustainable touristic use of show caves. We provide a literature-based dataset relative to the knowledge on the ecological status of 265 show caves worldwide. Data were collated from 289 papers selected through a systematic literature survey of an initial set of more than 1,000 scientific papers. We made the compiled information available through two complementary datasets, reporting: (i) references of the selected papers and (ii) 44 fields relative to the main characteristics of show caves investigated in literature. These fields encompass information about geographic locations, cave general characteristics, natural heritage, and the specific environmental components—and related environmental parameters—investigated in each of the considered study. Such a dataset improves our accessibility to the basic information provided by literature on the ecological status of show caves, also pointing out some literature gaps that should be addressed by future research. By making these data freely available and re-usable, we hope to stimulate research in the field of cave tourism, cave conservation, and cave-based ecology.

Keywords
Cave heritage, environmental components, environmental parameters, subterranean ecosystems, systematic search

Introduction

Cave ecosystems are nutrient-deprived environments characterized by the absence of light, spatial confinement, climatic stability, and low biodiversity (Culver and Pipan 2019). Given such peculiar environmental conditions, caves are extremely susceptible to both natural and anthropogenic disturbance and subjected to multiple environmental pressures (Mammola et al. 2019). Among other threats, disturbance posed by cave tourism is gaining international attention in show cave managements (Cigna 2016) as well as remarkable traction in scientific literature (Mammola 2019). The use of caves by humans has long been central in history. If in the past we mostly used caves as shelters, places for rituals, or food storage (Mulec 2014), in later centuries several caves have been converted into touristic attractions—the so-called “show caves” defined as “any cavity where a fee is paid to gain access and visit it” (Cigna and Forti 2013). In show caves, paying visitors experience the natural beauty of caves via constructed trails, guided tours, artificial lighting systems, and regular opening hours (Cigna and Burri 2000). These infrastructural and environmental alterations, along with the presence of visitors themselves, threaten the integrity of the cave ecosystem across all its environmental components—i.e. atmosphere, lithosphere, hydrosphere, and biosphere.

For example, the presence of visitors may have direct impacts on the cave temperature (both in the air and in the water; Šebela and Turk 2014). Temperature increases cause “thermal waves” when caves are visited by high numbers of people which can persist even on subsequent days (Dominguez-Villar et al. 2010). These perturbations to the subterranean microclimate, together with the associated increase of CO_2 air concentration caused by tourists’ breath, may enhance carbonate dissolution, damaging geological formations, i.e. speleothems (Sanchez-Moral et al. 1999; Martin-García et al. 2010, 2011).

Moreover, tourists visiting the cave carry dust pollutants and propagules of microorganisms through their clothes and hands, which can be found on speleothems (e.g. Saiz-Jimenez et al. 2012; Iliev et al. 2018), in the water (e.g. Ando and Murakami 2020; Moldovan et al. 2020), in the air (e.g. Porca et al. 2011; Martin-Sanchez et al. 2014), and in the sediments on the ground (e.g. Mammola et al. 2017; Kukla et al. 2018). Another human-driven pressure that may enhance the growth of alien microorganisms in show caves is the presence of high input of organic matter in both the sediments (Marques et al. 2016, 2017) and in the water (Jiménez-Sánchez et al. 2008). In parallel, the presence of artificial lighting often drives massive growths of photosynthetic microorganisms, such as cyanobacteria, diatoms, and green algae (Falasco et al. 2015; Piano et al. 2015, 2021), but also bryophytes, ferns, and vascular plants (Castello 2014). All these organisms constitute the so-called '*lampenflora*' (Mulec et al. 2008), causing aesthetic damage due to the formation of extensive patinas on speleothems and paleo-archaeological heritage (Saiz-Jimenez et al. 2012). Furthermore, the environmental instability generated by tourists (e.g. increasing temperature, high organic matter inputs, trampling) and artificial lights may negatively affect the subterranean invertebrate fauna (Isaia et al. 2011; Pellegrini and Ferreira 2012, 2016; Alonso et al. 2019; but see Faille et al. 2014; Nicolosi et al. 2021), but also bats reproducing or overwintering in caves, which may be disturbed by both visitors' noise and artificial lighting (Mann et al. 2002; Cardiff et al. 2012; Ivanova 2017).

The sustainable touristic use of show caves represents an emerging topic in the frame of the conservation of subterranean ecosystems—also in light of the Sustainability Goals proposed by the United Nations (UN 2015). A publicly available systematic collection of the natural heritage of show caves worldwide and information about the status of the different environment components, i.e. atmosphere, lithosphere, hydrosphere and biosphere, in show caves is therefore necessary to set a base for the implementation of scientifically sound environmental monitoring programs. This could facilitate cave managers to measure the impact of tourism in show caves.

To mitigate this knowledge gap, we here provide a data paper based on systematic research in which we describe a database that builds on scientific and peer-reviewed literature. Our aims are: i) to quantify available information on the ecological status of show caves worldwide; and ii) to identify knowledge gaps in the study of ecological impacts in show caves globally. Our database includes a georeferenced set of show caves where researchers have evaluated variations of a certain environmental indicator used to monitor the impact of tourism and its related activities on the subterranean ecosystem. For each show cave, we provide information on the main cave's characteristics, including its natural heritage, and the environmental components investigated therein. This database could, therefore, represent a basis to evaluate, support, and promote the study of the impacts caused by tourism on these fragile ecosystems in light of their conservation.

Methods

Data search

We conducted a systematic literature search of studies investigating show caves using the Web of Science (Clarivate analytics) Core Collection database over all citation indices except chemical, all document types, all years, and all languages (initial database query 27 May 2020, final database query 07 July 2022). Different search terms were initially trialed in a scoping exercise to refine the procedure by running searches and considering the relevance of the first 100 references. Our final research query was based on the following combination of search terms: ("show cave*") OR (tour* AND cave*)

OR (visitor* AND cave*) OR (cave* AND "public access"). This resulted in a total of 1187 potential publications, whose titles and abstracts were initially screened to remove clearly inappropriate references. We included studies that: (i) investigated the state of cave ecosystem components potentially impacted by tourism and related activities; (ii) investigated the impact of tourism and related activities on the cave ecosystem; and (iii) investigated the effect of management practices in show caves (see Fig. 1).

Data compilation

After screening, we retained 289 relevant papers and, for each of them, we extracted information about: i) how many caves were included in the study; and ii) which environmental component was considered, i.e. biosphere, atmosphere, lithosphere and hydrosphere. For each environmental component, we identified all environmental parameters that have been evaluated therein: i) invertebrates, bats, other vertebrates, fungi, prokaryotes, and 'lampenflora' for the biosphere; ii) microclimate, and the concentration of carbon dioxide (CO_2), particulate, and radon for the atmosphere; iii) physical and chemical composition of sediments and crystalline structure of speleothems and paleo-archaeological findings for the lithosphere; and iv) water geochemistry, water level, and water quality for the hydrosphere.

For each examined show cave, we used Google Earth to obtain: i) the geographical coordinates of the cave entrance projected to the WGS84 latitude and longitude system; ii) the elevation of the cave entrance; and iii) the country where the show cave is located. We also assigned each show cave to one out of seven biogeographic regions: Western Palearctic, Eastern Palearctic, Nearctic, Afrotropical, Neotropical, Indo-Malaysian, and Australasian. We also retrieved information on: i) the environmental component(s) that has/have been evaluated in literature within the show cave; ii) which parameter(s) has/have been evaluated in literature within the show cave; iii) the cave extension (usually corresponding to the total planimetric development); iv) the length of the tourist path; v) presence/absence of any formal accreditation referring to their cultural and/or natural heritage, e.g. inclusion of a protected area, UNESCO World Heritage list, etc; vi) the presence/absence and type of artificial lights; vii) the year of the cave opening to the public; viii) the duration of the opening period during the year; and ix) the number of maximum opening hours during one day. We then recorded whether the cave hosts: i) geological; ii) archaeological; iii) paleontological; iv) biological; or v) cultural heritage. When data were not available in the analyzed papers, we retrieved available information from the websites of the International Show Caves Association (https://www.i-s-c-a.org) and Show Caves of the World (https://www.showcaves.com).

Data description

Information obtained from this research is presented as an Excel file (Suppl. material 1) deposited in the open repository Figshare (DOI: 10.6084/m9.figshare.18320363) including two sheets. The Sheet labelled "Papers" includes the list of papers retrieved

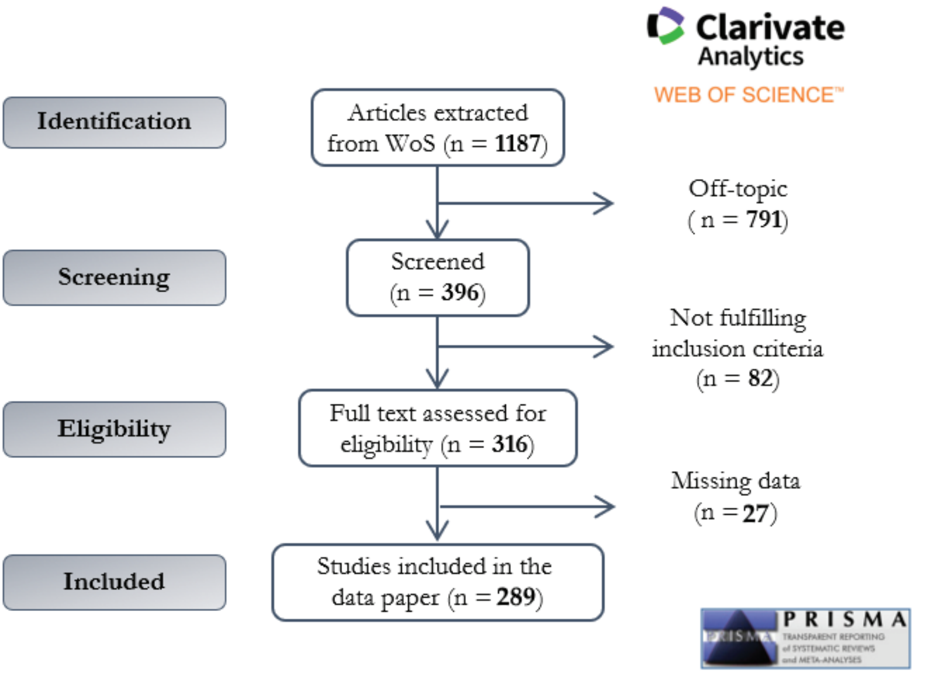

Figure 1. PRISMA diagram of the systematic literature search.

with this systematic search, while the sheet labelled "Caves" is a dataset including the list of show caves examined in the papers and related information.

The sheet "Papers" is an Excel table of 289 rows, each one corresponding to a paper, and two columns containing the following fields:

ID: a unique identification progressive number provided to each reference.
Citation: APA citation for each paper.

The sheet "Caves" is a database composed of 265 rows, each one corresponding to one of the examined show caves, and 44 columns belonging to the following groups of fields: 'geographic data, cave characteristics, natural heritage, environmental components, environmental parameters, and summary statistics'.

The group of 'geographical data' includes the following fields:

Name: the name of the show cave.
Latitude: latitude of the show cave in the WGS84 system (EPSG: 4326) expressed in decimal degrees (°).
Longitude: longitude of the show cave in the WGS84 system (EPSG: 4326) expressed in decimal degrees (°).
Elevation (m): altitude of the show cave expressed as meters a.s.l.

The group of 'cave characteristics' includes the following fields:

Cave extension (m)*: a binary variable that distinguish caves extending for less than 1 km (≤ 1000) and caves extending for more than 1 km (> 1000); NS is used when no information is provided in literature or on the web.

Tourist path*: a Boolean variable (yes/no) indicating whether a tourist path is present in the cave; NS is used when no information is provided in literature or on the web.

Tourist path length (m)*: a binary variable that distinguishes tourist paths extending for less than 1 km (≤ 1000) and tourist paths extending for more than 1 km (> 1000); NS is used when no information is provided in literature or on the web.

Tourist flux (visitors/year)*: a categorical variable that distinguishes caves based on their tourist flux (≤ 1000 visitors/year = "very low"; 1000 < visitors/year ≤ 10000 = "low"; 10000 < visitors/year ≤ 50000 = "intermediate"; 50000 < visitors/year ≤ 100000 = "high"; > 100000 = "very high"); NS is used when no information is provided in literature or on the web.

Light presence*: a Boolean variable (yes/no) indicating whether an artificial lighting system is present in the cave; NS is used when no information is provided in literature or on the web.

Light type*: a categorical variable reporting the type of lights installed within the cave (incandescent lamps, mercury lamps, carbide lamps, colored lights, fluorescent lamps, and LED; flashlights are indicated for show caves where there is not an artificial lighting system); NS is used when no information is provided in literature or on the web.

Opening year*: a categorical variable indicating the historical period during which the cave was opened to the public (before 1900; 1900–1950; 1950–2000; 2000–2021); NS is used when no information is provided in literature or on the web.

Opening period*: a binary variable indicating whether the cave is opened for less than 6 months per year (≤ 6 months) or for more than 6 months per year (> 6 months); NS is used when no information is provided in literature or on the web.

Opening time*: a binary variable indicating a range of hours during which the cave is opened to the public per day (≤ 4 hours; > 4 hours); NS is used when no information is provided in literature or on the web.

Conservation*: a Boolean variable (yes/no) indicating the presence or absence of any formal accreditation referring to cultural and/or natural heritage of the show cave, e.g. the inclusion of a protected area, UNESCO World Heritage list, etc; NS is used when no information is provided in literature or on the web.

The group of 'natural heritage' includes the following fields:

Geological heritage: a Boolean variable (yes/no) indicating whether specific information about the geological heritage —here intended as the presence of speleothems

* Fields converted into categorical variables to: i) allow researchers to differentially visualize show caves based on these parameters; and ii) to keep into account the error generated by the fact that the absolute value can be referred to different years, ranging from 2000 to 2022. Thresholds used to generate the categories are arbitrary.

or geological formations that represent an attraction for tourists— of the show cave is made available in the surveyed literature; NS is used when no specific information could be retrieved.

Archaeological heritage: a Boolean variable (yes/no) indicating whether specific information about the archaeological heritage —here intended as the presence of archaeological remains that represent an attraction for tourists— of the show cave is made available in the surveyed literature; NS is used when no specific information could be retrieved.

Paleontological heritage: a Boolean variable (yes/no) indicating whether specific information about the paleontological heritage —here intended as the presence of paleontological remains that represent an attraction for tourists— of the show cave is made available in the surveyed literature; NS is used when no specific information could be retrieved.

Biological heritage: a Boolean variable (yes/no) indicating whether specific information about the biological heritage —here intended as the presence of living organisms that represent an attraction for tourists (e.g. *Proteus anguinus*, *Speleomantes* species, large bat colonies, bioluminescent glowworms…)— of the show cave is made available in the surveyed literature; NS is used when no specific information could be retrieved.

Cultural heritage: a Boolean variable (yes/no) indicating whether specific information about the cultural heritage —here intended as the presence of cultural values related to the cave that attract tourists— of the show cave is made available in the surveyed literature; NS is used when no specific information could be retrieved.

The group of 'environmental components' includes the following fields:

Atmosphere: number of papers examining the atmosphere —here intended as the gas composition and climatic variations— in the show cave.

Lithosphere: number of papers examining the lithosphere —here intended as the bedrock and sediments within the cave— in the show cave.

Hydrosphere: number of papers examining the hydrosphere —here intended as the groundwater and condensation water— in the show cave.

Biosphere: number of papers examining the biosphere —here intended as all the organisms living in the cave— in the show cave.

The group of 'environmental parameters' includes the following fields:

Microclimate: number of papers examining the microclimate in the show cave.

Carbon dioxide: number of papers examining the carbon dioxide concentration in the show cave.

Radon: number of papers examining the radon concentration in the show cave.

Particulate: number of papers examining the air particulate concentration in the show cave.

Speleothems: number of papers examining the crystalline structure of the speleothems in the show cave.

Paleo-archaeological findings: number of papers examining the crystalline structure of the paleo-archaeological findings in the show cave.
Water quality: number of papers examining the water quality parameters in the show cave.
Water geochemistry: number of papers examining the water geochemistry in the show cave.
Water level: number of papers examining variations in the water levels in the show cave.
Invertebrates: number of papers examining the invertebrates in the show cave.
Bats: number of papers examining bats in the show cave.
Fungi: number of papers examining fungi in the show cave.
Prokaryotes: number of papers examining prokaryotes in the show cave.
Lampenflora: number of papers examining the '*lampenflora*' in the show cave.

The group of 'summary statistics' includes the following fields:

N_components: number of environmental components (atmosphere, lithosphere, hydrosphere, and biosphere) evaluated in the show cave across the examined literature.
N_parameters: number of environmental parameters (invertebrates, bats, other vertebrates, fungi, bacteria, 'lampenflora', microclimate, carbon dioxide concentration, air particulate concentration, radon content, status of speleothems, status of paleo-archaeological findings, and water quality) evaluated in the show cave across the examined literature.
N_papers: number of the papers in which the cave was studied.
PapersID: list of IDs obtained to Suppl. material 1 referring to the papers where the cave was studied.

Results and discussion

Our survey encompassed 265 show caves located in 39 countries. Most show caves are located in the Western Palearctic region (Fig. 2a), given the overrepresentation of European countries, namely Spain, Czech Republic, and France (Fig. 2b). The most studied show cave is Postojna cave in Slovenia, which is also recognized as the most important global subterranean biodiversity hotspot (Zagmajster et al. 2021), followed by two Spanish show caves, i.e. Nerja Cave and Castañar de Ibor Cave, and by Lascaux Cave in France (Fig. 2c). Although they are currently closed to tourism, Lascaux and Altamira caves are among the most studied show caves, pointing out that tourism-induced environmental changes may perdure much longer after eliminating the pressures exerted by tourism. Most studies were focused on a single study site, while only in a few cases, more than one show cave was investigated (Fig. 2d).

Concerning environmental components (Fig. 3a) and their related parameters (Fig. 4a), most papers examined a single component and a single parameter. Similarly, in most of the caves, a single component and a single parameter were examined throughout

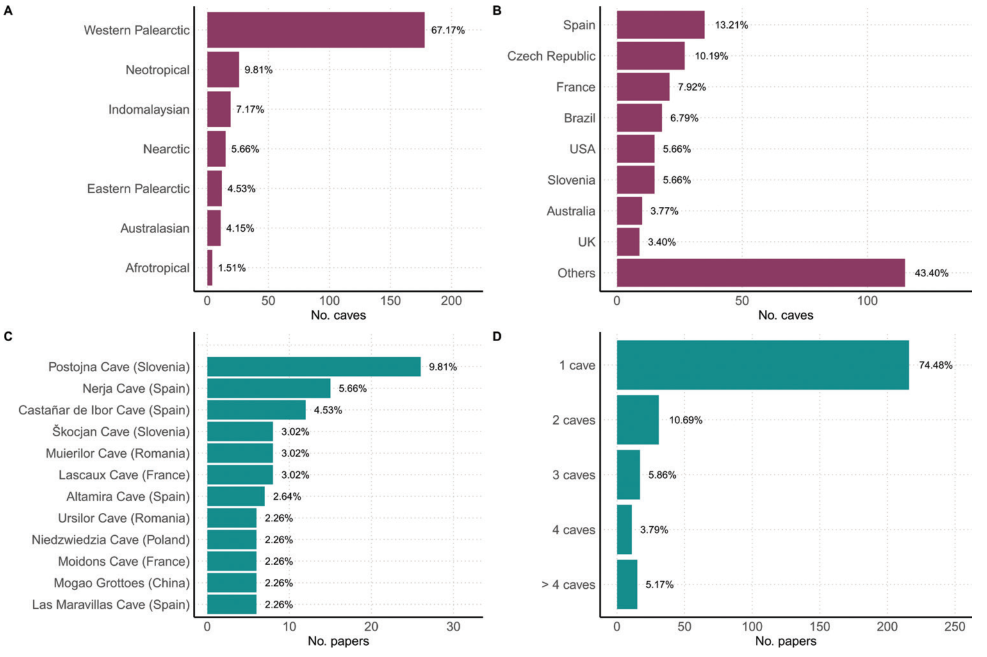

Figure 2. A number of examined caves and relative percentages for the different biogeographic regions **B** list of countries where most of the studied show caves are located with their frequencies and relative percentages **C** list of the show caves most frequently studied in literature and their relative frequency and percentage in the considered papers **D** number of studied show caves and relative percentages within the examined papers. Percentages are calculated with respect to the total number of show caves in **A, B**, and with respect to the total number of papers in **C, D**.

literature. These results highlight the need to create collaborations among researchers of different disciplines to implement multidisciplinary research studies encompassing different environmental components and parameters. The atmosphere was the most studied component, followed by the biosphere and the lithosphere, while the hydrosphere was the least investigated (Fig. 3b). When considering the investigated parameters (Fig. 4b), an overwhelming interest towards factors potentially affecting human health in subterranean environments emerged. In this regard, the greatest part of the studies dedicated to the atmosphere focused on radon—mostly evaluated to quantify its potential negative effect on the human health and not as a proxy of the anthropogenic impact on show caves (e.g. Lario et al. 2006; Lu et al. 2009; Cevik et al. 2011)—, followed by the microclimate and CO_2 concentration; air particulate was the least investigated atmospheric parameter. Similarly, most of the available literature dealing with the biosphere focuses on microorganisms (fungi and prokaryotes), possibly due to their potential repercussions on human health, followed by the '*lampenflora*' and fauna (invertebrates and bats). Regarding lithosphere, most of the papers focused on the crystalline structure of speleothems and, to a lesser extent, of paleo-archaeological findings, while the sediment composition was the less examined parameter. Papers dealing with the hydrosphere mostly focused on the water geochemistry, followed by water level and the water quality.

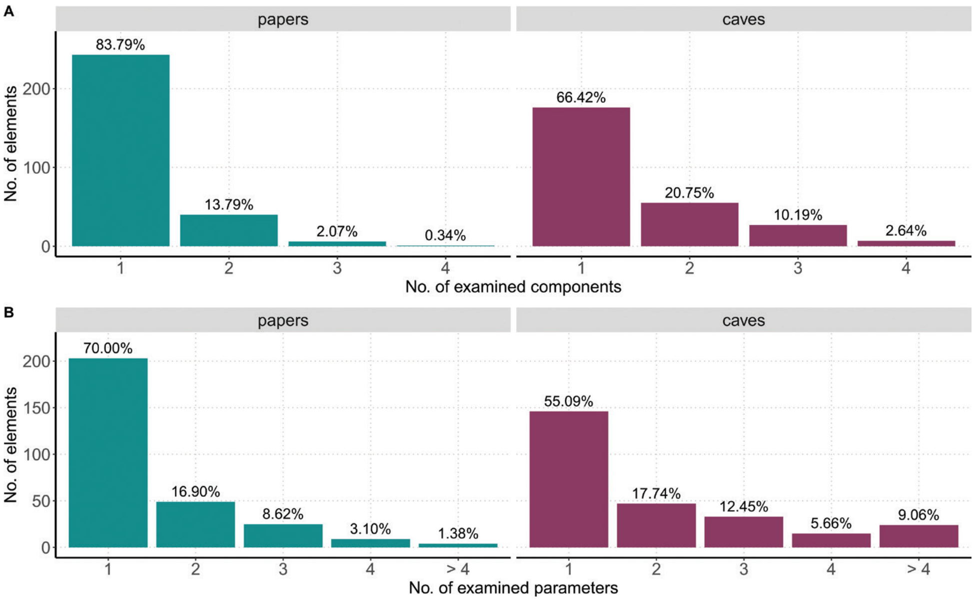

Figure 3. A number of studied components and relative percentages within examined papers (left panel) and studied show caves (right panel) **B** frequency and relative percentage of papers (left panel) and show caves (right panel) examining the different environmental components.

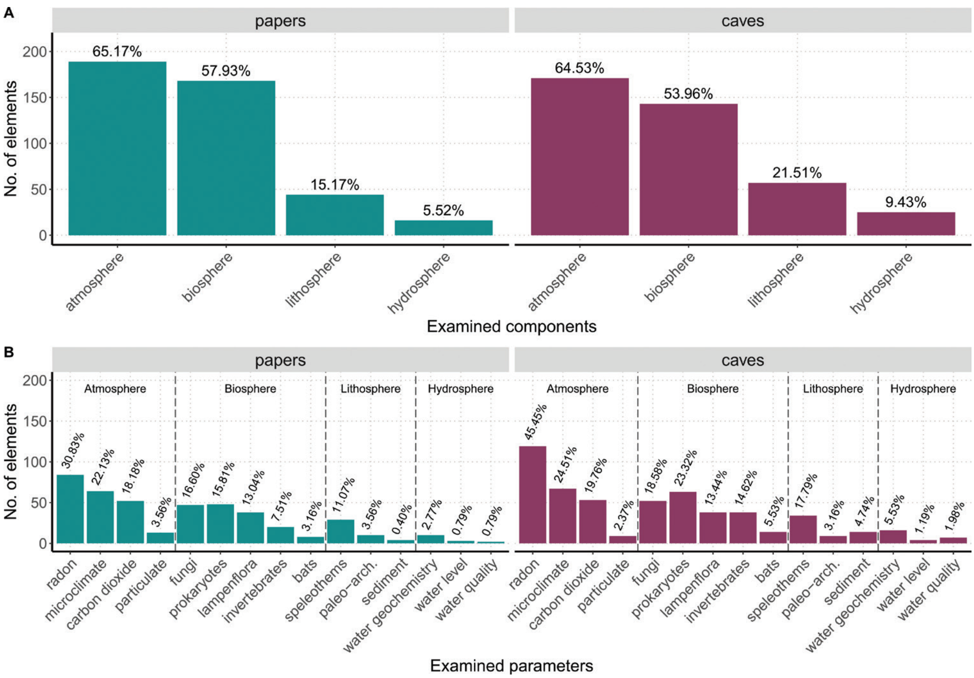

Figure 4. A number of studied parameters and relative percentages within examined papers (left panel) and studied show caves (right panel) **B** frequency and relative percentage of papers (left panel) and show caves (right panel) examining the different parameters.

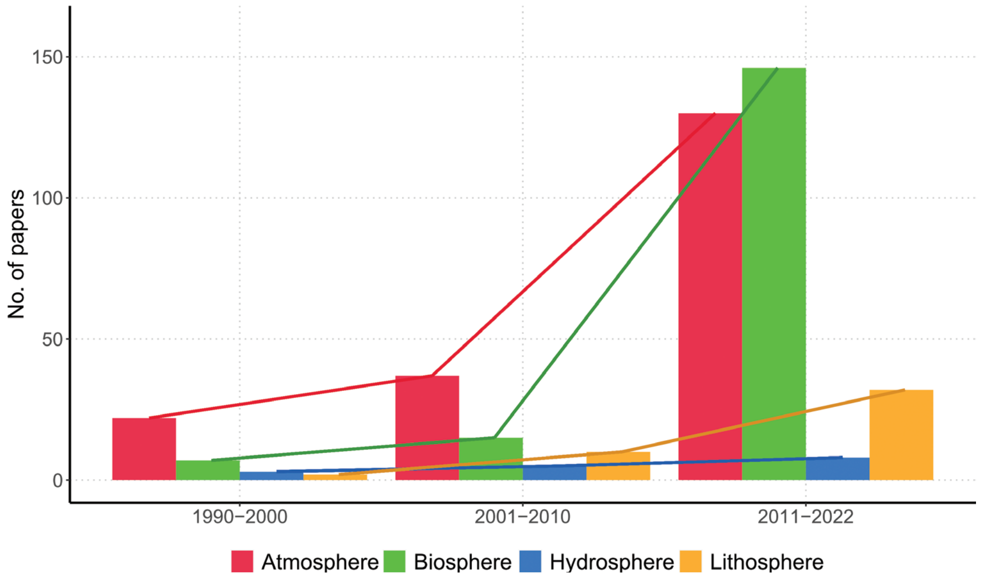

Figure 5. Temporal trend in the study of the different environmental components across considered publications.

According to the temporal trend of examined components (Fig. 5), studies on atmosphere and biosphere faced a huge increase in the last decade (from 2011 to 2022), probably thanks to the advent of advanced molecular techniques, e.g. Next-Generation Sequencing for the microbial component of the biosphere (e.g. Pfendler et al. 2018; Alonso et al. 2019), while the number of papers dealing with hydrosphere and lithosphere showed a less pronounced increase across decades.

Conclusions

Based on the data overview provided by our database, future research in the field of tourism sustainability in show caves should be dedicated to:

- the implementation of interdisciplinary studies encompassing multiple environmental components and parameters as well as multiple show caves;
- the development of our knowledge on show caves located outside the Western Palearctic Region;
- the increase of available information with reference to the lithosphere and especially of the hydrosphere, which are extremely underrepresented components in the current literature;
- the increase of our awareness on the possible impacts of tourism on the subterranean fauna and microorganisms and their interactions with other global impacts (e.g. climate change and land use change) in order to promote the conservation of subterranean biodiversity (Bontemps et al. 2021; Mammola et al. 2022).

In addition, information presented in this data paper could also be used to perform studies that:

- investigate which factors attract tourists in show caves in order to highlight which features may expose them to a touristic overexploitation;
- provide management guidelines that allow a sustainable touristic development of show caves not only from an environmental, but also from an economic and social point of view (Buonincontri et al. 2021).

Overall, this data paper could fill the lack of awareness towards the fragility of the natural heritage of show caves to favour a sustainable touristic use that would guarantee their preservation for future generations as well as the economic development of local communities (Chiarini et al. 2022).

Funding

This work was realized within the framework of the PRIN SHOWCAVE "A multidisciplinary research project to study, classify and mitigate the environmental impact in tourist caves" - code 2017HTXT2R (PI: Marco Isaia), funded by the Italian Ministry of Education, University and Research. SM is supported by the European Commission (program H2020-MSCA-IF-2019; grant award: 882221). The grant of EP is co-financed by the PON "Research and Innovation" Programme (Axis IV "Education and Research for recovery" – Action IV.6 "Research contracts on Green themes").

Authors' contribution

EP, SM, GN and MI set the lines of enquiry and designed the study. AP, BB, EC, EP, GN, NM and VB collected the data. EP and GN summarized the data. EP led the writing of the paper. MI and SM critically reviewed the first draft of the paper. All authors provided important improvements to the original text.

References

Alonso L, Pommier T, Kaufmann B, Dubost A, Chapuillot D, Doré J, Douady CJ, Moënne-Loccoz Y (2019) Anthropization level of Lascaux Cave microbiome shown by regional-scale comparisons of pristine and anthropized caves. Molecular Ecology 28(14): 3383–3394. https://doi.org/10.1111/mec.15144

Ando K, Murakami T (2020) Detection of human-associated bacteria in water from Akiyoshi-do Cave, Japan. Water Environment Research 92(11): 1866–1873. https://doi.org/10.1002/wer.1355

Bontemps Z, Alonso L, Pommier T, Hugoni M, Moënne-Loccoz Y (2021) Microbial ecology of tourist Paleolithic caves. The Science of the Total Environment 816: 151492. https://doi.org/10.1016/j.scitotenv.2021.151492

Buonincontri P, Micera R, Murillo-Romero M, Pianese T (2021) Where Does Sustainability Stand in Underground Tourism? A Literature Review. Sustainability 13(22): e12745. https://doi.org/10.3390/su132212745

Cardiff SG, Ratrimomanarivo FH, Goodman SM (2012) The effect of tourist visits on the behavior of *Rousettus madagascariensis* (Chiroptera: Pteropodidae) in the caves of Ankarana, Northern Madagascar. Acta Chiropterologica 14(2): 479–490. https://doi.org/10.3161/150811012X661783

Castello M (2014) Species diversity of Bryophytes and ferns of lampenflora in Grotta Gigante (NE Italy). Acta Carsologica 43(1): 185–193. https://doi.org/10.3986/ac.v43i1.576

Cevik U, Kara A, Celik N, Karabidak M, Celik A (2011) Radon Survey and Exposure Assessment in Karaca and Çal Caves, Turkey. Water Air Soil Pollution 214: 461–469. htpps://doi.org/10.1007/s11270-010-0437-6

Chiarini V, Duckeck J, De Waele J (2022) A global perspective on sustainable show cave tourism. Geoheritage 14(3): 1–27. https://doi.org/10.1007/s12371-022-00717-5

Cigna AA (2016) Tourism and show caves. Zeitschrift für Geomorphologie. Supplementary Issues 60(2): 217–233. https://doi.org/10.1127/zfg_suppl/2016/00305

Cigna AA, Burri E (2000) Development, management and economy of show caves. International Journal of Speleology 29(1): 1–27. https://doi.org/10.5038/1827-806X.29.1.1

Cigna AA, Forti P (2013) Caves: The most important geotouristic feature in the world. Pesquisas em Turismo e Paisagens Cársticas 6(1): 9–26. https://digitalcommons.usf.edu/cgi/viewcontent.cgi?article=5723&context=kip_articles#page=12

Culver DC, Pipan T (2019) The biology of caves and other subterranean habitats, 2nd Edn. Oxford University Press, New York, 336 pp. https://doi.org/10.1093/oso/9780198820765.001.0001

Dominguez-Villar D, Fairchild IJ, Carraasco RM, Pedraza J, Baker A (2010) The effect of visitors in a touristic cave and the resulting constraints on natural thermal conditions for palaeoclimate studies (Eagle Cave, central Spain). Acta Carsologica 39(3): 491–502. https://doi.org/10.3986/ac.v39i3.78

Faille A, Bourdeau C, Deharveng L (2014) Weak impact of tourism activities on biodiversity in a subterranean hotspot of endemism and its implications for the conservation of cave fauna. Insect Conservation and Diversity 8(3): 205–215. https://doi.org/10.1111/icad.12097

Falasco E, Bona F, Isaia M, Piano E, Wetzel CE, Hoffmann L, Ector L (2015) *Nuphela troglophila* sp. nov., an aerophilous diatom (Bacillariophyta) from the Bossea cave (NW Italy), with notes on its ecology. Fottea 15(1): 1–9. https://doi.org/10.5507/fot.2015.001

Iliev M, Mitova M, Ilieva R, Groudeva V, Grozdanov P (2018) Bacterial isolates from rock paintings of Magura Cave and sensitivity to different biocides. Comptes Rendus de l'Academie Bulgare de Science 71: 640–647. https://doi.org/10.7546/CRABS.2018.05.08

Isaia M, Giachino PM, Sapino E, Casale A, Badino G (2011) Conservation value of artificial subterranean systems: A case study in an abandoned mine in Italy. Journal for Nature Conservation 19(1): 24–33. https://doi.org/10.1016/j.jnc.2010.04.002

Ivanova S (2017) Influence of tourists on the summer bat colonies in the Devetashka Cave, Bulgaria. Acta Zoologica Bulgarica 8: 211–221. https://arnhemspeil.nl/docs/2017-06-28-acta-zoologica-bulgaria-influence-of-tourists-on-the-summer-bat-colonies-in-the-devetashka-cave-bulgaria.pdf

Jiménez-Sánchez M, Stoll H, Vadillo I, López-Chicano M, Domínguez-Cuesta M, Martín-Rosales W, Meléndez-Asensio M (2008) Groundwater contamination in caves: Four case studies in Spain. International Journal of Speleology 37(1): 53–66. https://doi.org/10.5038/1827-806X.37.1.5

Kukla J, Holec M, Trögl J, Holcová D, Hofmanová D, Kuráň P, Popelka J, Pacina J, Kříženecká S, Usťak S, Honzík R (2018) Tourist traffic significantly affects microbial communities of sandstone cave sediments in the protected landscape area "Labské Pískovce" (Czech Republic): Implications for regulatory measures. Sustainability 10(2): 396–410. https://doi.org/10.3390/su10020396

Lario J, Sanchez-Moral S, Cuezva S, Taborda M, Soler V (2006) High 222Rn levels in a show cave (Castañar de Ibor, Spain): Proposal and application of management measures to minimize the effects on guides and visitors. Atmospheric Environment 40(38): 7395–7400. https://doi.org/10.1016/j.atmosenv.2006.06.046

Lu X, Li LY, Zhang X (2009) An Environmental Risk Assessment of Radon in Lantian Karst Cave of Shaanxi, China. Water Air Soil Pollution 198: 307–316. htpps://doi.org/10.1007/s11270-008-9847-0

Mammola S (2019) Finding answers in the dark: Caves as models in ecology fifty years after Poulson and White. Ecography 42(7): 1331–1351. https://doi.org/10.1111/ecog.03905

Mammola S, Di Piazza S, Zotti M, Badino G, Isaia M (2017) Human-induced alterations of the cave mycobiota in an Alpine Show Cave (Italy, SW-Alps). Acta Carsologica 46(1): 111–123. https://doi.org/10.3986/ac.v46i1.2531

Mammola S, Cardoso P, Culver DC, Deharveng L, Ferreira RL, Fišer C, Galassi DMP, Griebler C, Halse S, Humphreys WF, Isaia M, Malard F, Martinez A, Moldovan OT, Niemiller ML, Pavlek M, Reboleira ASPS, Souza-Silva M, Teeling EC, Wynne JJ, Zagmajster M (2019) Scientists' warning on the conservation of subterranean ecosystems. Bioscience 69(8): 641–650. https://doi.org/10.1093/biosci/biz064

Mammola S, Meierhofer MB, Borges PA, Colado R, Culver DC, Deharveng L, Delić T, Di Lorenzo T, Dražina T, Ferreira RL, Fiasca B, Fišer C, Galassi DMP, Garzoli L, Gerovasileiou V, Griebler C, Halse S, Howarth FG, Isaia M, Johnson JS, Komerički A, Martínez A, Milano F, Moldovan OT, Nanni V, Nicolosi G, Niemiller ML, Pallarés S, Pavlek M, Piano E, Pipan T, Sanchez-Fernandez D, Santangeli A, Schmidt SI, Wynne JJ, Zagmajster M, Zakšek V, Cardoso P (2022) Towards evidence-based conservation of subterranean ecosystems. Biological Reviews of the Cambridge Philosophical Society 97(4): 1476–1510. https://doi.org/10.1111/brv.12851

Mann SL, Steidl RJ, Dalton VM (2002) Effects of cave tours on breeding *Myotis velifer*. The Journal of Wildlife Management 66(3): 618–624. https://doi.org/10.2307/3803128

Marques ELS, Dias JCT, Silva GS, Pirovani CP, Rezende RP (2016) Effect of organic matter enrichment on the fungal community in limestone cave sediments. Genetics and Molecular Research 15(3): e15038611. https://doi.org/10.4238/gmr.15038611

Marques ELS, Dias JCT, Silva GS, Pirovani CP, Rezende RP (2017) Organic matter enrichment affects Archaea community in limestone cave sediments. Journal of Caves and Karst Studies 79(2): 95–99. https://doi.org/10.4311/2016MB0138

Martín-García R, Martín-Pérez A, Alonso-Zarza AM (2010) Petrological study as a tool to Evaluate the degradation of speleothems in touristic caves, Castañar de Ibor Cave, Cáceres, Spain. In: Carrasco F, Valsero JJD, LaMoreaux JW (Eds) Advances in research in karst media. Springer, Berlin, Heidelberg, 509–514. https://doi.org/10.1007/978-3-642-12486-0_78

Martín-García R, Martín-Pérez A, Alonso-Zarza AM (2011) Weathering of host rock and corrosion over speleothems in Castañar cave, Spain: An example of a complex meteoric environment. Carbonates and Evaporites 26(1): 83–94. https://doi.org/10.1007/s13146-010-0039-9

Martin-Sanchez PM, Pedro M, Jurado V, Porca E, Bastian F, Lacanette D, Alabouvette C, Sáiz-Jiménez C (2014) Airborne microorganisms in Lascaux cave (France). International Journal of Speleology 43(3): 295–303. https://doi.org/10.5038/1827-806X.43.3.6

Moldovan OT, Bercea S, Năstase-Bucur R, Constantin S, Kenesz M, Mirea IC, Petculescu A, Robu M, Arghir RA (2020) Management of water bodies in show caves – A microbial approach. Tourism Management 78: 104037. https://doi.org/10.1016/j.tourman.2019.104037

Mulec J (2014) Human impact on underground cultural and natural heritage sites, biological parameters of monitoring and remediation actions for insensitive surfaces Case of Slovenian show caves. Journal for Nature Conservation 22(2): 132–141. https://doi.org/10.1016/j.jnc.2013.10.001

Mulec J, Kosi G, Vrhovšek D (2008) Characterization of cave aerophytic algal communities and effects of irradiance levels on production of pigments. Journal of Caves and Karst Studies 70(1): 3–12. https://caves.org/pub/journal/PDF/v70/cave-70-01-3.pdf

Nicolosi G, Mammola S, Costanzo S, Sabella G, Cirrincione R, Signorello G, Isaia M (2021) Microhabitat selection of a Sicilian subterranean woodlouse and its implications for cave management. International Journal of Speleology 50(1): 53–63. https://doi.org/10.5038/1827-806X.50.1.2370

Pellegrini TG, Ferreira RL (2012) Management in a neotropical show cave: Planning for invertebrates conservation. International Journal of Speleology 41(2): 359–366. https://doi.org/10.5038/1827-806X.41.2.19

Pellegrini TG, Ferreira RL (2016) Are inner cave communities more stable than entrance communities in Lapa Nova show cave? Subterranean Biology 20: 15–37. https://doi.org/10.3897/subtbiol.20.9334

Pfendler S, Karimi B, Maron PA, Ciadamidaro L, Valot B, Bousta F, Alaoui-Sosse L, Alaoui-Sosse B, Aleya L (2018) Biofilm biodiversity in French and Swiss show caves using the metabarcoding approach: First data. The Science of the Total Environment 615: 1207–1217. https://doi.org/10.1016/j.scitotenv.2017.10.054

Piano E, Bona F, Falasco E, La Morgia V, Badino G, Isaia M (2015) Environmental drivers of phototrophic biofilms in an Alpine show cave (SW-Italian Alps). The Science of the Total Environment 536: 1007–1018. https://doi.org/10.1016/j.scitotenv.2015.05.089

Piano E, Nicolosi G, Isaia M (2021) Modulating lighting regime favours a sustainable use of show caves: A case study in NW-Italy. Journal for Nature Conservation 64: 126075. https://doi.org/10.1016/j.jnc.2021.126075

Porca E, Jurado V, Martin-Sanchez PM, Hermosin B, Bastian F, Alabouvette C, Saiz-Jimenez C (2011) Aerobiology: An ecological indicator for early detection and control of fungal outbreaks in caves. Ecological Indicators 11(6): 1594–1598. https://doi.org/10.1016/j.ecolind.2011.04.003

Saiz-Jimenez C, Miller AZ, Martin-Sanchez PM, Hernandez-Marine M (2012) Uncovering the origin of the black stains in Lascaux Cave in France. Environmental Microbiology 14(12): 3220–3231. https://doi.org/10.1111/1462-2920.12008

Sánchez-Moral S, Soler V, Canaveras JC, Sanz-Rubio E, Van Grieken R, Gysels K (1999) Inorganic deterioration affecting the Altamira Cave, N Spain: Quantitative approach to wall-corrosion (solutional etching) processes induced by visitors. The Science of the Total Environment 243: 67–84. https://doi.org/10.1016/S0048-9697(99)00348-4

Šebela S, Turk J (2014) Natural and anthropogenic influences on the year-round temperature dynamics of air and water in Postojna show cave, Slovenia. Tourism Management 40: 233–243. https://doi.org/10.1016/j.tourman.2013.06.011

United Nations (2015) Transforming our world: the 2030 agenda for sustainable development. https://sustainabledevelopment.un.org

Zagmajster M, Polak S, Fišer C (2021) Postojna-Planina cave system in Slovenia, a hotspot of subterranean biodiversity and a cradle of speleobiology. Diversity (Basel) 13(6): e271. https://doi.org/10.3390/d13060271

Supplementary material 1

Literature-based dataset

Authors: Elena Piano, Giuseppe Nicolosi, Stefano Mammola, Benedetta Baroni, Elena Cumino, Nicola Muzzulini, Valentina Balestra, Rossana Bellopede, Marco Isaia

Data type: database

Explanation note: Literature-based dataset including: **1.** the references to the papers extracted with the systematic search (Sheet entitled "Papers") **2.** the list of show caves and their related information based on papers retrieved with a systematic bibliographic research (Sheet entitled "Caves")

Link: https://doi.org/10.3897/natureconservation.50.80505.suppl1