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Ask the audience: Characterization of diving pressure on marine caves using diving operators' knowledge

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Abstract

Marine caves are considered biodiversity hotspots and serve as refuge habitats for both endemic and non-endemic species. Due to their low resilience, this habitat is considered vulnerable and is included as a key habitat in the European Union's (EU) Habitats Directive (92/43/EEC). Recreational diving has been identified as a significant threat to this habitat, causing sediment resuspension, destruction of epibenthic organisms by contact, and the accumulation of exhaled air from divers on the ceiling, which can lead to the death of benthic organisms trapped in the air pockets. Consequently, urgent management measures for recreational diving in this fragile habitat are necessary, particularly since this activity has experienced substantial growth during the last decades, evolving into a form of mass tourism. The development of effective management strategies for marine caves is challenging, as their exploitation and distribution are poorly known and cannot be estimated using traditional oceanographic mapping techniques applied to other benthic habitats. In this study, we conducted face-to-face, semi-structured questionnaires with dive operators, and used their Local Ecological Knowledge to estimate the spatial distribution of submerged and semi-submerged marine caves affected by recreational diving, the frequency of this activity, and the perception of diving centers regarding the impact of their activity on marine caves of the islands of Majorca and Menorca (Balearic Islands, Spain). Additionally, diving centers were asked to suggest potential measures to mitigate these impacts. Our results indicate that this approach is effective in identifying marine caves affected by recreational diving (a total of 111 marine caves were identified) and in determining key factors regarding the impact of recreational diving (accessibility of the cave and proximity to the diving center). This methodology also reveals that dive operators are generally aware of the reasons for protecting marine caves and the good practices required to protect this habitat, but little effort is made to implement these practices. These findings underline priority areas for intervention and suggest conservation practices to manage recreational diving in marine caves.

Keywords: marine caves; Local Ecological Knowledge; conservation policy; public engagement; tourism

Introduction

Marine caves constitute an emblematic ecosystem of the Mediterranean Sea and are vulnerable habitats with unique and diverse biocoenoses. The Mediterranean coast hosts more than 3000 marine caves harboring more than 2300 taxa; they represent genuine reservoirs of biodiversity of high conservation value (Gerovasileiou & Voultsiadou, 2012; Giakoumi *et al.*, 2013; Gerovasileiou & Bianchi, 2021). As a consequence, in the Mediterranean Sea, marine caves are considered priority habitats by the Habitats Directive (code 8330) (EU, 1992). They are included in the Dark Habitats Action Plan (UNEP/MAP - SPA/RAC, 2021), due not only to the rich biodiversity they host, but also to their fragility, low resilience, unique features, and biological wealth (Harmelin *et al.*, 1985; Rastorgueff *et al.*, 2015; Gerovasileiou & Bianchi, 2021).

Marine caves are characterised by a wide variety of geomorphological features and topography, due to the interaction between marine and continental processes. These conditions influence the structure of benthic communities, such as decreasing light levels, water flow, and nutrient supply towards the inner, more confined parts of the cave (Gerovasileiou & Voultsiadou, 2016; Gerovasileiou & Bianchi, 2021). These abiotic gradients result in high biotic heterogeneity in marine caves (Martí *et al.*,

2004; Guarnieri *et al.*, 2012); here, fauna from 15 different phyla coexist, including rare, protected, endemic, and deep-water species, as well as living fossils (Pérès & Picard, 1964; Harmelin *et al.*, 1985; Bussotti *et al.*, 2015; Gerovasileiou *et al.*, 2015; Ouerghi *et al.*, 2019; Gerovasileiou & Bianchi, 2021; Ragkousis *et al.*, 2021; Digenis *et al.*, 2025). Despite this heterogeneity, the main taxonomic groups show similar patterns in most marine caves: assemblages dominated by filter-feeding invertebrates, especially poriferans, which are the most abundant and species-rich phylum (Corriero *et al.*, 2000; Gerovasileiou & Voultsiadou, 2012; Manconi *et al.*, 2013; Gerovasileiou & Voultsiadou, 2016; Longo *et al.*, 2023; Derrien *et al.*, 2024). Other representative taxa include cnidarians, bryozoans, foraminifera, serpulids, and brachiopods (Pérès & Picard, 1964; Harmelin *et al.*, 1985; Harmelin, 1997; Gerovasileiou *et al.*, 2015; Ouerghi *et al.*, 2019; Gerovasileiou & Bianchi, 2021; Romano *et al.*, 2022). In marine caves, biostalactites form intricate meshes of serpulid polychaetes (bioconstructions), which form a microhabitat that boosts the biodiversity through the creation of suitable substrates for other epibionts, such as serpulids, sponges, foraminifers, bivalves, brachiopods, and scleractinian corals (Sanfilippo *et al.*, 2017; Jimenez *et al.*, 2019; Rosso *et al.*, 2019; Kazanidis *et al.*, 2022). Marine caves thus host unique benthic assemblages and bioconstructions formed by fragile and slow-growing organisms that are highly vulnerable (Gerovasileiou & Bianchi, 2021). For these reasons, the marine caves' ecological status must be monitored and preserved to mitigate human impact and minimize deterioration.

Despite their ecological importance and protection status, natural and anthropogenic pressure and threats (e.g., climate change and water acidification, coastal construction and habitat loss, pollution, and recreational diving) affect the communities of marine caves (Chevaldonné & Lejeusne, 2003; Parravicini *et al.*, 2010; Giakoumi *et al.*, 2013; Nepote *et al.*, 2017; Montefalcone *et al.*, 2018; Sala *et al.*, 1996; Di Franco *et al.*, 2009; Guarnieri *et al.*, 2012).

The unique features of fauna and landscape morphology make marine caves popular destinations for recreational divers (Rodrigues *et al.*, 2016), increasing the vulnerability of these habitats to the degradation caused by the high number of visits, due to the presence of fragile species and the reduced space, which increases the probability of damage caused by divers (Lloret *et al.*, 2006). The impact of recreational diving on marine caves has already been demonstrated (Di Franco *et al.*, 2010), especially during the last decades, as this activity has progressively evolved into a form of mass tourism (Davis & Tisdell, 1996). More recently, studies have shown that unregulated diving can cause cumulative damage to benthic organisms. Thus, mitigation strategies such as site zoning, pre-dive briefings, and training programs have been proposed to reduce the anthropogenic impact on these habitats (Giglio *et al.*, 2020).

The impact of recreational diving on marine caves is manifested through accidental collision of the diver against the caves' walls and ceilings, which damages epibenthic communities, particularly those with slow growth rates, larger sizes, and calcareous structures (Garrabou *et al.*, 1998; Guarnieri *et al.*, 2012; Pagès-Escolà *et al.*, 2020), including those created by engineering species such as gorgonians or bryozoans (Linares *et al.*, 2010; Casoli *et al.*, 2017). As a result, cave communities can shift from being structurally complex to being dominated by simple encrusting organisms (Lloret *et al.*, 2006; Di Franco *et al.*, 2010; Guarnieri *et al.*, 2012). Furthermore, sediment resuspension and the accumulation of exhaled air bubbles by divers in the ceiling of the caves also cause significant damage to cave benthic organisms (Milazzo *et al.*, 2002; Di Franco *et al.*, 2010; Jimenez *et al.*, 2019). These impacts are exacerbated in caves with a peculiar geomorphology and a favorable location (Shivlani & Suman, 2000).

Many popular marine caves are located within Marine Protected Areas (MPAs), and their protection status often increases their attractiveness to divers, which makes sustainable management more difficult (Davis & Tisdell, 1996). In fact, despite several initiatives put forward in recent years to minimize the impact of recreational diving (Giglio *et al.*, 2018; Giglio *et al.*, 2022), the massification of this activity has become a cause for concern due to its impact on marine caves and rocky bottoms in general (Giglio *et al.*, 2020).

The conservation and sustainable management of marine caves are essential, but there are still important gaps in scientific knowledge that hinder the development of effective management measures (Gerovasileiou & Bianchi, 2021). For example, available information on the distribution of marine caves is fragmented (Gerovasileiou & Voultsiadou, 2012; Gerovasileiou *et al.*, 2015), and data on their geomorphology and ecological features are limited (Gerovasileiou & Bianchi, 2021). Compared to other marine habitats, mapping the distribution of marine caves is more challenging (Dailianis *et al.*, 2022; Navarro-Barranco *et al.*, 2023). Several techniques, such as acoustics, LiDAR, sonar imaging and Autonomous Underwater Vehicles surveys can be used to detect and estimate the coverage of habitats listed in the Habitats Directive, such as rocky reefs (1170), *Posidonia oceanica* beds (1120), or sandbanks (1110) (Kenny *et al.*, 2003; Chust *et al.*, 2008; Bruno *et al.*, 2011). However, due to their unique nature, these conventional distribution mapping methods are not suitable for locating marine caves. As a result, knowledge from stakeholders (speleologists, technical divers, and diving operators) (Local Ecological Knowledge, LEK) on the location of marine caves becomes extremely valuable. Therefore, the use of questionnaires is a practical way to obtain data on the distribution and the level of human pressure on marine caves and is a practical way to gather relevant, standardized information that cannot be easily obtained using other techniques.

In the last decade, citizen science projects and the use of LEK have been proposed to help fill the knowledge gaps in species distribution (Zhang *et al.*, 2020; Turicchia *et al.*, 2021), to assess the intensity of pressure from marine activities (Byrnes *et al.*, 2016) and scuba diving (Dearden *et al.*, 2007; Hammerton *et al.*, 2012; Wong-

thong & Harvey, 2014), and to contribute to the conservation of coastal communities. Some citizen science initiatives have also involved dive operators directly, aiming to collect feedback on the effectiveness of management measures (Suman *et al.*, 1999; Shivlani & Suman, 2000; Edney, 2017). In addition, the use of LEK from dive operators and divers has recently been used for filling the gaps in species distribution knowledge and conservation purposes (de la Ballina *et al.*, 2025; Garcia-Bustos, 2025).

In the Balearic Islands (Spain), marine caves and anchialine systems have been the subject of many speleological surveys for more than 50 years (Gràcia *et al.*, 2011; Vicens *et al.*, 2011; Encinas, 2014; Gràcia & Fornós, 2021). The marine communities inhabiting Balearic caves have also been studied in these surveys (Bibiloni & Gili, 1982; Vacelet & Uriz, 1991; Bibiloni *et al.*, 1998; Martí *et al.*, 2004; Busquets *et al.*, 2014; Quiles-Pons *et al.*, 2022; Díaz *et al.*, 2024). However, to our knowledge, no studies have addressed the pressure of recreational diving on marine caves in the Balearic Islands, despite being a highly popular diving destination.

In this study, we sought to map the distribution of marine caves affected by recreational diving in Majorca and Menorca (Balearic Islands, Spain), and to evaluate the pressure of this activity on these habitats using face-to-face, semi-structured questionnaires with scuba diving operators. We also investigated the perception of diving operators regarding the impact of their activities on marine caves, and initiated a participatory process to identify possible regulatory measures to mitigate it. It is worth noting that because of the objective of this study, the terrestrial caves and anchialine systems were not addressed here.

Materials and Methods

Study area

The present study was conducted between July and September 2019, in Majorca and Menorca (Balearic Islands, Spain). These islands are among the most popular tourist destinations in Europe, with roughly 17.6 million (± 1.1 million SD) tourists visiting them each year (Instituto Nacional de Estadistica, IBESTAT FRONTUR open data 2022-2024, https://ibestat.es/estadistica/economia/turismo/flujo-de-turistas-frontur/). Diving is one of the most popular activities in the area, with more than 60 diving centers across the islands providing services to approximately 800 000 divers annually (RSTC-Europe, 2020). Regarding MPAs, Majorca and Menorca possess seven Marine Reserves, three Natural Parks, and one National Park where recreational diving takes place and is subject to specific regulations depending on the legal framework of each area: Marine Reserves website and Natural and National Parks website.

Questionnaire design

Data were collected through face-to-face, semi-structured questionnaires containing direct, multiple-choice, and open-ended questions. An initial contact was made by phone with all the diving centers operating in the study area; all centers willing to participate were interviewed. Each interview lasted around 60 minutes and consisted of 36 questions divided into five sections (Table 1, Suppl. A).

The first section collected data about the general profile of each diving operator, covering topics such as workforce size, available equipment, and seasonal operation. The second section focused on business characteristics, including pricing, working months, high and low season periods, number of divers per season and per dive, and the number of customers per trip diving at regular sites and in caves. This section also recorded whether the centers advertised cave diving, and how important cave diving was for each establishment (measured as the proportion of cave dives relative to the total number of dives offered). The third section of the questionnaire focused on identifying and characterizing marine caves, including the number of divers visiting each cave and the main features that make a cave suitable for diving. Participants were asked to mark on an interactive map the caves they were familiar with and to describe, when possible, their main characteristics, such as entrance depth, length, type of cave, and number of entrances. They also identified which caves they commonly visit with customers, and provided information about the frequency of those visits. The fourth section aimed to evaluate the respondents' knowledge of Habitat Directive 8330, their perception of its ecological value, and the potential anthropological impact they associate with this habitat. Additionally, participants were asked to rate, on a Likert scale from 1 to 5 (where 1 means very negative and 5 very positive), a list of possible regulatory measures that could mitigate the impact of recreational diving on cave communities.

Table 1. Structure of the questionnaire to collect data for marine caves distribution, quantification of cave diving activity, and dive operators' knowledge and perception of marine caves.

Section	Topic	Nº of questions
1	Diving operators	8
2	Economic significance of cave diving	13
3	Identifying and characterizing marine caves	5
4	Knowledge of Habitat type 8330	6
5	Willingness to promote the protection	4

Finally, the fifth section aimed to assess the level of environmental awareness among operators and their willingness to engage in activities to support the protection of marine caves.

After analyzing the data on the questionnaires, we focused on the most relevant results that provide information about the objectives of this manuscript and thus included only the data related to the overall number of divers, the location of the caves, and the opinions of dive center owners relevant to the sustainable management of cave diving. Information about the caves' characteristics was not used, as in most cases it was vague and incomplete. Further information on the results not included in this manuscript can be found in the final report of the INTEMARES C1.4 project in Spanish: Download report in PDF.

Data analysis

Localization of caves where recreational diving took place was considered reliable, whereas the position of the caves where diving does not take place was considered to be approximate. Since the operators also provided the toponyms of the visited caves, it was possible to distinguish them to avoid duplicate counts of the caves visited by multiple operators. To estimate the number of customers visiting each cave per year, we multiplied the number of divers each center brings per cave dive by the frequency of visits to each cave, considering high and low seasons separately. This result was then multiplied by the number of months each center identified as high or low season. Finally, the estimated number of divers from all centers was summed for each cave.

In all the cases, the diving operators provided all the information they considered relevant for choosing a cave as a diving spot, as well as the management measures that could mitigate the impact of diving in these caves. Therefore, the percentages shown in the results reflect the proportion of dive centers that agreed with a given statement in the questionnaire.

To explore perceptions and management preferences, the questionnaire included different types of questions. To analyze the factors involved in choosing a cave as a diving site, dive operators were provided with a predefined list of factors and asked to rate each factor on a Likert scale from 1 (not important) to 5 (very important). Perceived impact of recreational divers in caves, depending on diver characteristics, was also evaluated using a predefined list and rated on a Likert scale from 1 (very positive) to 5 (very negative). In both cases, respondents could provide additional open answers. Questions about the reasons for protecting marine caves and preferred management measures were open-ended and later categorized by the researchers. The percentages presented in the results, reflect the proportion of dive centers that selected or mentioned a given option.

Results

Characterization of diving activity in marine caves

A total of 49 diving centers were active at the time of the survey. Of these, 39 agreed to participate and provided information on the distribution of marine caves. Each diving center was treated as a single diving operator, regardless of the number of locations from which it operated. These operators were interviewed during a single visit and were asked to provide specific information about all the sites where they operate. Questions related to individual perception were treated as a single response per operator during analysis, to avoid duplicating opinions from businesses that owned more than one center. This approach ensured that each operator's views on the impacts of diving and the proposed mitigation measures were only counted once. Centers that did not participate in the survey stated that they either did not have time or did not dive in marine caves and were therefore not relevant for this study.

Of the 111 marine caves visited by recreational divers, 65 caves (58.6%) were located in Majorca and 46 (41.4%) in Menorca (Fig. 1). In Majorca, the most visited caves were located in the eastern (53.4%) and northern (35.9%) sectors of the island. In Menorca, the visited caves were primarily concentrated in the western (37.0%) and south-eastern (34.8%) areas. Information on cave characteristics was often vague or incomplete, and operators did not consistently differentiate between submerged and semi-submerged caves. Most of the caves visited by diving operators were blind caves (33.9%) and tunnels (23.2%), although some more complex cave systems (4.5%) and tunnel systems (1.8%) were also reported. In 35.7% of the caves, no cave type was specified (Table 2). The reported maximum depth ranged from 9 to 40 meters, with an average of 20.9 ± 5.9 m. Cave entrances were reported at depths between 0 and 24 meters, with an average of 9.1 ± 5.4 m. Although no information regarding the presence of air bubbles was provided for most caves (92), their presence was reported in 16 caves. The diving frequency at the caves containing air bubbles was very low, low, average, and very high (see below for definition of the categories of diving frequency).

The dive operators reported an average of 8.6 ± 3.0 clients per dive during the high season and 5.3 ± 2.7 during the low season. After sorting the caves by the estimated number of divers per year, 32.4% had a very low visitation (<50 divers), 33.3% had a low visitation (50-300 divers), 18.1% had an average visitation (300–500 divers), 11.7% had a high visitation (500-900 divers), and 11.7% had a very high visitation (> 900 divers) (Fig. 2C). Notably, five caves stood out with the highest number of divers per year: Illa de Toro-Buoy 5 (1890 divers), Pwele and Aguilot caves (both 1715 divers) in Majorca, and "Queso Suizo" (1836 divers) and Pont d'en Gil (1601 divers) caves in Menorca (Fig. 3, Suppl. B).

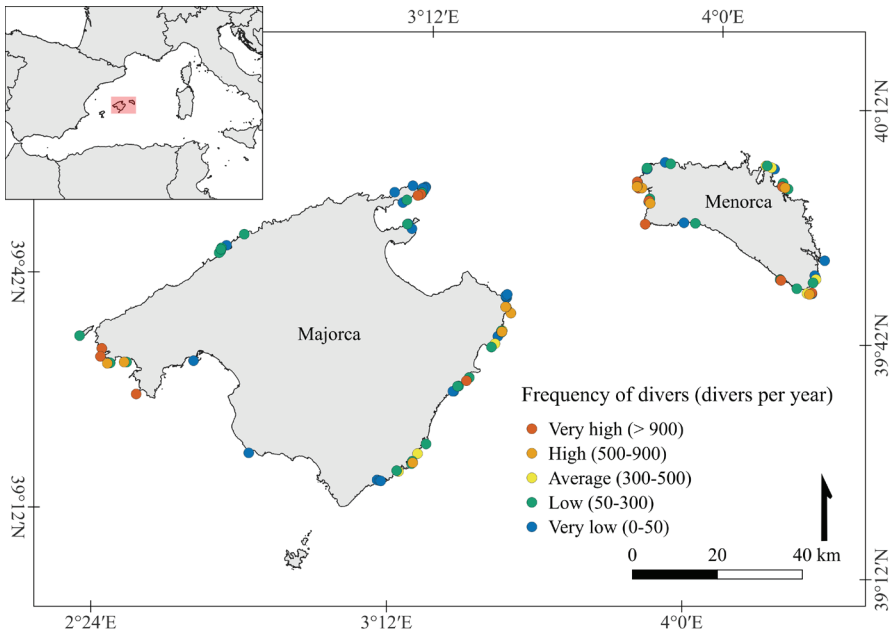

Fig. 1: Distribution of marine caves visited by recreational divers in the Islands of Majorca and Menorca (Suppl. B), based on the survey submitted to local diving centers (n = 39). Different colors indicate the number of estimated divers per year in each cave.

Table 2. Proportion of the different types of caves where recreational diving takes place, according to dive operators.

Cave type	Number	Percentage
Blind cave	38	33.9 %
Cave system	5	4.5 %
Overhang	1	0.9 %
Tunnel	26	23.2 %
Tunnel system	2	1.8 %
Unspecified	40	35.7 %

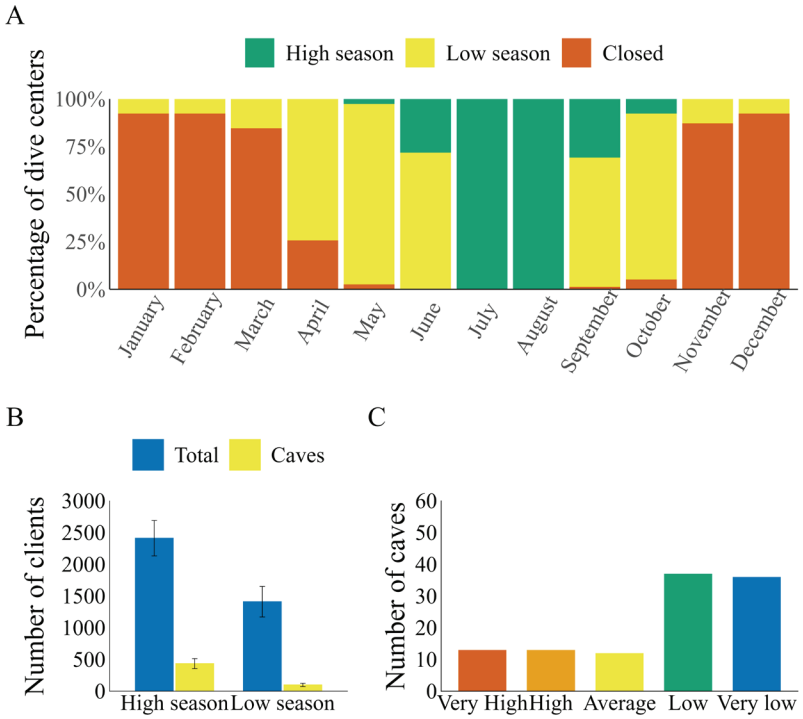

Fig. 2: Characterization of recreational diving in the study area. A) Seasonal activity of diving operators in the study area (n= 39). B) Average number of customers (± Standard Error) per dive center (n=39) diving in caves or elsewhere in relation to diving seasons. C) Number of caves according to the category of frequency of divers.

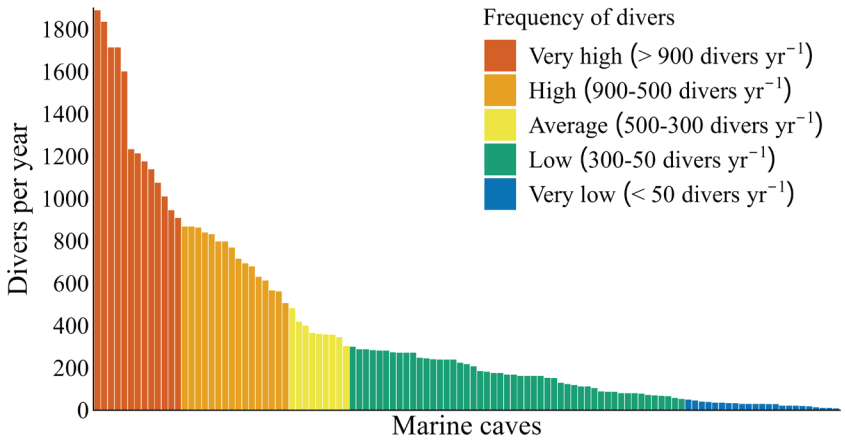

Fig. 3: Number of divers in each cave per year. Each bar corresponds to one cave, ordered on the x-axis according to the frequency of divers, from cave one to cave 111 (Suppl. B).

At the study site, diving centers are open for an average of 7.1 ± 0.1 months per year (n = 39), operating mainly from April to November. The peak activity occurs during the summer months, especially in July and August (Fig. 2A). According to the survey participants, 81.4% of cave dives also take place during the high season. During this period, an average of 2411.6 ± 278.9 customers per dive center engage in any type of diving activity, with 18.0% (434.1 ± 50.2) of them visiting the caves. During the low season, customer numbers decrease to an average of 1410.4 ± 240.5 customers per dive center, with only 7.1% (100.1 ± 17.1) diving in caves (Fig. 2B). Overall, we estimate that 16956 customers dove in marine caves during the high season, and 3874 during the low season.

Factors for choosing a cave for diving

According to the diving operators interviewed, the main factors determining whether a cave was chosen as a dive spot were its proximity to the diving centre (57.1%, $n = 20$) and its accessibility (in terms of ease of entry, low depth, or spaciousness) (48.6%, $n = 17$). Other, less frequently mentioned factors included the visual appeal of the cave and simply being aware of its existence (Fig. 4A).

Dive operators' perception of the conservation of marine caves

We focused on the perception of diving operators regarding the effects of diving on marine caves. We found that more than half (51.4%, $n = 18$) of the diving centers were unaware that marine caves are protected by the EU's Habitats Directive. Additionally, among the operators who were aware of this protection (70.6%, $n = 12$), most had learned about it out of personal interest.

When questioned about their opinion on the reasons to protect marine caves, most operators mentioned their unique biodiversity (62.9%, n = 22), peculiar morphology (20%, n = 7), and to protect caves from destruction (11.4%, n = 4) as the main factors. Other reasons included

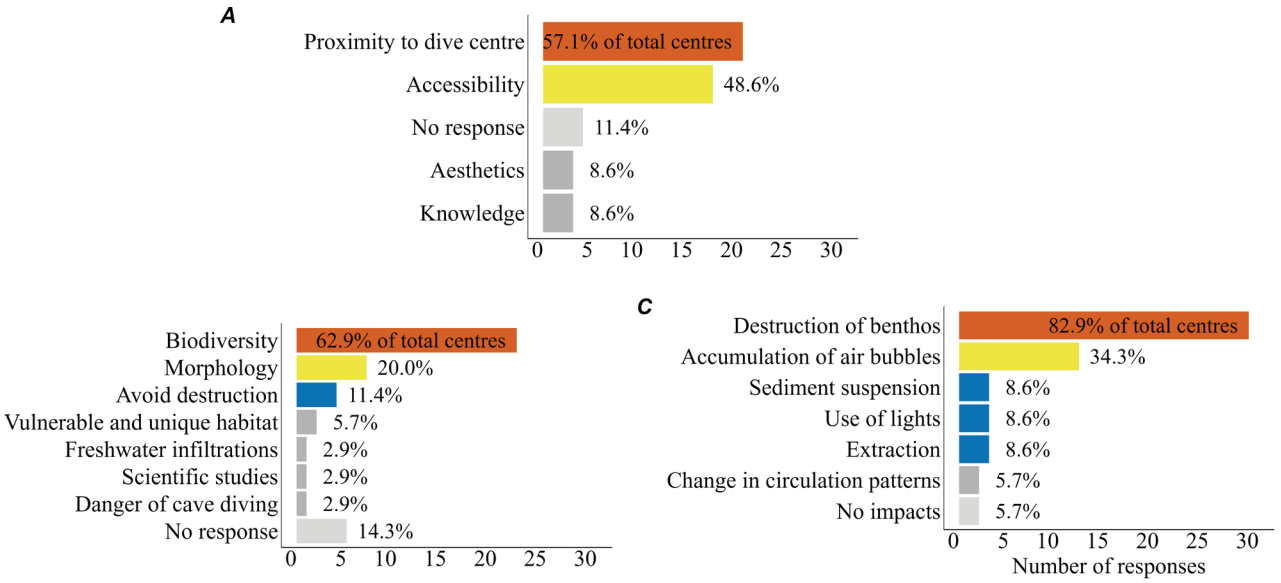

Fig. 4: Responses of the dive centers (n = 35) regarding: A) criteria used by the diving operators for choosing a marine cave as a diving spot, B) causes for protection of marine caves, and C) Impact of recreational diving on marine caves.

the vulnerability and singularity of marine caves (5.7%, n= 2), their importance for scientific studies (2.9%, n = 1), freshwater infiltrations (in the sense of "clean" water) (2.9%, n = 1), and the inherent danger associated with cave diving (2.9%, n = 1), meaning that caves should be regulated to limit such danger (Fig. 4B).

The last two operators answered the question one from an erroneous concept of healthy environment and the other from the point of view of diving safety, rather than ecosystem conservation, which could indicate the lack of adequate ecological knowledge in a small proportion of diving operators.

In addition, diving operators perceived that the main impacts of recreational diving on marine caves include the destruction of epibenthic organisms (82.9%, n = 29) and the accumulation of air bubbles on the ceilings (34.3%, n = 12). The sediment resuspension (8.6%, n = 3), the use of lights (8.6%, n = 3), the extraction of organisms and/or stalactites (8.6%, n = 3), and the alteration of circulation patterns (5.7%, n = 2) were also mentioned. However, 5.7% (n = 2) of the operators believe that recreational diving has no impact on marine caves (Fig. 4C).

All of the operators considered that eco-briefings before the dive and diving with a professional guide were positive or very positive measures to mitigate the impact of divers on marine caves. Furthermore, most operators considered it positive to visit caves in small groups (97% n = 34) and customer experience, measured as total number of dives (91% n = 32), frequency of dives (86% n = 30), and certification level (83% n = 29). The use of underwater cameras was considered positive on average (51% n = 18), but some operators (17% = 6) considered it negative or very negative, as they believe the use of cameras makes photographers less aware of their contact with the benthos (Fig. 5).

All the participating operators declared that they perform eco-briefings before the dives. When asked about the key points of these eco-briefings, 85.7% of operators (n = 30) demanded that the divers not touch anything, while 68.6% (n = 24) emphasized the importance of buoyancy control to avoid accidental contact with the cave surface or benthos. Other information operators included in their eco-briefings was the prohibition to take any living or dead organisms (28.6%, n = 10), general information about marine biodiversity (14.3%, n = 5), the importance of MPAs (14.3%, n = 5), and the preservation of *Posidonia oceanica* meadows (11.4%, n = 4). A few operators actually checked the buoyancy control of their customers before diving in vulnerable areas (8.6%, n = 3) or explicitly prohibited littering at the sea (5.7%, n = 2). Finally, one operator limited the time spent inside the caves to reduce the impact of the divers' visit (Fig. 6).

Discussion

Characterization of diving activity in marine caves

In this study, we presented the location of 111 marine caves reported to be used for diving activity, across the islands of Majorca and Menorca, as well as estimates of the number of divers visiting each cave annually. In their review of Ecosystem-Based Management (EBM), Cogan *et al.* (2009) highlight several key elements that contribute to the effective management of any natural area. These include taking into account the interconnectedness among ecosystems, maintaining or improving the ecosystem functioning, and taking into account the range of human activities along with their social, economic, and institutional dimensions. To achieve an effective EBM, knowledge of the distribution of the habitats is fundamental (Cogan *et al.*, 2009; Gerovasileiou *et al.*, 2019; Baker & Harris, 2020) and could be essential to achieve such interconnectedness.

In the case of marine caves, habitat mapping is a notoriously difficult task due to the cryptic nature of this

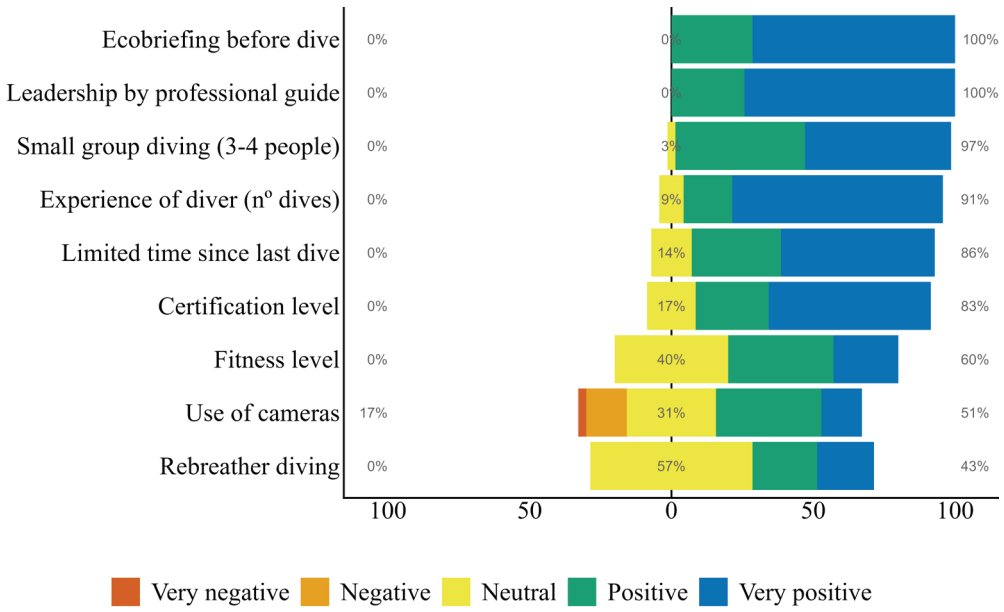

Fig. 5: Perception of diving centers on the effectiveness of a set of measures to mitigate the impact of divers on marine caves in a Likert scale from 1 to 5, being 1 very negative and 5 very positive (n = 35).

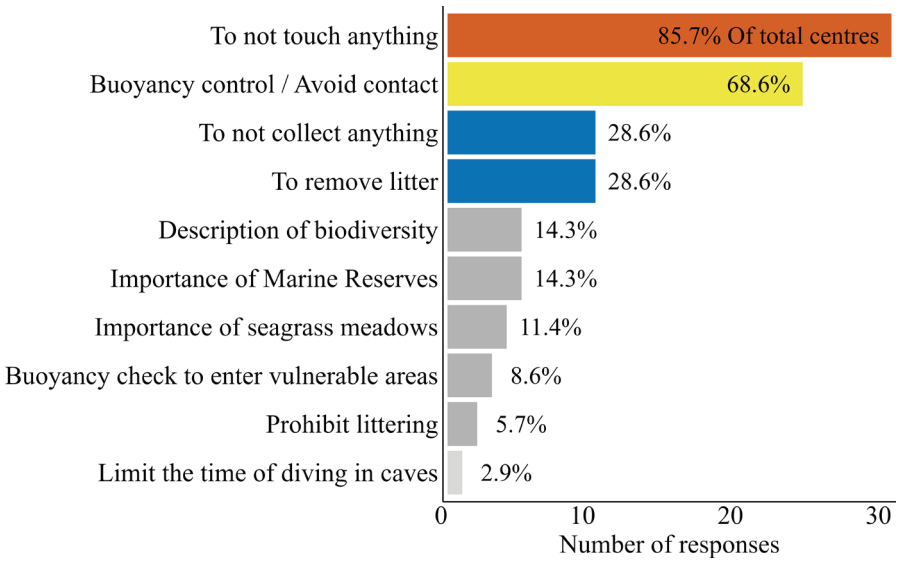

Fig. 6: Key aspects of the eco-briefings provided by diving operators to their customers before diving (n = 35).

habitat (Gerovasileiou *et al.*, 2015). Numerous studies are available for marine caves, most of which focus on their ecology (Uriz *et al.*, 1993; Martí *et al.*, 2004; Bianchi *et al.*, 2022), biodiversity (Gerovasileiou & Voultsiadou, 2012; Gerovasileiou *et al.*, 2015; Díaz *et al.*, 2024), and distribution (Ouerghi *et al.*, 2019; Gerovasileiou & Bianchi, 2021). In fact, studies on cave characterization, mapping, and distribution have been conducted in the Balearic Islands since 1972 (Gràcia *et al.*, 2011). Nonetheless, while scientific studies remain key to cave characterization, mapping, and biological evaluation, to implementing the interconnectedness principles of the EMB, standardized citizen science is a valuable complementary tool for conservation purposes and for stakeholders' involvement (Blosear *et al.*, 2015; Hammerton, 2017; March *et al.*, 2022). For example, despite the available knowledge on marine caves in the study area, no studies addressing the localization of marine caves impacted by recreational diving had been found to date. One way to solve this knowledge gap might be to appeal to the local experience, especially if it comes from dive operators, since they share an interest in localizing marine caves and hold valuable information about their natural environment. Indeed, in their attempt at mapping the distribution of marine caves, among other habitats, in the Mediterranean Basin for conservation purposes, Giakoumi *et al.* (2013) also appealed to the LEK in several cases. Similarly, this study also appealed to local knowledge of dive operators to map the location of specific marine caves (those of interest for recreational diving) and to spot priority areas for the management of recreational diving activity through the use of standardized questionnaires at a relatively low cost.

Additionally, this method identified key factors relevant for management purposes. For example, most diving operators choose to bring their customers to caves that are located near their headquarters and are easily accessible. These factors likely limit the number of caves heavily affected by recreational divers and point to where conservation measures should be implemented (e.g., setting a maximum on the number of daily visitors or establishing a cave rotation system). In such cases, accessibility should take into account the location of diving centers in relation to such caves, along with targeted monitoring programs to assess their ecological status. Similarly, although recreational cave diving takes place all year round, most activity takes place in July and August, which may help define a time frame to enhance the enforcement of management measures or even for enforcing seasonal surveillance patrols in the high seasons.

It is important to note that the main limitation of the habitat characterization by local knowledge is that it only allows the identification of the marine caves that are within the operational range of diving centers, and it is limited by the knowledge of the diving operators. Therefore, this approach is a starting point for a comprehensive mapping of the distribution of marine caves, as during the study, no information could be gathered regarding caves in remote and/or deep areas or anchialine systems. Therefore, a more thorough approach in mapping of the distribution of this habitat, requires a collaborative effort by coupling preliminary information obtained by LEK and citizen science projects, through specialists of the diving community, such as technical and rebreather divers (Giakoumi *et al.*, 2013), with a more rigorous characterization performed by researchers and speleologists.

Dive operators' perception of the conservation of marine caves

Regarding the dive operators' awareness of the fragility and ecological importance of marine caves, as well as about their impacts, the results of the present study indicate that more than half of the operators who participated in the survey were not aware that marine caves are officially protected under the Habitats Directive and two Mediterranean Action Plans. Furthermore, only a small proportion of diving centers were aware of the vulnerability of these habitats. On the other hand, despite

the lack of awareness regarding the protection status of marine caves, most diving operators did recognize that recreational diving has an impact on this habitat. These figures indicate the lack of interconnectedness between governmental institutions, local operators, other stakeholders (such as academia, NGOs, and diving certification companies), and, ultimately, the divers. Therefore, management of marine caves could benefit from initiatives focused on raising dive operators' awareness of the vulnerabilities, ecological features of this habitat, and the existence of protection status granted by different institutions.

Regarding appropriate conservation practices for marine caves, diving operators generally agreed that to instruct the customers through eco-briefings and to enter the cave in small groups of experienced divers (max 3-4 people) is a good practice. They agree that these practices minimize sediment suspension and accidental destruction of organisms. However, only four of them declared that they actively implement protective measures (such as performing buoyancy control or limiting the diving time in the caves), suggesting that there is still much to improve to achieve sustainable diving in marine caves. In fact, the dive operators' involvement in the management process is key to the success of conservation practices (Trave *et al.*, 2017). For example, the delivery of eco-briefings alone does not appear sufficient to alleviate the impact of recreational diving on the seabed, but the active intervention of a guide does actually make a difference in such impact (Barker & Roberts, 2004). Therefore, the capacitation of diving guides towards best practices might benefit the conservation of marine, as well as long-term availability of an attractive, healthy ecosystem to be appreciated by divers (the latter might be an attractor for dive operators toward more sustainable diving practices). An initial step to achieve such capacitation could be to make recreational cave diving certification mandatory for dive guides and/or customers who want to take part in this kind of diving (as is the case for deep dives, nitrox dives, etc.) (Betti *et al.*, 2023), and including training in the best practices, information on the ecological importance of caves and their conservation status into these certifications.

Due to their unique ecological features, marine caves attract thousands of recreational divers per year, particularly those caves that are most accessible and closest to the diving center. It is widely reported that recreational diving has an impact on benthic organisms; hence, given the low resilience of marine caves, it is required to conserve the ecosystem services they provide. Some of the management measures toward marine cave conservation could be to limit the duration and the number of people and of entering any cave simultaneously, to consider cave diving as for an experienced-only dive that requires proper certification (as for wreck and deep dives), encouraging the use of rebreather and to establish periodic surveys for monitoring the status of the cave conducted by specialists.

Additionally, it is also important to diving, raise awareness that the lack of measures can rapidly degrade the habitat status, hence the quality of the dive spot, as well as establishing a network of stakeholders in order to share knowledge, to generate multi-directional feedbacks and to map the distribution and intensity of pressures across the territory (Di Camillo *et al.*, 2025). In this regard, the present study has proven to be valuable to characterize the recreational diving activity in caves. It highlights the main factors which influence diving operators to choose where to dive in any particular cave, and when to expect the maximum impact of recreational divers. This could be useful to plan monitoring surveys and to close the diving activity in any cave which might result in poor conditions after the evaluation from the surveys.

Although most diving operators do acknowledge the impact of their activity on marine caves, more than half of them do not know that this habitat is protected by international regulations. Similarly, the majority of the diving centers have an idea of how to mitigate them, but only a few of them actually implement these mitigation measures. These findings highlight that more work is needed to increase the awareness on the importance of this habitat and on the concept that healthy caves (hence a more spectacular dive spot) could benefit the dive operator, as well as the establishment of management measures, such as the ones suggested within this research to effectively work towards the conservation of this valuable and fragile habitat.

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Supplementary Data

The following supplementary information is available online for the article:

Supplementary A: Questionnaire for Recreational diving in Marine Caves.

Supplementary B: Checklist of marine caves resulted from responses to the questionnaire.