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Review

Advancing tourism sustainability in show caves

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SUMMARY

Show caves are important tourism attractions around the world, generating profits of approximately 850 billion dollars per year. However, the touristic use of caves may jeopardize the conservation of these fragile ecosystems. It is therefore crucial to examine the tourism-related impacts on show caves and the management measures needed to preserve subterranean ecosystems. Here, we analyze the literature published over the last 30 years on show caves with a driver-pressure-state-impact-response (DPSIR) approach, which includes 101 papers examining human impacts on the subterranean ecosystem and 67 papers examining management actions. The introduction of allochthonous microorganisms and microclimate alterations emerged as the most concerning impacts, given their cascading effects on all ecosystem components. Our analysis shows that management actions directly address these impacts, but the use of a multidisciplinary approach is overlooked. As a result, we offer a roadmap for a sustainable and scientifically sound usage of show caves.

INTRODUCTION

Cultural heritage represents one of the most significant and fastest-growing tourism sectors in the twenty-first century.[1] Tourism can have significant social repercussions on local populations by favoring economic growth and people's awareness of the intrinsic value of the resource.[2] Cultural heritage tourism, however, relies on a delicate balance between economic needs and the impacts of tourism to guarantee the conservation of its cultural and, ultimately, touristic value.[3] Geotourism, which primarily focuses on geological and geomorphological features in landscapes as tourist attractions, represents an excellent arena to examine the trade-off between the impacts caused by tourism on cultural heritage and social outcomes.[4–7] Show caves—officially defined as "any cavity where a fee is paid to gain access and visit it[8]"—are natural caves that have been made accessible to the public where groups of paying visitors experience the cave environment along well-lit artificial pathways, with guided tours during regular opening hours.[8] Since the first evidence of cave visitors in 1213 in the Postojna Jama (Slovenia) and the early experiments with electric light in Australian caves in 1881, cave tourism has grown considerably, and show caves have become one of the most important geotourism attractions worldwide in the last century.[9] For this reason, the interest in subterranean environments and their natural wonders has also grown scientifically[9] and economically[8] in the last two centuries. The impressive numbers of visitors (up to 500,000 per year for a single show cave[9]) and the profits deriving from such activities (the total amount of money spent to visit show caves was estimated to be around $3 billion USD in 2008[9]) have acquired substantial importance on a global scale.

Visiting a show cave is arguably an unforgettable experience, allowing people to explore a unique world that otherwise would be inaccessible to most.[10] However, while enjoying a guided tour into a cave, people tend to forget that their presence has substantial ecological impacts on caves. Caves are energy-poor ecosystems characterized by the absence of light, spatial confinement, climatic stability, and low biodiversity, characterized by highly specialized and short-ranged organisms.[11,12] Given these unique conditions, subterranean ecosystems are highly susceptible to anthropogenic pressures across all ecosystem components with synergistic impacts, often with difficult-to-predict consequences.[13] The need to obtain a nuanced understanding of such ecological complexity, allowing stakeholders to implement sound and effective management plans to ultimately guarantee the conservation of show caves,[14] has been recently highlighted as a lacking yet critical research area in subterranean biology.[15]

In this review, we outline sustainable strategies for show cave management by quantitatively analyzing the literature published over the last 30 years[16] dedicated to the study of human-induced environmental changes in show caves. First, we carried out a bibliometric analysis to examine geographic and topic biases in cave tourism literature. Next, through a systematic literature survey, we provided a multidisciplinary perspective on the combined effect of human pressures on different ecosystem components (i.e., atmosphere, lithosphere, hydrosphere, and biosphere) in show caves. To achieve this goal, we extracted

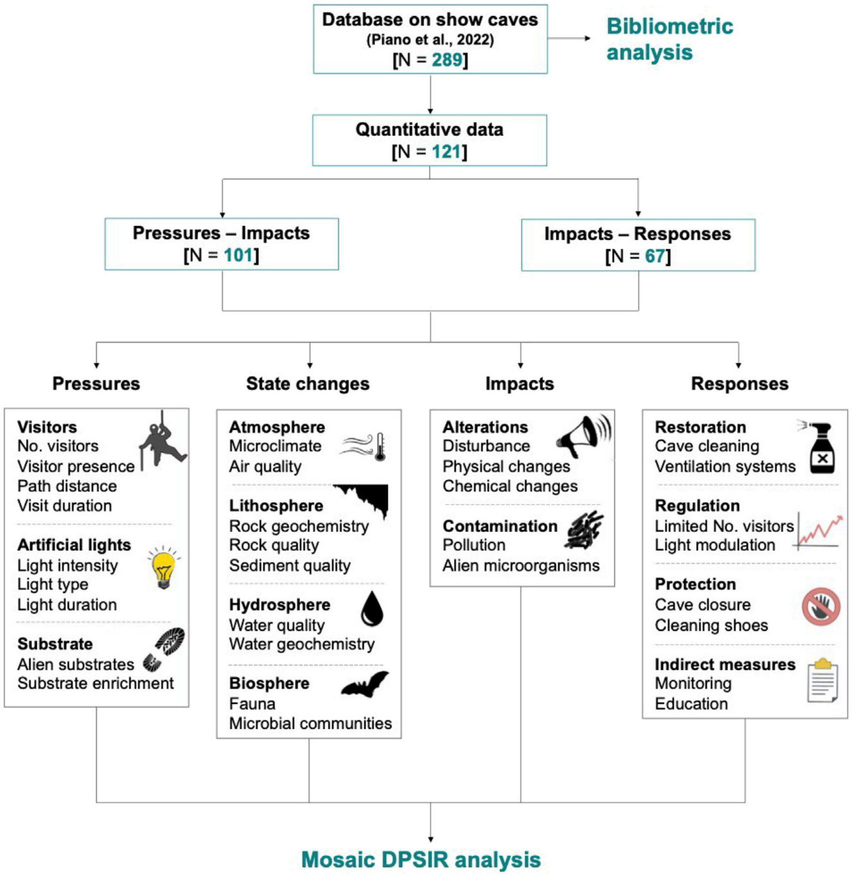

Figure 1. Conceptual scheme of the review

Summary of the sampled literature and data extracted to perform the drivers-pressures-state-impact-response (DPSIR) analysis. Readaptation of original silhouettes by Irene Frigo[19] or modified from www.phylopic.org and www.istockphoto.com.

information from the selected literature and elaborated it into a drivers-pressures-state-impact-response (DPSIR) mosaic model,[17] where pressures of one environmental component may feed on the state and impacts of other components. DPSIR is a causal framework that was first introduced by the European Environmental Agency to describe the interactions between society and the environment.[18] This analysis offers an easy-to-understand tool to look at any complex environmental problem by establishing simple causal relations among all elements and making apparent integrated responses to mitigate or adapt the problem. We end the review by highlighting management actions toward sustainable tourism by focusing on specific impacts or addressing a wider range of impacts in a multidisciplinary framework (Figure 1).

LITERATURE OVERVIEW

The outcome of the bibliometric analysis shows a rapid increase in literature dedicated to the study of show caves in the last 15 years. On the basis of an initial survey of 289 papers, we observe an annual growth rate in published literature of 8.27%, with a peak after 2007 (Figure 2A). The distribution of studies is largely concentrated in Europe, North America, Brazil, and Southeast Asia (Figure 2B), where most of the show caves are located.[9,16] The final dataset accounts for 760 unique author's keywords, separated into three clusters concerning biological contamination, cave atmosphere, and general management (Figure 2C). After the screening phase, we retain 121 (41.7%) papers responding to the inclusion criteria, among which 54 papers (45%) reported about possible effects of tourism on the subterranean ecosystem, 20 papers (16%) examined potential management actions, and 47 papers (39%) provided insights about both impacts and management actions.

In most papers, inference about the relationships between pressures and impacts is limited to qualitative analysis. Similarly, the efficacy of proposed management actions was rarely tested, even if in some cases statistical tests have been adopted to evaluate the efficacy of eradication methods to reduce the spread of microorganisms. Overall, only 25% of the examined studies adopted statistical inference to demonstrate the environmental effects of tourism-related pressures on different ecosystem components or to test the effectiveness of management strategies. This lack of statistical tests in the examined literature ultimately hampered the possibility of performing a meta-analysis.

ABIOTIC IMPACTS

Based on the analyzed literature, tourism in show caves causes changes of the abiotic conditions in caves (i.e., physical and chemical changes) or the introduction of pollutants.

Physical changes

Visitors release heat in caves due to their body temperature, resulting in consequent physical changes in the cave atmosphere (Figure 3). The potential impacts of this stress interaction have been evaluated by considering or testing changes in the subterranean microclimate,[20–22] with cascading effects on water physical parameters, such as water temperature.[23] This impact is mostly linked to the number of visitors and the time they spend in the cave.[24,25] Large events attracting great numbers of visitors (e.g., cave concerts) may cause thermal waves, which persist in the following day(s),[26] not only in the air but also in the water.[23] Despite this, the increase in air temperature is often ephemeral, as the recovery usually occurs within 1 day[26,27] depending on the cave shape and length. However, it may become longer when the natural ventilation of caves is reduced or absent due to low

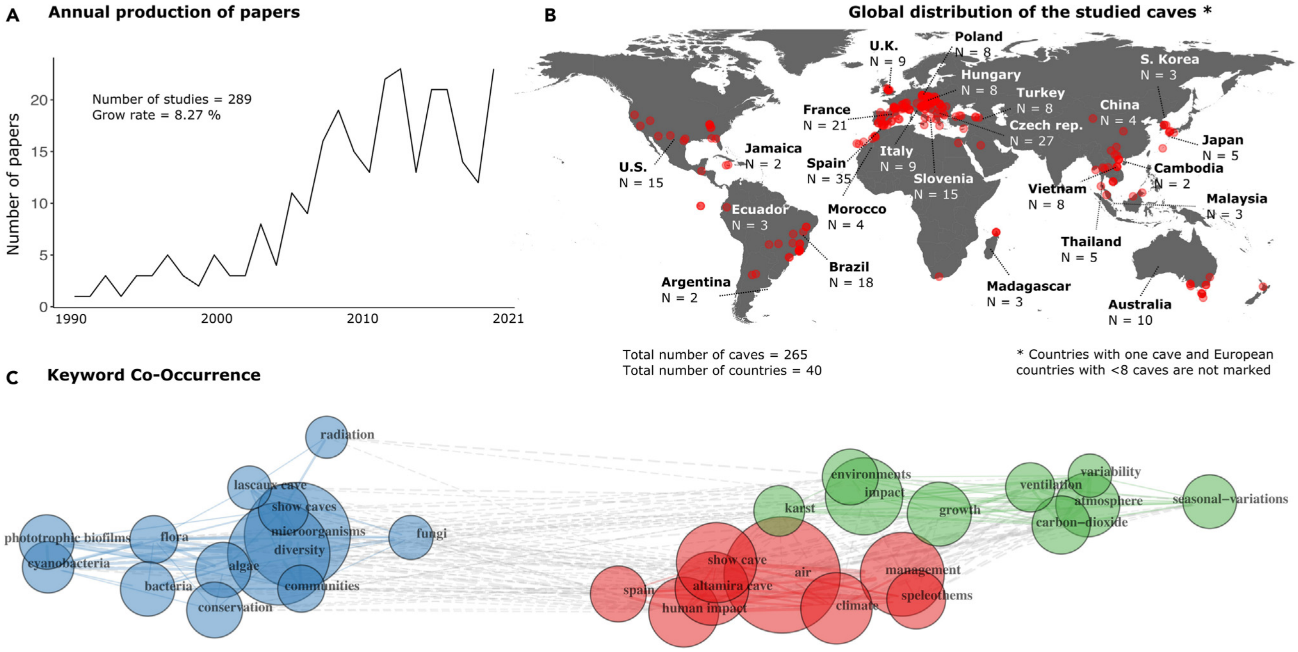

Figure 2. Bibliometric overview of the analyzed literature on show caves

(A) Annual growth in the number of papers between 1990 and 2021.

(B) Global distribution of the studied caves.

(C) Keyword co-occurrence among studies, based on the 30 most frequent keywords. Colors mark keywords that are more closely associated with one another, according to a Louvain clustering analysis. Size of circles is proportional to the number of co-occurrences.

air exchange with the external environment,[28] while changes in the water temperature usually require longer periods to recover.[23]

Chemical changes

Visitors' breath is responsible for chemical changes in the subterranean atmosphere due to an increase in CO_2 concentration[29–31] (Figure 3). Such an increase may become particularly high during periods of limited air circulation within the cave.[24] Although the increase in CO_2 concentration is a temporary change and caves may recover during closure periods, usually at night, changes may persist for a longer time or even become permanent by interacting with the karst phenomena[32–34] and changing the chemical composition of groundwaters.[27] Visitors are also responsible for indirect chemical changes by transporting nutrients, such as nitrogen and phosphorous, the concentration of which may increase both in terrestrial sediments[35] and in groundwaters.[36]

Pollutants

The presence of pollutants in show caves is enhanced by visitors (Figure 3) and has been evaluated mostly on the rock by means of mineralogical analysis. With this approach, the appearance of black stains has been found to be related to human activities and to the deposition of urban combustion products, presumably carried into the cave by visitors[37] or produced by fire torches[38] or infrastructures aiming at facilitating tourist transportation (e.g., train railway[39]).

Opening a cave to tourism also causes an increase in aerial pollutants, due to the introduction of dust carried in by visitors, or by internal cave production related to visitor disruption.[37] Notably, the introduction of pollutants inside the cave also occurs because of air exchange; therefore, the natural ventilation of the cave may contribute to mitigating or exacerbating this effect.[40,41] A particular case of pollution is represented by lint (i.e., clothes fibers), the presence of which is strictly correlated with the presence of visitors.[42]

The impact generated by pollutants is expected to be temporary both in atmosphere and lithosphere due to natural air and water circulation that can remove pollutant particles suspended in the air[41] and pollutants deposited in the dust.[39] However, the deposition of pollutants, e.g., heavy metals, may cause the formation of black deposits on cave speleothems and walls,[37,38] with consequent permanent impact on the lithosphere.

IMPACTS ON THE BIOTIC COMPONENT

Based on the analyzed literature, tourism in show caves may be responsible for the alteration of the biotic component, affecting both the fauna and the microflora inhabiting caves.

Disturbance to the fauna

The presence of tourists in a cave may represent a source of direct or indirect environmental instability for the subterranean fauna, with trampling, substrate changes, and microclimate alterations being regarded as the main pressures for invertebrates,[43–47] while noise and artificial lights being identified as the main pressures for bats[48–52] (Figure 3).

Regarding invertebrates, substrate changes (e.g., soil compaction and the introduction of allochthonous organic matter) proved

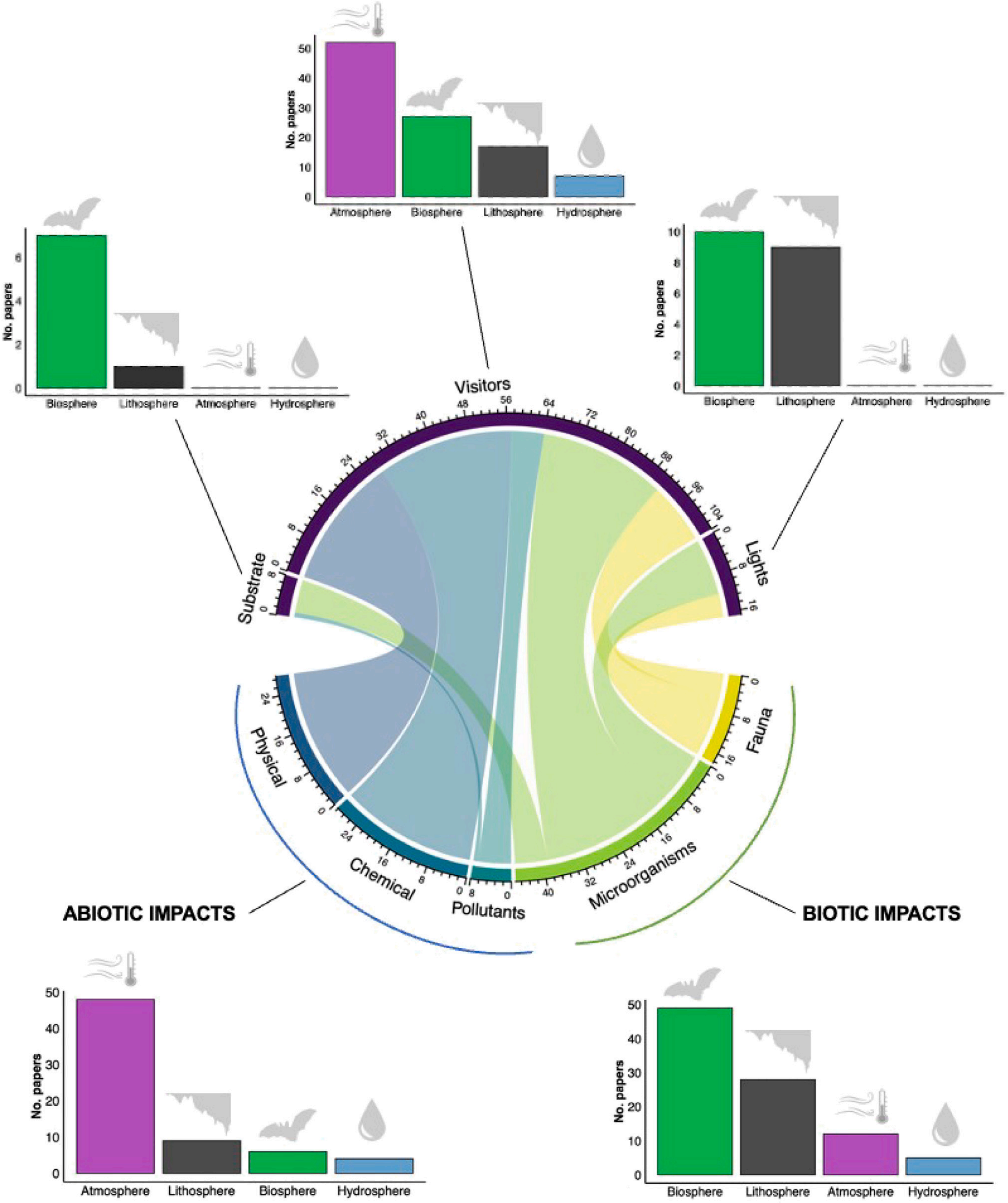

Figure 3. Circular visualization of the relationships between pressures and impacts

Relationships among pressures (upper part of the chord diagram) and impacts (lower part of the chord diagram) with frequencies of studies examining the different ecosystem components reported in bar plots for each category of pressures and impacts (chemical = chemical changes; physical = physical changes; fauna = disturbance to the fauna; microorganisms = allochthonous microorganisms).

to affect the local invertebrate communities by reducing the number of highly adapted subterranean species in Lanquín Cave (Guatemala).[43] Also, microclimatic changes proved to influence the invertebrate community of the Monello cave (Sicily, Italy), where increased thermal instability reduced the abundance of the endemic subterranean isopod *Armadillidium lagrecai*.[44] Seemingly, cave lightning has limited direct effects on invertebrates, except for the bioluminescent larvae of *Arachnocampa* spp., an important tourist attraction in New Zealand's caves, whose bioluminescent display is affected by the cave illumination associated with visitor access.[46] However, studies performed on the invertebrate fauna also showed that the direct disturbance generated by tourists, such as trampling, may be limited by the fact that the invertebrate fauna can easily escape from disturbed areas by hiding in the network of cracks.[47] It is still unclear whether subterranean invertebrates can recover from temporary temperature changes induced by the presence of tourists.

The touristic use of caves used by bats for overwintering or reproduction may impact colonies due to both visitors' noise and artificial lighting.[48–50] In addition, when the period of highest tourist presence corresponds to the breeding period, the survival of newborns may be highly compromised.[51] Despite this, studies suggest that bats can get used to the presence of tourists if mitigation strategies are adopted, like excluding breeding or overwintering areas from the guided tours.[50–52]

Allochthonous microorganisms

Microflora in caves is naturally composed of fungi and prokaryotes adapted to the low availability of organic matter in subterranean ecosystems,[53] but opening caves to visitors may favor the growth of allochthonous microorganisms with cascading effects on all ecosystem components.[54]

Tourists visiting caves may mediate the entrance of propagules of allochthonous microorganisms through their clothes and hands (Figure 3), spreading them throughout the cave, i.e., on speleothems and walls,[55,56] in the air,[57,58] in groundwaters,[36,59] and in sediments.[60,61] In particular, geological substrates (i.e., speleothems and walls) are the most impacted because bacteria and fungi constitute extended biofilms on their surfaces, where allochthonous photosynthetic microorganisms, primarily cyanobacteria, diatoms, and green algae, may proliferate thanks to the presence of artificial lighting[62–64] (Figure 3). These biofilms are generated due to the secretion of a hydrated matrix of extracellular polymeric substances that induces the adsorption of cations and dissolved organic molecules from the mineral surface, causing the deterioration of the substrate (i.e., biocorrosion[65]). In addition, some species can penetrate the substrate and grow into endolithic forms, causing physical alterations that include structural changes and mechanical disintegration of the substrate.[62] An extensive proliferation of these biofilms may also result in thick green, brown, and grayish patinas, causing aesthetic degradation of walls and speleothems.[66] One of the most iconic examples of microbial deterioration in show caves is represented by the Lascaux cave in France,[58] renowned across the world for its extraordinary Paleolithic paintings. The cave was discovered in 1940, opened to the public in 1948, and reached 100,000 visitors in 1962. Such massive entrance of tourists in the cave led to an extensive growth of the alga *Bracteacoccus minor* (the so-called *maladie verte*) that caused serious damages to the prehistoric paintings in 1963, requiring the closure of the cave to the public.[54] Despite being closed since that time, the cave has suffered other microbiological crises, such as the outbreak of the fungus *Fusarium solani* in 2001 and the growth of black stains produced by the fungus *Ochroconis lascauxensis* in 2012.[55]

Visitors are also responsible for increasing the local availability of organic matter in caves deposited from skin, clothing, and shoes, increasing nutrient concentration in both sediments[35] and groundwaters.[36] This, in turn, may alter microbial communities, for instance, by increasing the number of operational taxonomic units (OTUs) of fungi[67] and prokaryotes[68] (Figure 3). The introduction of artificial substrates related to human activities, such as bottles of aging wine in Saint Marcel Cave (France),[69] may influence the local microbial community, causing the proliferation, and even outbreaks, of microbial species strictly related to the new substrate.[69–71]

The growth of allochthonous microorganisms also constitutes a potential impact on human health and the subterranean fauna, as demonstrated by the increase of human-associated bacteria in groundwaters[59] and by the diffusion of other pathogenic microorganisms affecting humans[72] or bats.[61] Thanks to the advancement of molecular techniques, some authors have highlighted that allochthonous microorganisms may have consequences for the species richness and composition of the autochthonous microbial communities.[53,54] For instance, when comparing different show caves experiencing different levels of tourism exploitation in France, a higher proportion of Bacteroidetes and a lower proportion of Archaea characterized sites with higher touristic pressure.[54]

SUSTAINABLE MANAGEMENT OF SHOW CAVES

Management in this review refers to all actions adopted to compensate for, mitigate, or eliminate the environmental impacts. We classified management actions into four different categories addressing different levels of disturbance in show caves: (1) "restoration" actions are intended to reduce the impacts, i.e., alterations and contamination; (2) "regulation" measures aim at limiting changes in the state of the different ecosystem components of the subterranean ecosystem; (3) "protection" strategies aim at limiting the human pressure on the subterranean ecosystem; and (4) "indirect measures" contribute to increasing awareness about the consequences of tourism in caves.

Restoration

Cave cleaning

This strategy is employed to remove the outbreak of microorganisms on speleothems and walls (Figure 4). The use of chemical treatments has been broadly tested,[73,74] providing substantial help in controlling the growth of microbial communities. Chemical substances, such as hydrogen peroxide,[73] sodium hypochlorite,[74] and biocides,[56] are effective in reducing the growth of microbial biofilms, even if no clear effects of bleach were detected on bacteria.[53] However, the use of chemical substances is responsible for cave pollution by releasing byproducts in the

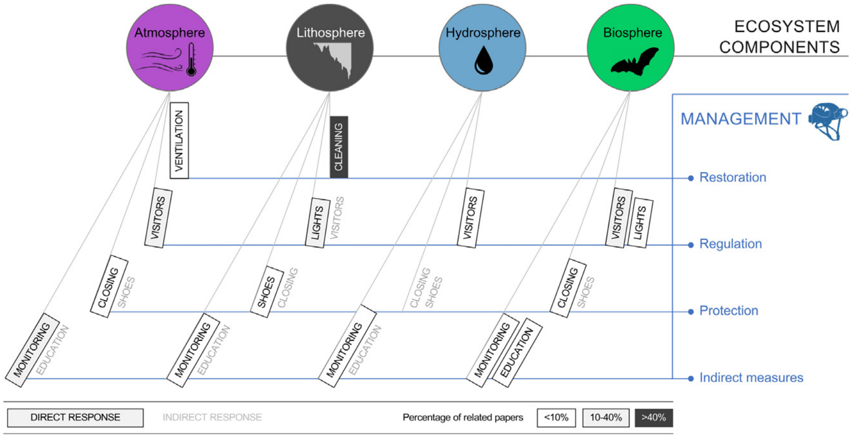

Figure 4. Relationships among responses and ecosystem components

Relationships among the different responses and ecosystem components for each response category, with classes of percentages of papers reporting the relationships indicated with different colors. Indirect relationship components not explicitly analyzed in the examined literature are also reported.

atmosphere and in groundwaters and rock damaging by causing calcite dissolution with the consequent corrosion of carbonate formations.[56,73] For example, calcite dissolution due to hydrogen peroxide was documented in Kateřinská Cave (Czech Republic).[73] Although hydrogen peroxide should be preferred over sodium hypochlorite due to the release of water as byproduct, it reacted with calcium carbonates at 15% concentration and displayed a slower cleaning rate with respect to sodium hypochlorite. On the other hand, bleach is responsible for chlorine release in the atmosphere, and it may even impact the invertebrate fauna feeding on biofilms.[74] For instance, in the Crystal Cave (California, USA), the probability of presence of the cave springtail *Tomocerus celsus* was significantly reduced on speleothems treated with sodium hypochlorite compared with non-treated speleothems, but no effect of hydrogen peroxide was observed.[74] The implementation of non-aggressive cleaning techniques, such as UV-C light,[75,76] should therefore be preferred. In this context, the effectiveness of UV-C light as non-aggressive cleaning techniques to eliminate the microbial component on speleothems and paintings has been broadly demonstrated.[76–78] However, the use of UV-C may not completely halt the growth of *lampenflora*,[75] and, in turn, the accumulation of dead organic matter may enhance the growth of decomposing fungi and bacteria.[79] To overcome all these limitations, the use of natural products is currently being tested as a possible solution to control the growth of microbial biofilms.[56] Preliminary outcomes suggest that thymol may be effective as biocide at high concentrations (5% or 10%) to eradicate *lampenflora* and should be preferred over other chemical compounds especially in caves with archaeological paintings.[56]

Air flow control

Controlling air flows was indicated as an action that could restore the natural state of the cave atmosphere (Figure 4) by re-establishing the microclimatic conditions within the cave[58,80] or by reducing the airborne concentration of allochthonous microorganisms.[81] For instance, in Lascaux cave (France), the presence of a climate-control system is used to recreate convection currents during warm months and thus avoid the condensation of water vapor on the cave walls.[58] Similarly, the use of a mechanical ventilation system has been tested in the Mogao Grottoes (China) during the tourist peak season to favor air exchange and prevent the increase of CO_2 concentration.[80] On the other hand, in the Naracoorte Cave (Australia), the installation of compartment doors has been suggested to prevent the income of allochthonous microorganisms from the outside.[81] The best strategy therefore strongly depends on cave characteristics and on the impacts that need to be mitigated.

Regulation

Regulation of visitors

Regulation of the number of people visiting show caves has been proposed to reduce the sediment eutrophication and the consequent growth of the microbial component in the cave complex of Labské Pískovce (Czech Republic).[35] In Brazilian show caves, e.g., Santana Cave, the regulation of the number of visitors has been reported as an important strategy to reduce changes in cave temperature and CO_2 concentration,[24,82] with potential benefits for karst phenomena and groundwaters (Figure 4). More in detail, the Brazilian researchers proposed to calculate the tourist carrying capacity based on the microclimatic parameters and their seasonality.[83,84] This information has been used to set the daily limit of tourists and to modify the time of permanence or the interval between the groups entering the cave.[85] However, the evaluation of tourist carrying capacity requires the installation of *in situ* equipment that allows ‘‘monitoring’’ of changes in atmospheric parameters. The implementation of this strategy is therefore limited to those show caves where sufficient financial resources are available to install and maintain permanent meteorological stations. Other strategies can be adopted in case of economic limitation, for instance, the implementation of cave protection indices based on expert opinion, e.g., show cave assessment model (SCAM)[86] or the management evaluation index (MEI).[87] The application of these indices requires the assignment of scores by experts to different parameters referring to anthropogenic disturbance, such as the number of tourists or sources of artificial lights to provide an estimate of the human impact in show caves. Although subject to a certain degree of subjectivity, these indices represent one of the few attempts to gain an interdisciplinary view on the level of human disturbance in show caves, especially from an environmental monitoring perspective.

Light modulation

Even with different outcomes, this strategy could be adopted to limit the growth of *lampenflora* on speleothems and walls (Figure 4). For instance, the installation of LED lights reduces, but not eliminates, *lampenflora*.[88] Likewise, a modest effect is observed using colored or low temperature lights.[89] Conversely, reducing the ‘‘light intensity’’[64] and the duration of illumination[90] seems to significantly affect the growth of photosynthetic microorganisms.

‘‘Light modulation’’ also emerged as a key management strategy to reduce disturbance to bat colonies (Figure 4). Indeed, avoiding any direct illuminance of bat roosts, either with lamps or flashlights, reduces the impact on summer colonies.[48,49] Moreover, a well-calibrated intermittent light exposure guaranteed a rapid recovery of *Arachnocampa* larvae bioluminescence without substantially affecting their bioluminescent display.[46]

Protection

Cave closing

Regulating access to the cave aims at reducing the human impact on the cave climate,[27,91] with positive repercussions on karst phenomena and groundwaters. For instance, limiting the access of tourists in areas with reduced air circulation may help in reducing the condensation of water vapor, and, in turn, rock corrosion[27] (Figure 4). Also, regulating access to those parts of the caves where bat roosts are present has been indicated as one of the most important management practices to protect bats[50–52] (Figure 4).

A milder alternative is to redesign the touristic path to avoid disturbance to the fauna[45] or pollution of groundwaters,[36] while the complete closure of the cave to visitors has been applied in Lascaux and Altamira caves to reduce the risk of ‘‘microbial outbreaks’’ and the deterioration of Paleolithic paintings.[55,92]

Minimize external inputs

The role of visitors’ clothes and shoes in transporting organic matter and propagules of allochthonous microorganisms within show caves has been pointed out in literature as an important threat to cave conservation.[93,94] Yet, the need for cleaning visitors’ shoes as a strategy to prevent impacts on the subterranean ecosystem has been clearly identified only in one case[65] (Figure 4). This method presents some limitations because it requires the installation of cleaning systems, e.g., watering pumps, or UV lamps to sterilize shoes at the entrance of the cave, which can be expensive or difficult to apply to visitors. However, the implementation of this strategy would possibly improve the state of the lithosphere with cascading effects on other environmental compartments.

Indirect measures

Monitoring

The environmental monitoring of show caves emerged as a crucial action to implement adequate management practices, especially to control the outbreak of allochthonous microorganisms,[95–97] and changes in the atmosphere[20,97] (Figure 4). For instance, the microbial composition of groundwaters has been suggested as a possible bioindicator to evaluate the anthropogenic impact,[36] together with bioaerosol.[97] Regarding the atmosphere, the use of different parameters has been proposed in literature, e.g., climatic parameters[98,99] and pollutant concentration.[20] For instance, in the Pertosa-Auletta Caves (Italy), the continuous monitoring of multiple atmospheric parameters including both microclimatic parameters (i.e., air temperature and relative humidity) and pollutant concentration (i.e., the concentration of volatile organic compounds [VOCs] and particulate matter) allowed researchers to capture temporal and spatial scales of tourism-induced alterations within the cave.[20]

Although cave monitoring is often emphasized as an appropriate strategy, how to make good use of the data obtained from monitoring plans is often unclear. For instance, monitoring air parameters is frequently encouraged,[100] but little information is provided about the possible use of these data for protecting the cave. Based on the permanent cascading effects of ephemeral changes in air parameters such as temperature or CO_2 concentration, monitoring activities such as rock corrosion in the lithosphere,[32–34] temperature increase in the hydrosphere,[23] and changes in species abundance in the biosphere[44] should not be self-referred to but should be considered as sentinels of long-term repercussions on other ecosystem components. Similarly, monitoring of microbial proliferation should be carefully planned to intercept possible outbreaks and anticipate restoration actions to prevent damage to speleothems and walls. Acquiring and analyzing data in an appropriate way should allow the timely implementation of regulation or even protection strategies to prevent the impairment of the subterranean ecosystem and its natural heritage.

Education

Educating both visitors and tour guides only emerged in two papers on biodiversity conservation[46,50] as a possible action. In both cases, informing visitors and tour guides about the importance of limiting the disturbance to biodiversity targets has been retained as a key element for their conservation (Figure 4). In general, we can point out that the ‘‘education’’ of tour guides and visitors is rarely evaluated in the literature, emerging as a shortcoming that needs to be quickly addressed. The implementation of effective educational practices should be encouraged as a transversal management action to support the long-lasting conservation of the natural heritage of show caves and thus enhance their sustainable touristic use. By promoting education, we can increase the awareness of show cave protection among the local populations and stakeholders, promoting, in the long term, the conservation of the natural heritage of show caves.

FUTURE PERSPECTIVES

We are living in a unique period in the history of cave tourism. On the one hand, the years 2021 and 2022 were designated as the International Years of Cave and Karst, enhancing the visibility of karst landscapes and touristic caves on the international scene. On the other hand, the COVID-19 pandemic has determined substantial rearrangements in the tourism industry globally,[101] including show caves.[19] We believe this is the right time to reconsider the economic exploitation of show caves and rethink it in a sustainable way to ensure the preservation of their natural and cultural heritage.

By taking stock of our knowledge, we highlighted that tourism has substantial ecological impacts on designated show caves, threatening their conservation. Pressures and impacts in show caves often encompass multiple facets of subterranean ecosystems, with alterations in one component triggering cascading effects on others (Figure 5). At the same time, show caves offer a unique setting for the public to experience an otherwise secluded

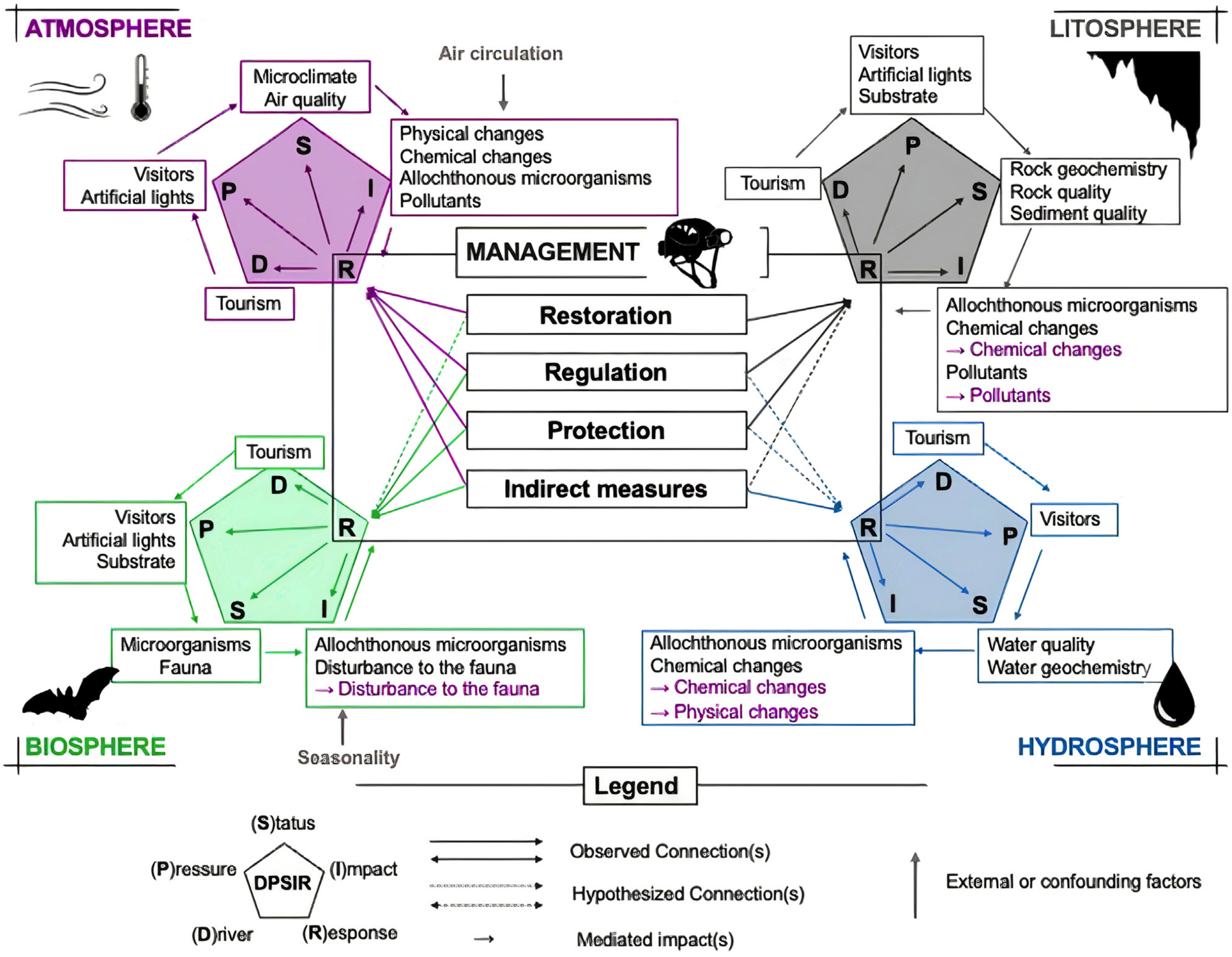

Figure 5. Mosaic DPSIR model

Driver-pressure-state-impact-response (DPSIR) cycles for the four environmental components, reporting their drivers (D), pressures (P), state (S), and impacts (I), showing the interconnections among DPSIR cycles (colored arrows) and the influence of confounding factors (gray arrows). The black square includes all the responses (R) from each cycle, highlighting the need to combine them into common integrated management practices for show caves.

world, leading people toward a deep understanding of the value of nature and favoring the development of their moral responsibilities toward nature.[102] In other words, conservation scientists could consider the possibility of opening a few selected caves to the public to achieve broad-ranging educational goals to improve social awareness of the aesthetic and scientific value of the geological heritage, the geodiversity, and the importance of protecting geological items.[103] This entails the question of whether to open caves to tourists. Although our analysis is far from resolving this dispute, we can point out that the implementation of management strategies encompassing multiple environmental compartments is necessary to guarantee the sustainable use of show caves.

Overarching long-term studies that explore interconnections among environmental components are essential to providing an integrated understanding of the alterations to which the subterranean ecosystem is subjected, facilitating the prioritization of effective management actions. In this context, cave monitoring emerges as a key element in gaining a long-term, integrated overview of human impacts. Moreover, the implementation of more tangible conservation actions, such as light modulation or cave cleaning, is compelling, even though the evidence supporting their efficacy is limited by the absence of appropriate data inference in the literature. Investigating the effects of possible responses with *in situ* experiments and focused statistical methods should represent the main research line in the future.

Simultaneously, the establishment of management units, grounded in a sound network of scientists, cave managers, stakeholders, and the public, becomes imperative. This collaborative approach is essential to achieving the delicate equilibrium between cave conservation and economic development, ensuring the sustainable use of show caves in the long run. Considering this, geoethics, an emerging discipline underscoring the ethical considerations inherent in managing geological sites,[104] represents a valuable guiding principle, thereby contributing to the sustainable touristic use of show caves and inherent conservation practices.[105,106]

EXPERIMENTAL PROCEDURES

Resource availability

Lead contact

Further information and requests for resources and reagents should be directed to and will be fulfilled by the lead contact, Elena Piano (elena.piano@unito.it).

Materials availability

This study did not generate new unique materials.

Data and code availability

The database supporting the findings of this study is available at https://figshare.com/ via the https://doi.org/10.6084/m9.figshare.22202263 and the dataset is provided as supplemental information in the submission (Table S1).

Bibliometric analysis

Initially, we carried out a bibliometric analysis on the freely available database collecting papers that refer to changes in the environmental components of show caves[16] to evaluate whether the scientific production is biased toward specific geographical areas and topics and to capture meaningful properties of the underlying research system. Bibliometric analyzes were performed in R version 4.1.0,[107] using the package *bibliometrix*[108] version 3.1.3. We used a Fruchterman network to explore the co-occurrence of keywords among papers, which we interpreted as a proxy of their interconnectedness. For each network, we used the *networkStat* R function to evaluate density and transitivity, respectively: (1) the portion of the potential connections in a network that are actual connections and (2) the overall probability for the network to have adjacent nodes interconnected.

Data extraction

Next, we screened the papers to identify those references where authors report information that could be assigned to one of the five components of the DPSIR model. More in detail, we retained those papers reporting the following: (1) quantitative information about the tourism disturbance (pressures) and its consequences on at least one of the four main ecosystem compartments of the subterranean environment, i.e., atmosphere, lithosphere, hydrosphere, and biosphere (state changes and/or impacts); and/or (2) suggestions for evidence-based management actions to reduce disturbance in the subterranean ecosystem (responses). During the screening phase, we also recorded information about possible recovery of the subterranean ecosystem. For all relevant references included in the final database, we then extracted information referring to the 5 elements of the DPSIR approach.

Drivers (D)

Drivers include human activities with an individual, social, or economic value that may influence the environment. We assumed tourism and its related activities as the unique driver in show caves.

Pressures (P)

Pressures are defined as a direct and quantifiable human-driven change in the system. To quantify pressures, we identified 10 quali-quantitative metrics quantifying the environmental pressure of tourism on show caves. We then subsequently grouped these metrics into three broad categories (Table S2): artificial lights (“light presence,” light intensity, “light type,” and “light duration”); visitors (“number of visitors,” “visitor presence,” “distance from the tourist path,” and “visit duration”); and substrate changes (“allochthonous substrates” and “substrate enrichment”).

State (S)

The state represents the environment and environmental resources that should be protected and preserved. To quantify state changes, we identified metrics quantifying tourism-induced changes in the four ecosystem components. Overall, we defined 20 categories of state changes (Table S3).

Regarding atmosphere, we included the following: (1) “subterranean microclimate,” encompassing changes in temperature or relative humidity; and (2) “air quality” that considers changes in the concentration of carbon dioxide, airborne particles, or bioaerosol. For lithosphere, we refer at the following: (1) “rock geochemistry,” which considers karst phenomena, i.e., reaction between atmospheric CO_2 and $CaCO_3$ in the rock; (2) “rock quality” that quantifies the concentration of heavy metals or other (bio)contaminants; and (3) “sediment quality,” which refers to the concentration of nutrients or human-mediated colonizations by prokaryotes/fungi. For state changes in hydrosphere, we referred to the quantification of (1) physical parameters, such as water temperature; (2) “water quality,” encompassing concentration of nutrients and human-mediated colonizations by bacteria; and (3) “water geochemistry” that considers $CaCO_3$ dissolution or CO_2 diffusion in the water. Regarding biosphere, we referred to (1) “fauna,” whose changes can be measured, for instance, in terms of fitness or presence of indicator species; and (2) “microbial communities” that are studied mostly in terms of abundance and species richness and composition.

Impacts (I)

Impacts include all environmental changes that ultimately reduce the ecosystem functioning and its related ecosystem services. To quantify impacts, we grouped the metrics used to measure state change into 5 groups of impacts, i.e., “physical changes,” “chemical changes,” “pollutants,” “allochthnous microorganisms,” and “disturbance to the fauna” that were further clumped into two broad categories (Table S4): (1) abiotic alterations (physical changes, chemical changes, and pollutants), here intended as changes of abiotic natural conditions in caves; and (2) biotic alterations (“allochthnous microorganisms” and “disturbance to the fauna”), here intended as the alterations of populations and communities of living organisms within caves. We used the packages *ggplot2*[109] version 3.3.4 and *circlize*[110] version 0.4.13 for visualizing the relationships between pressures and impacts.

Responses (R)

Responses refer to all actions adopted to compensate, mitigate, or eliminate the environmental impacts. To quantify responses, we identified different possible management actions a priori based on the guidelines provided by the International Show Cave Association.[111] We then classified them into 5 higher groups (Table S5): protection (“cave closing” and “minimize external inputs”); regulation (“regulation of visitors” and “light modulation”); restoration (“cave cleaning” and “air flow control”); and indirect measures (“monitoring” and “education”). The four different categories of responses address different element of the DPSIR cycle: (1) Restoration actions are intended to reduce the impacts; (2) Regulation measures should reduce the overall impact on the subterranean ecosystems by limiting the state change; (3) Protection strategies aim at limiting the pressures on the system; and (4) Indirect measures contribute to increase awareness about the consequences of tourism in caves thus influencing the driver.

DPSIR analysis

We then organized the data provided by each paper with a DPSIR approach by building a DPSIR model for each ecosystem compartment. As we aimed at highlighting the interconnections among the different environmental components within the subterranean environment, we structured the obtained information within a DPSIR mosaic,[17] where pressures of one environmental component may feed on the state and impacts of other components. To obtain a comprehensive picture, when appropriate, we mapped external factors that are not strictly related to the anthropogenic use of show caves, but that can strongly affect one of the DPSIR elements. Therefore, we could organize responses in an integrated framework for management, easy to understand not only for cave scientists and conservation biologists but also for tourist guides, show cave managers, and other stakeholders.

SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.crsus.2024.100057.

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AUTHOR CONTRIBUTIONS

Conceptualization: E.P., S.M., and M.I.; methodology: E.P. and G.N.; data analysis: S.M.; visualization: E.P., S.M., and M.I.; writing—original draft: E.P.; writing—review and editing: all authors.

DECLARATION OF INTERESTS

The authors declare no competing interests.

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