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Baseline for marine cave monitoring strategies in the Alboran Sea using modified Cave Ecosystem-Based Quality Index (CavEBQI)

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ABSTRACT

Marine caves constitute vulnerable habitats with unique and diverse biocoenoses. Monitoring these habitats is still challenging, which hinders the ability to evaluate global and local pressures that threatens their ecological value. In this study, ecological quality is estimated in twenty-one marine caves distributed along the northern and southern coasts of the Alboran Sea, a highly understudied area regarding marine caves. For that purpose, adjustments on the original Cave Ecosystem Based Quality Index (CavEBQI) are suggested in order to efficiently estimate the ecological quality of marine caves. Several methodological aspects regarding the assessment of biotic coverage, the visual census of motile fauna and the plasticity of the index usability were evaluated. Ecological quality of marine caves was in average "good" although it ranged between "poor", "moderate" and "good" depending on the features of each cave. This study emphasizes the importance of adapting biotic indicators to biogeographical differences and technological advancements.

1. Introduction

Marine caves are unique and vulnerable habitats occurring across the Mediterranean coastline (Gerovasileiou and Voultsiadou, 2012; Giakoumi et al., 2013). They harbour a rich biodiversity including rare, cave-exclusive, endangered, protected, and deep-water species which form distinct communities (Gerovasileiou and Bianchi, 2021 and therein references). Caves' biocoenoses are commonly shaped by strong environmental gradients such as the gradually reduced light intensity and hydrodynamism (Morri et al., 1994; Fichez, 1991; Gerovasileiou and Bianchi, 2021) and the steep decrease of allochthonous organic matter (Fichez, 1991; Rastorgueff et al., 2011) along the inner semidark and dark cave sections. As a result, different cave communities develop within distinct ecological zones. Hard substrates of the semidark ecological zone are characterised by the absence of photosynthetic organisms and the abundance of large sponges, cnidarians and bryozoans, while the dark zone, being more oligotrophic, mostly hosts smaller sized encrusting sponges, serpulids, and brachiopods (Pérès and Picard, 1964; Harmelin et al., 1985; Gili and Ballestero, 1991; Dimarchopoulou et al., 2018; Sempere-Valverde et al., 2019; Gerovasileiou and Bianchi, 2021). Some cave-dwelling species are endemic to these environments and/or can be restricted to certain Mediterranean regions, creating a large-scale spatial heterogeneity between marine cave communities in different biogeographic areas (Gerovasileiou and Voultsiadou, 2012; Bussotti et al., 2015; Gerovasileiou et al., 2015). However, even communities of closely located marine caves can differ due to their cave-specific morphological features inducing small-scale heterogeneity also known as "individuality" (Martí et al., 2004; Bussotti et al., 2006; Gerovasileiou and Voultsiadou, 2016; Gerovasileiou et al., 2017; Digenis et al., 2022).

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Although "Submerged or partially submerged sea caves" have been characterised as a protected habitat type (code 8330) under the European Union's Habitats Directive (92/43/EEC) and the "Dark Habitats Action Plan" of the Barcelona Convention (Pergent et al., 2015), various anthropogenic pressures and threats affect their communities (Bussotti et al., 2006; Giakoumi et al., 2013; Sempere-Valverde et al., 2019; Montefalcone et al., 2023). Among the main disturbances to marine cave communities are the impact of unregulated SCUBA diving (Di Franco et al., 2009; Terrón-Sigler et al., 2016), accumulation of marine litter (Mačić et al., 2018), coastal infrastructure construction (Nepote et al., 2017), expansion of non-indigenous species (Gerovasileiou et al., 2016; Digenis et al., 2022; Gerovasileiou et al., 2022) and the increasing water temperature (Parravicini et al., 2010; Rastorgueff et al., 2015; Montefalcone et al., 2018, 2023). For this reason, in the context of environmental monitoring, standardised methodologies that considers biogeographical variation and uses consistent up-to-date methodologies are essential for the development of ecosystem-based management actions and long-term strategies (Giakoumi et al., 2013; Bussotti et al., 2015; Boudouresque et al., 2020; O'Higgins et al., 2020).

Ecological indicators constitute useful tools in synthesizing scientific knowledge towards policy makers as they simplify complex ecosystem processes and dynamics (Bevilacqua et al., 2020). With the use of ecosystem-based indices (EBQI), the ecological status is assessed by considering different functional components, which have a different weight depending on their relative importance in the functioning of the given ecosystem (Personnic et al., 2014). Ecological quality of Mediterranean marine cave ecosystems was first assessed by Rastorgueff et al. (2015), who developed the Cave Ecosystem Based Quality Index (CavEBQI) based on the EBQI, a previously developed index to evaluate the status of *Posidonia oceanica* meadows (Personnic et al., 2014). According to the conceptual model of the cave ecosystem functioning developed by Rastorgueff et al. (2015), this ecological indicator considers three functional groups of sessile biota, distinguished by their feeding strategy (passive or active filterers) and size, vertical stratification, the presence of mysids inside the cave and finally the species richness and abundance of three different functional groups of motile fauna.

However, the CavEBQI was developed and originally applied in only 22 marine caves of France and Italy, and thus Rastorgueff et al. (2015) suggested modifications on the implementation of the index, considering biogeographical adaptations and methodological improvements. Since then, published information on the application of the CavEBQI are available from only one marine cave of the northern Alboran Sea (Western Mediterranean) by Navarro-Barranco (2015) and six marine caves of the Aegean Sea (Eastern Mediterranean) by Digenis et al. (2022). Both studies highlighted limitations, particularly the need for improvements and cross-calibration exercises to address large-scale biogeographic heterogeneity.

The Alboran Sea, the westernmost sub-basin of the Mediterranean Sea, is characterised by high productivity levels and rich biodiversity when compared to other Mediterranean sub-basins (Rodriguez et al., 1994; Real et al., 2021; Rueda et al., 2021), mainly driven by upwelling events (Sarhan et al., 2000) and the coexistence of Atlantic and Mediterranean species (Cebrián and Ballesteros, 2004; Bermejo et al., 2015; Navarro-Barranco et al., 2022). In addition, it encompasses multiple Marine Protected Areas that are well known from taxonomical and ecological studies (Cebrián and Ballesteros, 2004; García Muñoz et al., 2008; Navarro-Barranco et al., 2022), some of which focus on monitoring the ecological quality on a long-term basis (Bermejo et al., 2013; Marina et al., 2015). However, European and North African Alboran Sea coasts constitute the Mediterranean regions with the lowest number of known marine caves across their coastline, as well as the areas with the lowest numbers of studies regarding their cave biota (Giakoumi et al., 2013; Gerovasileiou and Voultsiadou, 2014; Gerovasileiou and Bianchi, 2021). Although a few studies aimed to fill part of this gap in the Alboran Sea, they were mainly focused on a small number of caves of its northern coasts and particular taxa, namely amphipods (Navarro-Barranco, 2015) and sessile benthos (Sempere-Valverde et al., 2019).

This study aims to assess the ecological quality of twenty-one (21) marine caves distributed along the northern and southern part of the Alboran Sea by applying the CavEBQI index. For this reason, we focus our work on a) investigating an optimal methodology for the assessment of biotic coverage with image analysis and b) elaborating a suitable list of key motile species inhabiting marine caves in the Alboran Sea. The implementation of this index in the westernmost sub-basin of the Mediterranean Sea led to the suggestion of several modifications to the CavEBQI index, one decade after its original development.

2. Materials and methods

2.1. Study area

During the years 2022 and 2023, a team of scientific divers surveyed twenty-one marine caves distributed along the Alboran Sea in collaboration with different management bodies of the area. Seventeen caves are located along the southern coast of the Iberian Peninsula [distributed in the Spanish provinces of Cadiz (1), Málaga (4), Granada (8) and Almeria (4)], while four are located in the northern coast of Africa [one cave in Belyounech (Morocco) and three caves in Chafarinas Islands, Spain] (Fig. 1). Nineteen of the studied caves are within the Natura 2000 Special Areas of Conservation (SAC) network including the protected areas ES000037-"Estrecho", ES6170002-"Acantilados de Maro-Cerro Gordo", ES6140016-"Acantilados y Fondos Marinos de la Punta de la Mona", ES6140014-"Acantilados y Fondos Marinos de Calahonda-Castell de Ferro", ES0000046-"Cabo de Gata-Níjar", and ES6300001-"Islas Chafarinas". Sampling of multiple caves were carried out by the technicians of the Agencia de Medio Ambiente y Agua within the life INTEMARES project (LIFE15 IP ES012), which aimed the preparation of a marine cave's inventory for the Andalusian region, the modification of the index for the Alboran Sea and the data collection for monitoring (Junta de Andalucía, 2015–2023, Remón et al., 2024). Studied caves have been named differently at multiple times, therefore, a table with all corresponding names of every cave is included (Table S1).

Among the surveyed caves, Cerro Gordo cave (Fig. 1) stand out due to its length (>100 m long) and topography (two distinct chambers separated by a narrow passage; Sempere-Valverde et al., 2019 and therein references). Its first chamber hosts a semidark community while the inner second chamber hosts a quite different dark cave community. Due to the high differentiation between the two chambers, Cerro Gordo semidark (SD) and Cerro Gordo dark (D) cave section were evaluated independently in order to investigate whether different cave zones within the same cave can be characterised by different ecological statuses. A single evaluation is provided for all other caves, which do not exhibit dark biocoenoses (their lengths range between 5 and 45 m). In general, most caves are either semisubmerged (12) or shallow (2) (although the bottom of the entrance might be deeper depending of the entrance morphology), and only a few of them are deeper than 7 m (4) and 15 m (2). In relation to topography of the cave, seventeen of the caves are blind ended (although they may have additional small entrances) and four of them are tunnel shaped.

2.2. Ecological quality assessment and adaptations of CavEBQI

In order to assess the ecological status of marine cave ecosystems in the Alboran Sea, CavEBQI was applied firstly as proposed by Rastorgueff et al., 2015. Then, some methodological modifications were incorporated to the index with the aim of maximizing and standardising sampling and data processing, and therefore to facilitate and improve monitoring tasks.

According to Rastorgueff et al. (2015), the main components of the CavEBQI are: i) the percent coverage of Passive Filter Feeders (PFF), Small Active Filter Feeders (SAFF) and Large Active Filter Feeders (LAFF); ii) the volumetric stratification of sessile taxa (as indicator of the

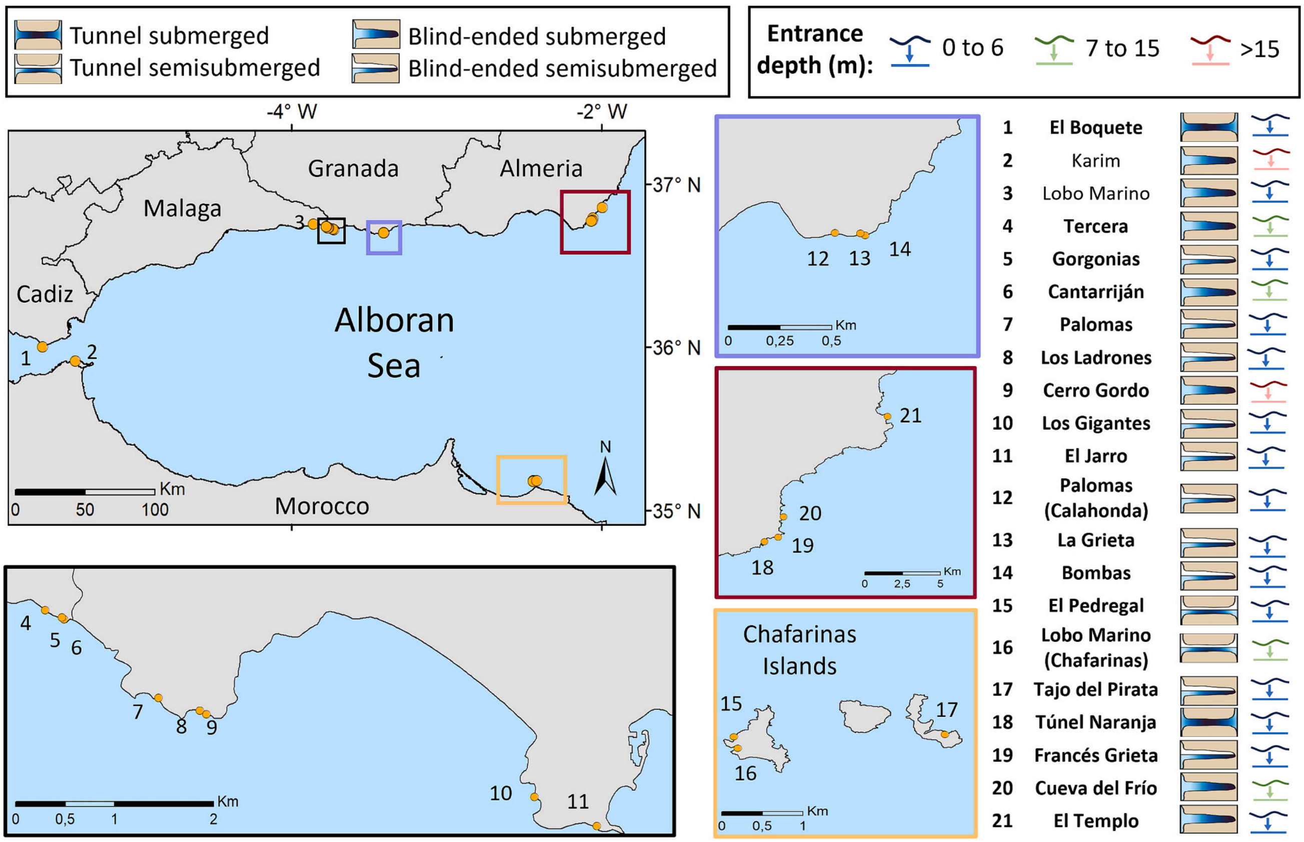


Fig. 1. Map of the Alboran Sea (top left) with more detailed coloured maps showing the location of the twenty-one studied marine caves as well as their morphological type (top), the depth range of their entrance and the cave name (right). Caves located within the Natura 2000 network are presented in bold. Caves that presented small air chambers at their inner semidark and/or dark sections and fully submerged cave entrances were considered as submerged.

health condition and food availability for erect growth forms); iii) the presence of mysid swarms inside the cave; iv) the species richness and abundance of motile taxa categorised into "Detritus Feeders and Omnivores", "Characteristic Cave Carnivores" and "Associate Carnivores". These components are evaluated in a semi-quantitative scale ("status") from 0 to 4, with 4 being the maximum status obtained. The methodological reliability is estimated through a Confidence Index (CI) ranged from 0 to 4, with 4 representing the recommended optimal methodology. Calculation of the final ecological status for each cave and CI consists of a weighted average of all the components (Rastorgueff et al., 2015). A complete description of the original methodology can be found along the manuscript of Rastorgueff et al., 2015. However, the following modifications to the original scheme are suggested.

- Coverage of the different sessile morphofunctional groups (PFF, SAFF and LAFF) was evaluated by a status of 4 for ≥30 % coverage, a status of 3 for ≥10–30 % coverage and a status of 2, 1 and 0 for ≥3–10 %, 0–3 % and no biotic coverage respectively. The respective percentages in the original guidelines are >75 %, 50–75 %, 25–50 %, 0–25 % and 0 %, respectively (Rastorgueff et al., 2015), however, new percentages were based on the highest coverage (per morphofunctional group) found at marine caves of the Alboran Sea, which barely exceeds a 30 %. The Confidence Index (CI) for coverage estimation ranges from 0 to 4, depending on if the applied methodology follows the recommendations in the photoquadrat analysis section (*see below).
- Volumetric Stratification of sessile cave-dwelling species was calculated by the average value of ten random measurements taken perpendicularly to the wall, while originally it was suggested to assign only one value through a visual assessment of an area between 1 m^2 and 4 m^2 (Rastorgueff et al., 2015). Thus, representativity of this component is increased within the same diving time as it can be conducted simultaneously with the photoquadrat collection. Regarding CI, if in situ measurements are not possible, estimating the vertical stratification from photoquadrats would correspond to a CI level of 3 while giving one single value per cave or using expert statement with no quantitative measurements would imply to a CI of 2 and 1, respectively.
- Motile cave fauna was assessed by a single diver during a 20–25 min dive, recording species richness and abundance of three trophic functional groups and semi-quantitatively checking for the presence of mysids (following Rastorgueff et al., 2015). Dives were conducted between 10:00 and 16:00 UT during the warm season, which spans from late spring to early autumn (Personnic et al., 2014). Aside from mysids, only taxa larger than 3 cm were considered during the visual census. It is important to note that for species forming schools (e.g., *Apogon imberbis*), the recommended maximum count of individuals was capped at 50, as higher numbers are difficult to estimate accurately and do not significantly affect the quality score. To facilitate the application of this methodology, a list of 66 motile taxa potentially present in marine caves of the Alboran Sea was compiled. Since the original methodology included only 24 motile species across the three trophic functional groups, the number of taxa considered for determining status was adjusted as follows:
- Detritus feeders/Omnivores: Species richness was scored with a maximum status of 4 for >8 species, and a status of 3, 2 and 1 for 8–6, 5–2 and 1 species, respectively. Abundance was scored by a status of 4 for >15 individuals, and a status of 3, 2 and 1 for 15–10, 9–5, 4–1 individuals, respectively. However, the respective numbers in the original guidelines are >5, 5–3, 2 and 1 species and > 10, 5–10, 3–4 and 1–2 individuals, respectively (Rastorgueff et al., 2015).

- Characteristic cave carnivores: Species richness was scored with a maximum status of 4 for >8 species, and status 3, 2 and 1 for 8–7, 6–4 and 3–1 species, respectively. The respective numbers in the original guidelines are 4 for fish species and 4–5 for decapod species for the maximum status followed by 3, 2 and 1 species for both, respectively (Rastorgueff et al., 2015). Abundance was scored with a maximum status of 4 for >80 individuals, and a status of 3, 2 and 1 for 80–30, 29–10 and 9–1 individuals, respectively. The original version of the CavEBQI does not incorporate abundance of characteristic carnivores.
- Associate carnivores: Species richness was scored with a maximum status of 4 for >6 species, and status 3, 2 and 1 for 6–5, 4–3 and 2–1 species, respectively. The respective numbers in the original guidelines are 2, 2, 1, 1 for fishes, 3, 2, 2, 1 for decapod crustaceans and > 2, 1–2 and 0 for associate carnivore anemones. Abundance was scored with a maximum status of 4 for >80 individuals, and a status of 3, 2 and 1 for 80–30, 29–10 and 9–1 individuals respectively. The original version of the CavEBQI does not incorporate abundance of associate carnivores.

As proposed by Rastorgueff et al. (2015), in each case, the final status of these last three components was calculated through the rounded mean of the 2 values obtained (in this case, values for species richness and abundance). Regarding motile fauna components, any non-compliance of the proposed mentioned methodology (e.g. census time being lower than 20–25 min, or census being conducted in winter season or at night) may affect the fauna encountered at the caves and would imply a CI of 3. If data was obtained merely from suitable expert statement (non-quantitatively assessed data from people familiar with local cave fauna), CI would decrease to 2. Given the same scenario but being non-recent data (>10 years according to Rastorgueff et al., 2015), CI would decrease to 1.

2.3. Photoquadrat analysis for coverage assessment

Functional groups of sessile benthic community (PFF, LAFF and SAFF) were evaluated through replicate quadrats (25 × 25 cm in size), randomly placed and photographed along each opposite vertical cave wall of the semidark or dark ecological zone of the twenty-one marine caves. All photoquadrats were captured through SCUBA diving with an Olympus TG-4 or similar underwater camera, always with flash, within the hours 10:00–16:00 UT during the warm season (late spring to early autumn) (Personnic et al., 2014).

The percent coverage of sessile morphofunctional groups was calculated through the PhotoQuad software (Trygonis and Sini, 2012) by randomly overlaying points on each photoquadrat image and assigning them into different morphofunctional groups. In order to find the most representable and time efficient method, both the optimal density of points and the number of quadrats were tested.

Firstly, the coverage (%) of the sessile morphofunctional groups was calculated four times ($n = 4$), with six different densities of points (p): 25, 50, 75, 100, 125 and 150 points, along 10 randomly selected photoquadrats. For every density of points (p) and morphofunctional group (f), the "Mean Deviation by Category" (MDC) was calculated through the equation

$$MDC_{p,f} = \frac{1}{qn}\sum_{1}^{q} \sum\nolimits_{1}^{n} \left| x - \overline{x}_i \right|$$

where $\overline{x}_i$ is the mean coverage of each morphofunctional group (PFF, LAFF and SAFF) in a selected quadrat and x_i represents each replicate coverage value for n replicates (with n = 4 in this study) of each quadrat (q = 10). MDC can be interpreted as the variability of coverage data within replicate quadrats, which is expected to decrease when increasing the number of points used. Differences on MDC values were tested for the fixed factor "points number" (six levels) through one-way ANOVA analysis and Pairwise tests.

Secondly, the optimal number of analysed photoquadrats for each cave was tested. To do so, the coverage (%) of each morphofunctional group (f) (PFF, LAFF and SAFF) was measured in a total of sixteen photoquadrats of four randomly selected caves (c = 4). In every photoquadrat, the previously calculated and selected optimal number of points was used (*see Results). Dispersion was evaluated through a comparison of the "accumulated Mean Deviation" (accMD) of each morphofunctional group cover (f), through the equation

$$accMD_{i,f} = \frac{1}{c}\sum_{1}^{c} \overline{x}_i - \overline{x}_{16}$$

where $\overline{x}_i$ corresponds to the mean coverage (with "i" being the number of photoquadrats) and $\overline{x}_{16}$ corresponds to the mean cover, computed with the maximum number of 16 photoquadrats per cave. For the calculation of $\bar{x}_i$, quadrats were randomly collected from vertical cave walls (left and right), since this factor could act as a source of variation (Sempere-Valverde et al., 2019). The accMD shows the variability in percent coverage obtained when using different number of quadrats per cave. Thus, when more quadrats are used, less variability is expected. Selection of the optimal number of photoquadrats would be indicated by a stabilisation in the accMD, as it should happen as well for each points density and the MDC.

Once the preferred methodology was assessed, the biotic coverage of the three morphofunctional groups was calculated. The typical sessile community that can be found on marine cave walls of the Alboran Sea host multiple taxa including sponges, anthozoans, polychaetes, molluscs, brachiopods, bryozoans and ascidians (Table 1). Consequently, any deviation from the proposed methodology would imply a variation in the CI of this component. Evaluating photoquadrats collected outside the proposed range (e.g., the cave entrance), not randomly collected, or with low quality photos would lower the CI from 4 to 3. Using a lower density of points or using less quadrats along the cave than proposed would lower the CI to 2, and a visual in situ estimation of cover data would result in a CI of 1, since expert statement should imply the lowest CI (Rastorgueff et al., 2015).

3. Results

In this study, multiple modifications of the original CavEBQI index were required to evaluate the ecological quality of marine caves in the Alboran Sea. To start with, sessile functional components PFF, LAFF and SAFF were evaluated through multiple sampling efforts (i.e. points density per quadrat and number of photoquadrats per cave) in order to find the most efficient methodology. The evaluation of densities of points used per quadrat resulted with the lowest Mean Deviation by Category (MDC) when 150 points were used. This outcome was consistent among the three morphofunctional groups, as expected. However, according to the pairwise analysis, MDC significantly decreased only from 25 to higher numbers of points (at least for LAFF and SAFF functional groups) and then stopped decreasing significantly from 50 points (Fig. 2; left). Regarding the evaluation of the optimal number of quadrats analysed per cave, accumulated Mean Deviation (accMD) started to stabilise after 10 quadrats per cave, showing little improvements when higher numbers were used (Fig. 2; right). Consequently, 10 quadrats per cave (5 from each opposite wall, when possible) analysed with 50 points per quadrat would be the minimum recommended effort for a reliable coverage assessment of sessile morphofunctional groups.

The total biotic coverage of sessile taxa ranged from 32.6 % for the "Cerro Gordo Dark" cave to 74 % for the "Gorgonias" cave, with most of the caves (17/21) presenting over 50 % of average total biotic coverage. In average, SAFF presented the highest percent coverage (33.35 %), followed by PFF (14.03 %) and PFF (8.25 %) (Fig. S1).

Regarding motile fauna, a list of 66 taxa potentially present in

Table 1
Sessile taxa commonly covering the hard substrate in marine caves of the Alboran Sea, categorised in morphofunctional groups and taxonomical groups (columns) (Ocaña et al., 2000; Sempere-Valverde et al., 2019; authors' pers. obs.). Mol.: Molusca. MFG: Morphofunctional Group, TXG: Upper Taxonomical Group.

MFG	TXG	Sessile taxa	MFG	TXG	Sessile taxa
Passive filter feeders	Cnidaria	*Parazooanthus axinellae* (Schmidt, 1862)	Small Active Filter Feeders	Porifera	*Crambe crambe* (Schmidt, 1862)
		Astroides calycularis (Pallas, 1766)			*Dysidea fragilis* (Montagu, 1814)
		Leptopsammia pruvoti Lacaze-Duthiers, 1897			*Spirastrella cunctatrix* Schmidt, 1868
		Hydrozoa		Annelida	Serpulidae
Large Active Filter Feeders	Porifera	*Petrosia (Petrosia) ficiformis* (Poiret, 1789)			*Sabella spallanzanii* (Gmelin, 1791)
		Chondrosia reniformis Nardo, 1847		Bryozoa	*Celleporina magnevillana* (Lamouroux, 1816)
		Haliclona sp.			Flustrina
		Clathrina sp.		Ascidiacea	*Didemnum* sp.
	Mol.	*Lithophaga lithophaga* (Linnaeus, 1758)			*Pycnoclavella* sp.
	Bryozoa	*Myriapora truncata* (Pallas, 1766)		Brachiopoda	*Argyrotheca* sp.
					Joania sp.
					Novocrania sp.
		Adeonella sp.			
		Cellaria fistulosa (Linnaeus, 1758)			
	Ascidiacea	*Phallusia* sp.			
		Halocynthia papillosa (Linnaeus, 1767)			

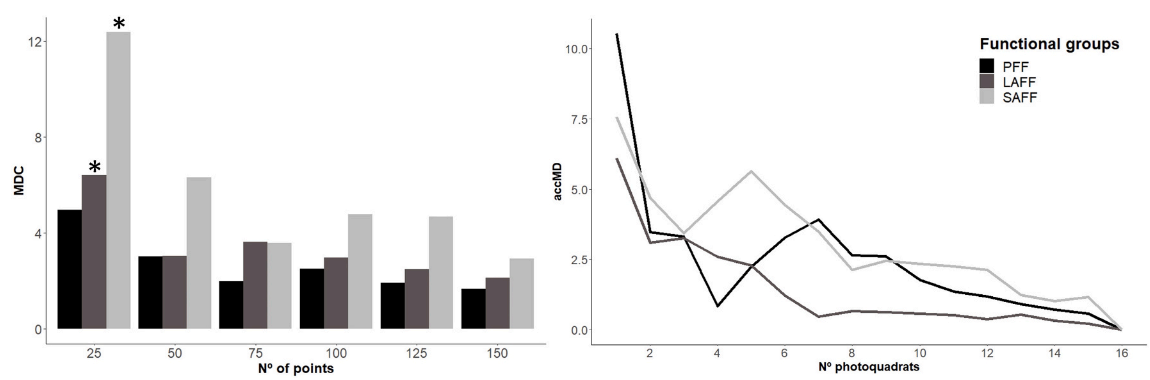


Fig. 2. Mean Deviation by Category (MDC) among quadrats analysed with different number of points for each morphofunctional group (left) and the accumulated Mean Deviation (accMD) for the different number of quadrats analysed per cave (right). *: Pairwise comparisons that were significantly different to the following category (p threshold <0.05). PFF: Passive Filter Feeders; LAFF: Large Active Filter Feeders; SAFF: Small Active Filter Feeders.

marine caves of the Alboran Sea is provided, along with the number of the herein studied caves where the species were recorded. In total, 59 motile species were recorded within the visual census conducted for this study (some species are rare and don't always appear in the visual census surveys), with species richness recorded in each cave ranging from 2 to 26 taxa (Fig. S1). Some of the most frequently recorded taxa were the cardinal fish *Apogon imberbis*, the European *conger Conger conger*, the shrimps *Stenopus spinosus*, *Palaemon serratus* and those of the genus *Lysmata*, echinoderms of the genus *Holoturia*, sea urchins and ophiuroids (Table 2).

When assessed with the adapted version of the index ten caves had a good status (6 < CavEBQI <8), eleven caves had a moderate status (4 < CavEBQI <6), and only "Karim" cave showed poor ecological quality (2 < CavEBQI <4). The ecological quality estimated with the original CavEBQI is generally lower for most of the caves (e.g. only five caves with good status) and the difference between the minimum and maximum quality (range) is also smaller (Table 3). Regarding the Confidence Index, nine caves presented a high confidence level (CI > 8), while ten caves were assessed with good confidence (6 < CI < 8), "Karim" cave showed moderate confidence (4 < CI < 6) and "Túnel Naranja" cave showed a poor confidence (2 < CI < 4) (Fig. 3).

4. Discussion

4.1. Considerations on the adapted CavEBQI

The implementation of ecosystem-based quality indices comes with important advantages such as the use of non-destructive methodologies, the collection of simplified data on ecosystem functioning and the limited required taxonomical skills. Despite the challenges concerning biogeographical heterogeneity, image analysis and post-processing (Giakoumi et al., 2013; Navarro-Barranco et al., 2023), using ecosystem-based approaches is essential for monitoring ecosystems (Personnic et al., 2014; Rastorgueff et al., 2015; Thibaut et al., 2017).

In this study, multiple methodological aspects were evaluated and adjusted in order to standardise and facilitate the use of the CavEBQI for the assessment of the ecological quality of marine caves in the Alboran Sea (Table 4). The suggested methodology is time effective, considering that all necessary data can be collected in a single dive by divers with basic taxonomic expertise.

The calculation of the CI provides the possibility of evaluating the cave's ecological status with poor or low-quality data, since the index allows a certain degree of flexibility (Table 5). In this sense, monitoring CI along with the ecological status is indeed relevant, since the application of significant changes in the methodology might alter the results on the ecological status and increase unreliability of such data. For this reason, it is highly recommended to apply the index only when CI is 2 or

Table 2
Commonly observed motile taxa used for visual census in marine caves of the Alboran Sea. FG: Functional Group, TXG: Upper taxonomical category, n: number of caves in which the taxa were present, Ech: Echinoderms, P: Platyhelminthes, C: Cnidarians.

FG	TXG	Taxa name	n
Detritus Feeders / Omnivores	Decapoda	*Dardanus arrosor* (Herbst, 1796)	2
		Dardanus calidus (Risso, 1827)	5
		Dardanus sp.	4
		Dromia personata (Linnaeus, 1758)	3
		Galathea strigosa (Linnaeus 1761)	5
		Herbstia condyliata (Fabricius, 1787)	7
		Percnon gibbesi (H. Milne Edwards, 1853)	2
		Scyllarus arctus (Linnaeus, 1758)	1
	Echinodermata	*Arbacia lixula* (Linnaeus, 1758)	8
		Centrostephanus longispinus (Philippi, 1845)	0
		Holothuria sanctori Delle Chiaje, 1823	11
		Holothuria tubulosa Gmelin, 1791	9
		Holothuria sp.	3
		Ophioderma longicauda (Bruzelius, 1805)	9
		Ophiuroidea	1
		Paracentrotus lividus (Lamarck, 1816)	10
		Psammechinus sp.	1
		Annelida (e.g. *Hermodice carunculata* (Pallas, 1766)	0
Characteristic carnivores	Pisces	*Apogon imberbis* (Linnaeus, 1758)	18
		Conger conger (Linnaeus, 1758)	8
		Gaidropsarus mediterraneus (Linnaeus, 1758)	0
		Grammonus ater (Risso, 1810)	0
		Phycis phycis (Linnaeus, 1766)	3
		Sciaena umbra Linnaeus, 1758	4
		Scorpaena notata Rafinesque, 1810 / S. *maderensis* Valenciennes, 1833	6
		Thorogobius ephippiatus (Lowe, 1839)	4
		Corcyrogobius liechtensteini (Kolombatovic, 1891) / *Didogobius splechtnai* Ahnelt & Patzner, 1995 / *Gammogobius steinitzi* Bath, 1971	2
	Decapoda	*Brachycarpus biunguiculatus* (Lucas, 1846)	4
		Lysmata nilita Dohrn & Holthuis, 1950 /*seticaudata* (Risso, 1816)	8
		Palaemon serratus (Pennant, 1777)	7
		Plesionika narval (Fabricius, 1787)	3
		Scyllarides latus (Latreille, 1803)	3
		Stenopus spinosus Risso, 1827	8
	Mollusca	*Luria lurida* (Linnaeus, 1758)	4
		Peltodoris sp.	3
Associate carnivores	Pisces	*Anthias anthias* (Linnaeus, 1758)	4
		Boops boops (Linnaeus, 1758)	1
		Chromis chromis (Linnaeus, 1758)	8
		Coris julis (Linnaeus, 1758)	5
		Diplodus sargus (Linnaeus, 1758)	2
		Diplodus vulgaris (Geoffroy Saint-Hilaire, 1817)	6
		Epinephelus marginatus (Lowe, 1834)	7
		Mullus surmuletus Linnaeus, 1758	5
		Muraena helenna Linnaeus, 1758	4
		Oblada melanura (Linnaeus, 1758)	3
		Gobius auratus Risso 1810 / *Gobius bucchichi* Steindachner, 1870	5
		Parablennius sp.	6
		Scorpaena scrofa Linnaeus, 1758 / *S. porcus* Linnaeus, 1758	2
		Serranus cabrilla (Linnaeus, 1758)	7
		Serranus scriba (Linnaeus, 1758)	5
		Serranus sp.	1
		Thalassoma pavo (Linnaeus, 1758)	0
		Torpedo marmorata Risso, 1810	2
		Tripterygion tripteronotum (Risso, 1810)	6
	Decapoda	*Homarus gammarus* (Linnaeus, 1758)	0
		Maja squinado (Herbst, 1788)	2
		Palinurus elephas (Fabricius, 1787)	0
	Ech.	*Marthasterias glacialis* (Linnaeus, 1758)	5
		Ophidiaster ophidianus (Lamarck, 1816)	8
	Mollusca	Mitridae	2
		Muricopsis cristata (Brocchi , 1814)	3
		Naria spurca (Linnaeus, 1758)	1
		Nudibranchia	4
		Stramonita haemastoma (Linnaeus, 1767)	4
	P	Platyhelmintes	1
	C	*Cerianthus membranaceus* (Gmelin, 1791)	2

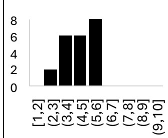
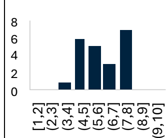
higher for long-term monitoring purposes. Data sampled in the past, expert statement and semiquantitative estimation of coverage are suggested to be avoided.

The assessment of percent coverage of sessile morphofunctional groups was optimized with the analysis of multiple quadrats through the PhotoQuad image analysis software. When 50 points were randomly overlayed in each of 10 quadrats (5 from each opposite wall, when possible) collected from each cave, dispersion levels (MDC and accMC of sessile functional groups) of coverage measurements were acceptably low. Lack of differences when higher sampling effort was applied (>50 points in >10 quadrats), indicated that this methodology provided a representative estimation of the coverage of different morphofunctional groups in the studied caves.

4.2. Ecological assessment of marine caves of the Alboran Sea

The adapted CavEBQI has represented the ecological status of different marine caves with acceptable reliability, since the sampled

Table 3
Ecological quality of the twenty-one marine caves of the Alboran Sea calculated with the original version of CavEBQI (Rastorgueff et al., 2015) and the herein adapted version of CavEBQI. Cerro Gordo SD and D corresponds to the semidark (9a) and dark (9b) chamber of the same cave respectively.

		CavEBQI (2015)	**CavEBQI** (Alboran)
Range (min - max)		2.71 - 5.54	3.54 - 7.93
Histogram			
El Boquete	1	5.22	7.50
Karim	2	2.71	3.54
Lobo Marino	3	3.70	5.22
Tercera	4	5.54	5.65
Gorgonias	5	5.54	7.93
Cantarriján	6	5.54	7.83
Palomas	7	5.00	7.07
Los Ladrones	8	3.91	5.11
Cerro Gordo SD	9a	5.11	7.72
Cerro Gordo D	9b	5.11	5.76
Los Gigantes	10	3.48	5.00
El Jarro	11	5.43	7.17
Palomas Calah.	12	5.43	6.74
La Grieta	13	4.13	6.74
Bombas	14	4.02	6.41
El Pedregal	15	3.75	4.34
Lobo Marino Chaf.	16	3.75	4.74
Tajo del Pirata	17	4.17	4.34
Túnel Naranja	18	4.17	7.92
El Francés Grieta	19	4.13	5.87
Cueva del Frío	20	2.83	4.67
El Templo	21	3.80	5.00

caves ranged from “good” to “poor”, falling into multiple outcomes, and following a Gaussian distribution. The ecological quality for most of the assessed caves (21 of the 22 caves studied, considering that Cerro Gordo has two sections) ranged between “moderate” and “good”. The range of values obtained through the adapted index is wider than the original, which indicates it is more sensitive to natural variations within the components. For example, Gorgonias, Cantarrijan and Palomas caves, all of them hosting high coverage sessile morphofunctional groups, never reach as good an ecological status with the original index than they do with the adapted one. This ensures the index gives accurate information about those caves with remarkable positive and negative ecological features. Although the index has been well adapted to the conditions of the Alboran Sea, there may be differences in reliability between caves with high and low CI.

Marine cave communities can have a strong degree of individuality even when they are proximate (Bussotti et al., 2006; Digenis et al., 2022) and exhibit similar environmental gradients (Martí et al., 2004; Gerovasileiou and Bianchi, 2021). Geomorphological factors (e.g., total length and width, number of entrances, cave entrance size) usually account for this spatial heterogeneity (Radolovic et al., 2015; Gerovasileiou et al., 2017; Digenis et al., 2022). Similar differences were observed when three closely located caves with the same depth (Cantarriján, Gorgonias and Tercera) were compared. The Tercera cave (CavEBQI = 5.65) is quite smaller in size and with an evident input of freshwater from its rear end (Digenis et al., 2024), which may cause some impoverishment in most sessile communities (Harmelin et al., 1985; Radolović et al., 2015). On the other hand, the Gorgonias cave (CavEBQI = 7,93) constitutes a small semi-submerged canyon-shaped cave, favouring the water flow and thus inducing suitable conditions for the growth of gorgonians (*Eunicella labiata*, *Eunicella verrucosa*, *Leptogorgia sarmentosa*) and erect bryozoans (*Myriapora truncata* and *Margaretta* sp.) (Harmelin et al., 1985; Morri and Bianchi, 2003), contributing to its good ecological status (the highest of all studied caves). The Cantarriján cave (CavEBQI = 7.83) has a small entrance, which may cause the rapid depletion of nutrients and large sessile taxa (Gerovasileiou et al., 2017) and thus resulting a higher coverage of SAFF. In this case, other stochastic factors such as the shape of the inner chambers, orientation towards coastal currents and wave exposure might be defining its diverse and rich biocoenosis. In this regard, it is important to note the fact that a moderate-good CavEBQI ecological status can be achieved in caves dominated by either large passive or active filter feeders (e.g., Los Gigantes cave), small filter feeders or even in those presenting a remarkable richness of motile taxa (e.g., El Templo), which reflects natural variations in cave ecosystems' quality.

This study compares for the first-time the ecological status of different zones of the same cave. The natural gradients and morphology of Cerro Gordo cave produce two differentiated communities, one in the semidark zone (SD) which is dominated by massive sponges and scleractinian corals, and one in the dark zone (D) which is dominated by encrusting sponges, brachiopods and serpulids (Harmelin et al., 1985; Gerovasileiou and Bianchi, 2021). This could be mainly caused by its length (>100 m) and the existence of a narrow passage which separates its two chambers (Navarro-Barranco et al., 2012; Sempere-Valverde et al., 2019) escalating the oligotrophic conditions in the inner darker section (Harmelin et al., 1985; Zabala et al., 1989). As expected, differences between the SD and D communities of Cerro Gordo cave leaded to a higher ecological status at SD (CavEBQI = 7.72) than D (CavEBQI = 5.76). This noticeable transition has also been quantitively exhibited in other Mediterranean caves such as Jarre cave in France (Rastorgueff et al., 2015) and Fara cave in Greece (Gerovasileiou and Voultsiadou, 2016; Gerovasileiou et al., 2017). Cave entrances have not been assessed in Alboran Sea caves, since the area included strictly as “entrance” was too small to be representative and their sessile community was mainly comminated by photosynthetic organisms such as Rhodophyta and other algae. Nonetheless, in other Mediterranean regions cave entrances are indeed a representative habitat, therefore it would be interesting to incorporate them to the adapted index and evaluate their ecological status along time (Pérès and Picard, 1964; Harmelin et al., 1985; Digenis et al., 2022).

Although sessile biotic coverage is expected to differ between the Alboran Sea and other Mediterranean regions due to its high productivity and diversity (Cebrián and Ballesteros, 2004; Real et al., 2021), values here reported are similar to those obtained in previous studies conducted in other marine caves of Italy and Greece. In order to achieve comparable monitoring of the sessile components of CavEBQI between different biogeographical regions, it is suggested to use consistent methodologies and report coverage data for each ecological cave zone. One example on how community structure varies between regions, is the dominance of massive sponges dominating the semidark communities of the Aegean Sea caves (East Mediterranean), while in the Alboran Sea caves, coverage is mainly determined by encrusting active filter-feeders (SAFF) and cnidarians (PFF) (Sempere-Valverde et al., 2019 Digenis et al., 2022; this study). These biogeographical differences are also reflected in motile organisms, which also show a different chorological behaviour towards dark environments (Bianchi et al., 2022). For example, the swallowtail seaperch (*Anthias anthias*) is considered to mostly inhabit marine caves or circalittoral bottoms in some Mediterranean regions (Bussotti et al., 2015; Digenis et al., 2022; Kovačić et al., 2024) while its occurrence in shallow waters of the Alboran Sea is not limited to dark environments (Peña and Sánchez Tocino, 2013). This highlights the importance of understanding the biogeographical patterns of habitats and adapting ecological indicators to the necessities of

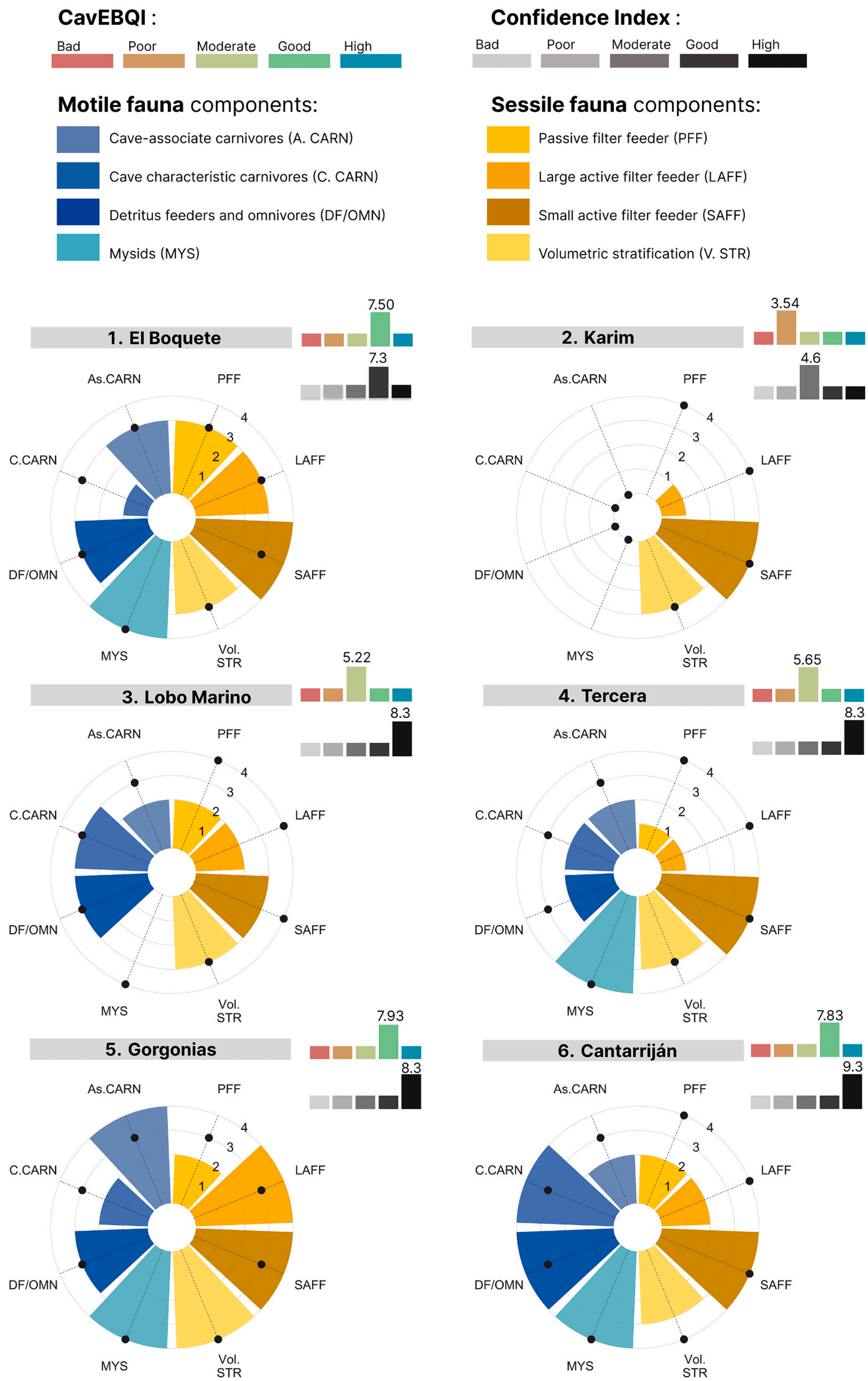


Fig. 3. Ecosystem-based ecological quality assessment of the 21 studied caves of the Alboran Sea. Each chart corresponds to a different cave with the ecological status (bars) and the Confidence Index (points) for the components: PFF: Passive Filter Feeders; LAFF: Large Active Filter Feeders; SAFF: Small Active Filter Feeders; V.STR: Volumetric Stratification; MYS: Mysids; DF/OMN: Detritus Feeders /Omnivores; C.CARN: Characteristic Carnivores; A.CARN: Associated Carnivores. The Cave Ecosystem-Based Quality Index (EBQI) and its corresponding Confidence Index (CI) are shown at the top right of each chart. The Cerro Gordo cave was assessed independently for its semidark (9a) and its dark zone (9b).

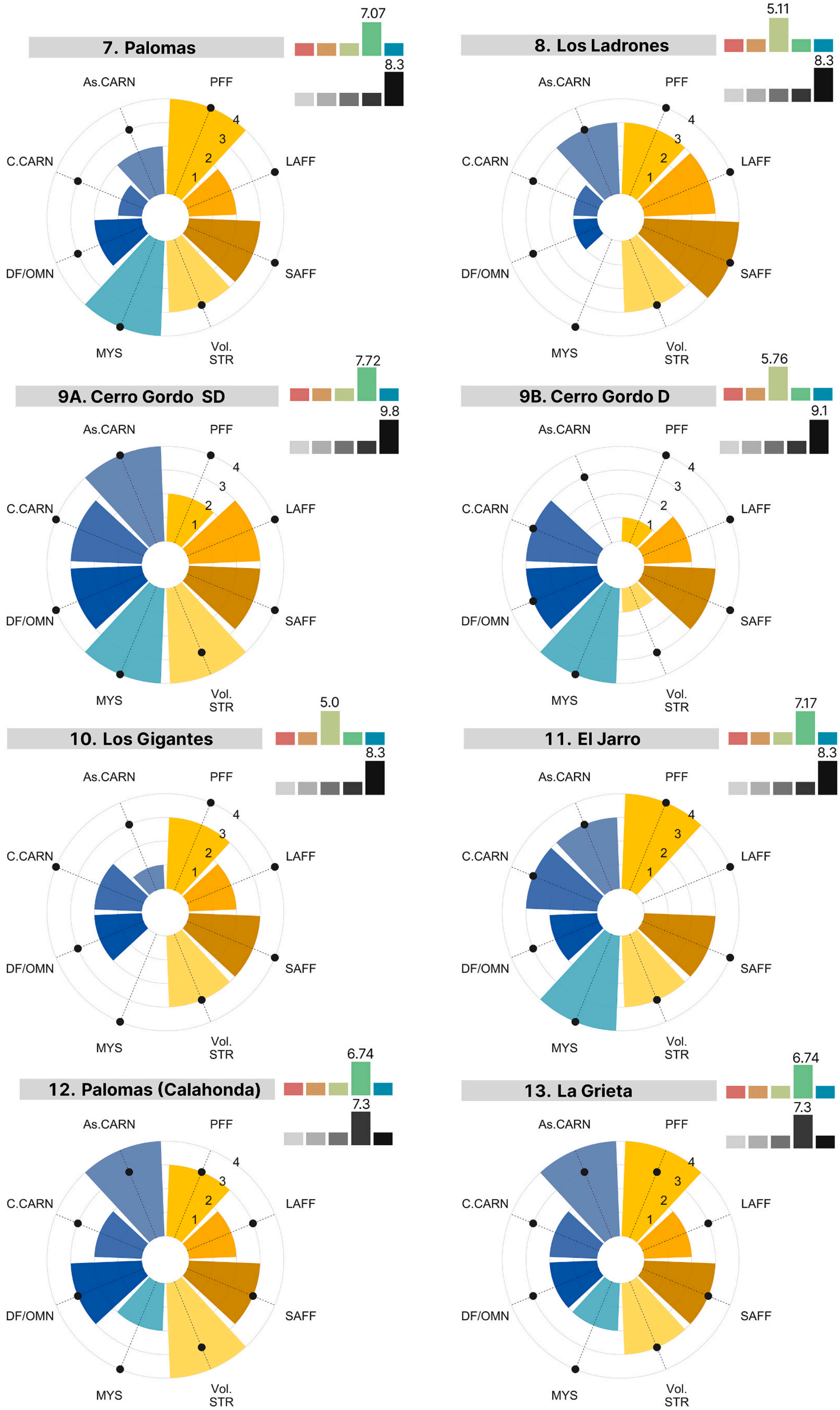


Fig. 3. (*continued*).

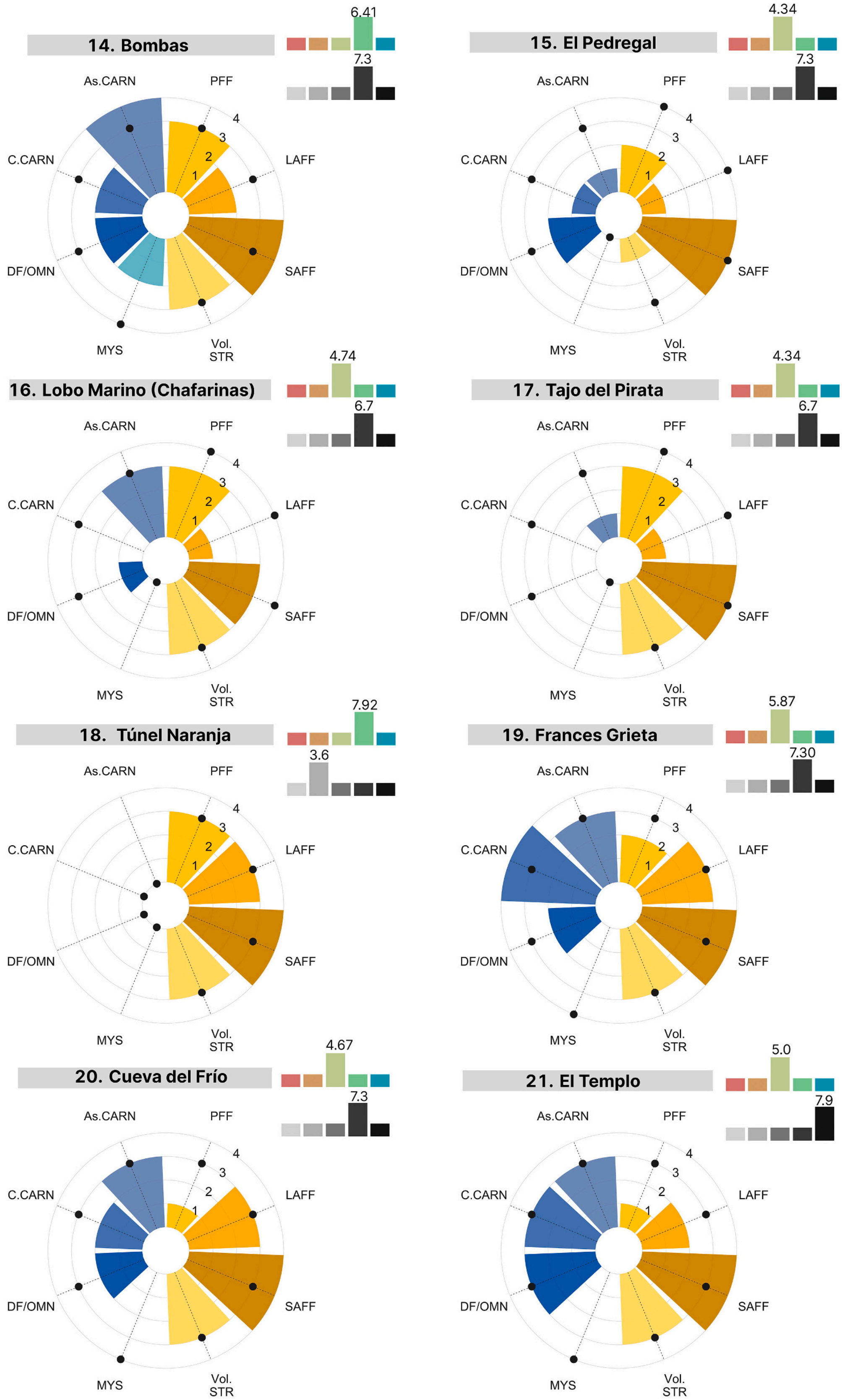


Fig. 3. (*continued*).

each region. Otherwise, comparing ecological quality at a geographical scale using the same methodology could lead to the false conclusion that habitats in certain regions (for example, those with less productive ecosystems or affected by other natural environmental gradients) have a lower ecological status when it is not the case.

It should be noted that the values here obtained do not determine the

Table 4
Weight, parameter units and criteria used to assess the status of CavEBQI components in the marine caves of the Alboran Sea.

Component			Status				
Name	Weight	Unit	0	1	2	3	4
1. Passive Filter Feeders (PFF)	5	Biotic cover (%)	0	0–3 %	≥3–10 %	≥10–30 %	≥30 %
2. Large Active Filter Feeders (LAFF)	3						
3. Small Active Filter Feeders (SAFF)	2						
4. Volumetric Stratification (V. STR)	2	Size scale of sessile taxa	0	< 1 cm		1–10 cm	> 10 cm
5. Cave-dwelling mysids (MYS)	4	Semi-quantitative abundance	0		Few		Swarm
6. Detritus feeders/omnivores (DF/OMN)	3	Species richness	0	1	2–5	6–8	>8
		Abundance	0	1–4	5–9	10–15	>15
7. Characteristic carnivores (C. CARN)	3	Species richness	0	1–3	4–6	7–8	>8
		Abundance	0	1–9	10–29	30–80	>80
8. Associate carnivores (A. CARN)	1	Species richness	0	1–2	3–4	5–6	>6
		Abundance	0	1–9	10–29	30–80	>80

Table 5
Suggested data collection and methodology for all CavEBQI components and alternatives that imply CI lowering.

Component	Methodology		Confidence Index (CI)				
	Data Collection through Scuba Diving	Parameter Estimation	0	1	2	3	4
Passive Filter Feeders Large Active Filter Feeders Small Active Filter Feeders	Photos of 25x25cm quadrats randomly placed over the opposite walls of the semidark and dark cave zones.	Mean biotic coverage (%) of 10 quadrats using 50 randomly placed points per quadrat	Not assessed	Expert semi-quantitative estimation of coverage	Lower density of points/Less quadrats than suggested	Lack of methodological aspect - not randomly taken/out of recommended area/ lower quality pictures	Suggested method
Volumetric Stratification	Measuring the stratification at 10 random stations perpendicularly to the cave walls	Average of 10 measurements of volumetric stratification	Not assessed		Semiquantitative estimation, expert statement or other methods	Estimation through quadrats	Suggested method
Cave-dwelling mysids	20–25 min visual census (not at the cave entrance)	Semiquantitative assessment: absence, few or swarm	Not assessed	Non recent expert statement		Recent expert statement	Suggested method
Detritus feeders/ omnivores Characteristic carnivores Associate carnivores	20–25 min visual census for targeted species of the cave (not at the entrance)	Calculation of species richness and abundance	Not assessed	Non recent expert statement	Recent expert statement	Lack of methodological aspect (season, duration, area of the cave)	Suggested method

conservation status of the caves, which should be only determined by a detailed assessment and temporal monitoring of their communities. Low ecological quality values could be found even in caves in pristine condition due to their natural environmental conditions. For example, sometimes the presence of freshwater springs in marine caves might result in impoverished communities (Radolović et al., 2015) and therefore lower the status with the updated CavEBQI. However, sometimes there might be a relationship between the conservational status and the CavEBQI. For example, a poor ecological status was found only for the Karim cave (although with a low CI), a cave located in a non-protected area of intense diving activity (Sempere-Valverde et al., 2021; per. Obs.). Meanwhile, Cantarriján and Gorgonias cave (included in a protected area) have showed good and high ecological status. Thus, lower pressures and threats (e.g., diving visit frequency, fishing activities) as a result of management and protection actions might be related with a better ecological status of these caves.

4.3. Threats and temporal approach for monitoring strategies

Taxonomical and morphological changes in marine cave communities have been related to multiple threats and pressures, mainly marine heatwaves (Parravicini et al., 2010; Rastorgueff et al., 2015; Sempere-Valverde et al., 2019; Montefalcone et al., 2023) and damage by physical contact (Sala et al., 1996; Guarnieri et al., 2012). In this respect, massive/erect sponges and corals are more affected than encrusting taxa (Gerovasileiou et al., 2018; Garrabou et al., 2022). Additionally, the invasive behaviour of the non-indigenous species such as the brown alga *Rugulopteryx okamurae* is a major threat for many marine ecosystems of the area, even for some sciaphilic habitats (García-Gómez et al., 2021; Sempere-Valverde et al., 2021; Florido et al., 2023). Given the example of two well characterised caves with good ecological status and confidence index (Cantarriján and Cerro Gordo SD), a potential effect of repeated strong heatwaves might reduce coverage of SAFF by a 9 %, LAFF by a 10 % and PFF by a 5 % approximately inside the main chambers of marine caves (Montefalcone et al., 2023). After those hypothetical events happening in the Alboran Sea (and assuming it would only affect sessile fauna), the ecological status of Cantarriján and Cerro Gordo SD would decrease from 7.83 to 6.63 and from 7.72 to 7.39 with the adapted index respectively, however, it would decrease from 5.54 to 5.22 and from 5.11 to 4.89 with the original index respectively. Despite having a greater sensibility to changes, long-term studies are needed in order to assess the suitability of the CavEBQI as an indicator of community responses against natural and anthropogenic disturbances. In this sense, the lack of long-time data series of sessile and motile communities also hinders the evaluation of past changes and impacts. Therefore, the ecological assessments conducted in this study constitute a relevant baseline for future long-term monitoring strategies in the Alboran Sea.

4.4. Recommendations for the use of the CavEBQI

Spatially heterogeneous and remote habitats such as marine caves are especially challenging to study and monitor (Navarro-Barranco et al., 2023). When using ecological indicators, their evaluation can easily lead to different outcomes depending on various stochastic factors. As previously stated, differences in cave-dwelling communities might be determined by human-induced impacts, but also caused by natural factors (e.g., freshwater input) (Giakoumi et al., 2013; Digenis et al., 2022). Consequently, when comparing the ecological status of different caves, several parameters need to be considered before drawing conclusions. In this sense, stakeholders are encouraged to use CavEBQI values for monitoring surveys individually for every cave and not for the comparison of caves, taking as well into account the potential biogeographical heterogeneity.

Studies on monitoring the ecological quality of marine ecosystems in the Alboran Sea are scarce (Cebrián and Ballesteros, 2004; Marina et al., 2015; Navarro-Barranco et al., 2022). Developing an optimal management strategy would require embracing studies across ecosystems through an integrative approach and a high-resolution knowledge of its biodiversity (Rowell et al., 2022). This is essential for marine caves and other strongly interconnected habitats since they rely on allochthonous resources (Harmelin et al., 1985; Rastorgueff et al., 2011, 2015; Bussotti et al., 2018). Additionally, monitoring these habitats located within Marine Protected Areas could show the performance of the environmental protection offered by the management bodies of the Natura 2000 network in surrounding habitats.

5. Conclusions

This study highlights the importance of assessing the ecological quality of marine caves of the Alboran Sea. The adapted CavEBQI provides a reliable, standardised and time-efficient methodology (mainly regarding biotic cover assessment and visual census) that improves marine cave monitoring strategies. Twenty-one marine caves have been assessed with this index, delivering mostly positive results in terms of biotic coverage, species richness and ecological quality while providing a good insight into this habitat functioning and indicating the high spatial heterogeneity between the different caves and also the ecological zones within each cave. Additionally, this study serves as a baseline for future monitoring strategies in the Alboran Sea and offers the potential to adapt methodologies of ecological indicators to other Mediterranean regions.

CRediT authorship contribution statement

Pablo Lanza-Arroyo: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Juan Sempere-Valverde:** Writing – review & editing, Methodology, Data curation, Conceptualization. **Markos Digenis:** Writing – review & editing, Data curation. **José Miguel Remón:** Writing – review & editing, Data curation. **Diego Moreno:** Writing – review & editing, Data curation. **Agustín Barrajón:** Writing – review & editing, Data curation. **Antonio de la Linde:** Writing – review & editing, Data curation. **Maria del Carmen Arroyo:** Writing – review & editing, Data curation. **Manuel Fernández-Casado:** Writing – review & editing, Data curation. **Eugenio Mallofret:** Writing – review & editing, Data curation. **Luis Sánchez-Tocino:** Data curation. **Vasilis Gerovasileiou:** Writing – review & editing, Conceptualization. **Carlos Navarro-Barranco:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.marpolbul.2024.117065.

References

Bermejo, R., de la Fuente, G., Vergara, J.J., Hernández, I., 2013. Application of the CARLIT index along a biogeographical gradient in the Alboran Sea (European Coast). Mar. Pollut. Bull. 72 (1), 107–118. https://doi.org/10.1016/j.marpolbul.2013.04.011.

Bermejo, R., Ramírez-Romero, E., Vergara, J.J., Hernández, I., 2015. Spatial patterns of macrophyte composition and landscape along the rocky shores of the Mediterranean-Atlantic transition region (northern Alboran Sea). Estuar. Coast. Shelf Sci. 155, 17–28. https://doi.org/10.1016/j.ecss.2015.01.009.

Bevilacqua, S., Katsanevakis, S., Micheli, F., Sala, E., Rilov, G., Sarà, G., Malak, D.A., Abdulla, A., Gerovasileiou, V., Gissi, E., Mazaris, A.D., Pipitone, C., Sini, M., Stelzenmüller, V., Terlizzi, A., Todorova, V., Fraschetti, S., 2020. The status of coastal benthic ecosystems in the Mediterranean Sea: evidence from ecological indicators. Front. Mar. Sci. 7 (June). https://doi.org/10.3389/fmars.2020.00475.

Bianchi, C.N., Gerovasileiou, V., Morri, C., Froglia, C., 2022. Distribution and ecology of decapod crustaceans in Mediterranean marine caves: a review. Diversity 14 (3). https://doi.org/10.3390/d14030176.

Boudouresque, C.F., Astruch, P., Bănaru, D., Blanfuné, A., Belloni, B., Changeux, T., Chevaldonné, P., Fernandez, C., Harmelin, H.J., Perez, T., 2020. Ecosystem-based quality indices: valuable tools for environment management. Vie Milieu – Life Environ. 70 (3–4), 2–15.

Bussotti, S., Terlizzi, A., Fraschetti, S., Belmonte, G., Boero, F., 2006. Spatial and temporal variability of sessile benthos in shallow Mediterranean marine caves. Mar. Ecol. Prog. Ser. 325 (May 2014), 109–119. https://doi.org/10.3354/meps325109.

Bussotti, S., Di Franco, A., Francour, P., Guidetti, P., 2015. Fish assemblages of mediterranean marine caves. PLoS One 10 (4), 1–16. https://doi.org/10.1371/journal.pone.0122632.

Bussotti, S., Di Franco, A., Bianchi, C.N., Chevaldonné, P., Egea, L., Fanelli, E., Lejeusne, C., Musco, L., Navarro-Barranco, C., Pey, A., Planes, S., Vieux-Ingrassia, J. V., Guidetti, P., 2018. Fish mitigate trophic depletion in marine cave ecosystems. Sci. Rep. 8 (1), 9193.

Cebrián, E., Ballesteros, E., 2004. Zonation patterns of benthic communities in an upwelling area from the western Mediterranean (La Herradura, Alboran Sea). Sci. Mar. 68 (1), 69–84. https://doi.org/10.3989/scimar.2004.68n169.

Di Franco, A., Milazzo, M., Baiata, P., Tomasello, A., Chemello, R., 2009. Scuba diver behaviour and its effects on the biota of a Mediterranean marine protected area. Environ. Conserv. 36, 32–40. https://doi.org/10.1007/s10531-008-9461-x.

Digenis, M., Arvanitidis, C., Dailianis, T., Gerovasileiou, V., 2022. Comparative study of marine cave communities in a protected area of the South-Eastern Aegean Sea, Greece. Journal of Marine Science and Engineering 10 (5), 660. https://doi.org/10.3390/jmse10050660.

Digenis, M., Akyol, O., Benoit, L., Biel-Cabanelas, Gerovasileiou, V., 2024. New records of rarely reported species in the Mediterranean Sea (March 2024). Mediterr. Mar. Sci. 25 (1), 84–115. https://doi.org/10.12681/mms.37214.

Dimarchopoulou, D., Gerovasileiou, V., Voultsiadou, E., 2018. Spatial variability of sessile benthos in a semi-submerged marine cave of a remote Aegean Island (eastern Mediterranean Sea). Reg. Stud. Mar. Sci. 17, 102–111. https://doi.org/10.1016/j.rsma.2017.11.015.

Fichez, R., 1991. Suspended particulate organic matter in a Mediterranean submarine cave. Mar. Biol. 108, 167–174.

Florido, M., Megina, C., García-Gómez, J.C., 2023. Coexistiendo con una invasora en el estrecho de Gibraltar: la integración de *Rugulopteryx okamurae* en la fauna y flora residente. Almoraima 58, 233–248.

García Muñoz, J.E., Manjón-Cabeza, M.E., García Raso, J.E., 2008. Decapod crustacean assemblages from littoral bottoms of the Alborán Sea (Spain, west Mediterranean Sea): spatial and temporal variability. Sci. Mar. 72 (3), 437–449.

García-Gómez, J.C., Florido, M., Olaya-Ponzone, L., Rey Díaz de Rada, J., Donázar-Aramendía, I., Chacón, M., Quintero, J.J., Magariño, S., Megina, C., 2021. Monitoring extreme impacts of *Rugulopteryx okamurae* (Dictyotales, Ochrophyta) in El Estrecho Natural Park (Biosphere Reserve). Showing radical changes in the underwater seascape. Front. Ecol. Evol. 9 (April). https://doi.org/10.3389/fevo.2021.639161.

Garrabou, J., Gómez-Gras, D., Medrano, A., Cerrano, C., Ponti, M., Schlegel, R., Bensoussan, N., Turicchia, E., Sini, M., Gerovasileiou, V., Teixido, N., Mirasole, A., Tamburello, L., Cebrián, E., Rilov, G., Ledoux, J.B., Ben Souissi, J., Khamassi, F., Ghanem, R., Benabdi, M., Grimes, S., Ocaña, O., Bazairi, H., Hereu, B., Linares, C., Kersting, D.K., Rovira, G., Ortega, J., Casals, D., Pagès-Escolà, M., Margarit, N., Capdevila, P., Verdura, J., Ramos, A., Izquierdo, A., Barbera, C., Rubio-Portillo, E., Anton, I., López-Sendino, P., Díaz, D., Vázquez-Luis, M., Duarte, C., Marbà, N., Aspillaga, E., Espinosa, F., Grech, D., Guala, I., Azzurro, E., Farina, S., Gambi, M.C., Chimienti, G., Montefalcone, M., Azzola, A., Pulido Mantas, T., Fraschetti, S., Ceccherelli, G., Kipson, S., Bakran-Petricioli, T., Petricioli, D., Jimenez, C., Katsanevakis, S., Tuney Kizilkaya, I., Kizilkaya, Z., Sartoretto, S., Rouanet, E., Ruitton, S., Comeau, S., Gattuso, J.P., Harmelin, J.G., 2022. Marine heatwaves drive recurrent mass mortalities in the Mediterranean Sea. Glob. Chang. Biol. 28, 5708–5725.

Gerovasileiou, V., Bianchi, C.N., 2021. Mediterranean marine caves: a synthesis of current knowledge. Oceanogr. Mar. Biol. Annu. Rev. 59, 1–88.

Gerovasileiou, V., Voultsiadou, E., 2012. Marine caves of the mediterranean sea: a sponge biodiversity reservoir within a biodiversity hotspot. PLoS One 7 (7), 1–17. https://doi.org/10.1371/journal.pone.0039873.

Gerovasileiou, V., Voultsiadou, E., 2014. Mediterranean marine caves as biodiversity reservoirs: a preliminary overview. In: Bouafif, C., et al. (Eds.), Proceedings of the 1st Mediterranean Symposium on the Conservation of Dark Habitats. Regional Activity Centre for Specially Protected Areas (RAC/SPA), Tunis, pp. 45–50.

Gerovasileiou, V., Voultsiadou, E., 2016. Sponge diversity gradients in marine caves of the eastern Mediterranean. J. Mar. Biol. Assoc. U. K. 96 (2), 407–416. https://doi.org/10.1017/S0025315415000697.

Gerovasileiou, V., Chintiroglou, C., Vafidis, D., Koutsoubas, D., Sini, M., Dailianis, T., Issaris, Y., Akritopoulou, E., Dimarchopoulou, D., Voultsiadou, E., 2015. Census of biodiversity in marine caves of the Eastern Mediterranean Sea. Mediterr. Mar. Sci. 16, 245–265.

Gerovasileiou, V., Voultsiadou, E., Issaris, Y., Zenetos, A., 2016. Alien biodiversity in Mediterranean marine caves. Mar. Ecol. 37, 239–256. https://doi.org/10.1111/maec.12268.

Gerovasileiou, V., Dimitriadis, C., Arvanitidis, C., Voultsiadou, E., 2017. Taxonomic and functional surrogates of sessile benthic diversity in Mediterranean marine caves. PLoS One 12 (9), 1–20. https://doi.org/10.1371/journal.pone.0183707.

Gerovasileiou, V., Dailianis, T., Sini, M., Otero, M., Numa, C., Katsanevakis, S., Voultsiadou, E., 2018. Assessing the regional conservation status of sponges (Porifera): the case of the Aegean ecoregion. Mediterr. Mar. Sci. 19, 526–537.

Gerovasileiou, V., Bancila, R.I., Katsanevakis, S., Zenetos, A., 2022. Introduced species in Mediterranean marine caves: an increasing but neglected threat. Mediterr. Mar. Sci. 23 (4), 995–1005.

Giakoumi, S., Sini, M., Gerovasileiou, V., Mazor, T., Beher, J., Possingham, H.P., Abdulla, A., Çinar, M.E., Dendrinos, P., Gucu, A.C., Karamanlidis, A.A., Rodic, P., Panayotidis, P., Taskin, E., Jaklin, A., Voultsiadou, E., Webster, C., Zenetos, A., Katsanevakis, S., 2013. Ecoregion-based conservation planning in the Mediterranean: dealing with large-scale heterogeneity. PLoS One 8 (10). https://doi.org/10.1371/journal.pone.0076449.

Gili, J.M., Ballestero, E., 1991. Structure of cnidarian populations in Mediterranean sublittoral benthic communities as a result of adaptation to different environmental conditions. Oecologia Aquatica 10, 243–254. http://hdl.handle.net/10261/171358.

Guarnieri, G., Terlizzi, A., Bevilacqua, S., Fraschetti, S., 2012. Increasing heterogeneity of sensitive assemblages as a consequence of human impact in submarine caves. Mar. Biol. 159 (5), 1155–1164. https://doi.org/10.1007/s00227-012-1895-8.

Harmelin, J.-G., Vacelet, J., Vasseur, P., 1985. Les grottes sous-marines obscures : un milieu extrême et un remarquable biotope refuge. Acta Universitatis Agriculturae et Silviculturae Mendelianae Brunensis 53 (9), 1689–1699.

Junta de Andalucía, 2015–2023. Informes Regionales sobre Gestión Sostenible del Medio Marino. Consejería de Sostenibilidad, Medio Ambiente y Economía Azul. Junta de Andalucía. http://www.juntadeandalucia.es/medioambiente/site/portalweb/. Accessed 15 Ago 2024.

Kovačić, M., Gerovasileiou, V., Patzner, R.A., 2024. Fishes in marine caves. Fishes 9, 243.

Mačić, V., Đorđević, N., Petović, S., Malovrazić, N., Bajković, M., 2018. Typology of marine litter in 'Papuča' (slipper) cave. Studia Marina 31, 38–43.

Marina, P., Rueda, J.L., Urra, J., Salas, C., Gofas, S., García Raso, J.E., Moya, F., García, T., López-González, N., Laiz-Carrión, R., Baro, J., 2015. Sublittoral soft bottom assemblages within a marine protected area of the northern Alboran Sea. J. Mar. Biol. Assoc. U. K. 95 (5), 871–884. https://doi.org/10.1017/S0025315414002082.

Martí, R., Uriz, M.J., Ballesteros, E., Turon, X., 2004. Benthic assemblages in two Mediterranean caves: species diversity and coverage as a function of abiotic parameters and geographic distance. J. Mar. Biol. Assoc. U. K. 84 (3), 557–572. https://doi.org/10.1017/S0025315404009567h.

Montefalcone, M., De Falco, G., Nepote, E., Canessa, M., Bertolino, M., Bavestrello, G., Morri, C., Bianchi, C.N., 2018. Thirty year ecosystem trajectories in a submerged marine cave under changing pressure regime. Mar. Environ. Res. 137 (November 2017), 98–110. https://doi.org/10.1016/j.marenvres.2018.02.022.

Montefalcone, M., Ferraro, V., Barbieri, F., Morri, C., Bianchi, C.N., 2023. Ecological gradients in a marine cave revisited 26 years after. Estuar. Coast. Shelf Sci. 293 (October), 108517. https://doi.org/10.1016/j.ecss.2023.108517.

Morri, C., Bianchi, C.N., 2003. Zonazione biologica. In: Cicogna, F., et al. (Eds.), Grotte Marine: Cinquant'Anni di Ricerca in Italia. Ministero dell'Ambiente e della Tutela del Territorio, Rome, pp. 257–265.

Morri, C., Bianchi, C.N., Degl'Innocenti, F., Diviacco, G., Forti, S., Maccarone, M., Niccolai, I., Sgorbini, S., Tucci, S., 1994. Gradienti fisico-chimici e ricoprimento biologico nella Grotta Marina di Bergeggi (Mar Ligure). Memorie dell'Istituto Italiano di Speleologia serie II 6, 85–94.

Navarro-Barranco, C., 2015. Estudio faunístico y ecológico de los anfípodos en cuevas submarinas del sur de la península ibérica [Doctoral Dissertation, Universidad de Sevilla] Database. https://idus.us.es/handle/11441/33622.

Navarro-Barranco, C., Guerra-García, J.M., Sánchez-Tocino, L., García Gómez, J.L., 2012. Soft-bottom crustacean assemblages in Mediterranean marine caves: the cave of Cerro Gordo (Granada, Spain) as case study. Helgol. Mar. Res. 66 (4), 567–576. https://doi.org/10.1007/s10152-012-0292-5.

Navarro-Barranco, C., Lanza-Arroyo, P., Gutiérrez-Serrano, J., Moreira, J., 2022. Amphipod assemblages associated with native habitat-forming seaweeds of the Alboran Sea: influence by environmental protection and biogeographical patterns. Mar. Freshw. Res. https://doi.org/10.1071/MF22080.

Navarro-Barranco, C., Ambroso, S., Gerovasileiou, V., Gómez-Gras, D., Grinyó, J., Montseny, M., Santín, A., 2023. Conservation of dark habitats. Chapter 6. p. 147–170. In: Espinosa, F. (Ed.), Coastal Habitat Conservation New Perspectives and Sustainable Development of Biodiversity in the Anthropocene. Academic Press, 276 pp.

Nepote, E., Bianchi, C.N., Morri, C., Ferrari, M., Montefalcone, M., 2017. Impact of a harbour construction on the benthic community of two shallow marine caves. Mar. Pollut. Bull. 114 (1), 35–45. https://doi.org/10.1016/j.marpolbul.2016.08.006.

Ocaña, A., Sánchez Tocino, L., López-González, P.J., 2000. Consideraciones faunísticas y biogeográficas de los antozoos (Cnidaria: Anthozoa) de la costa de Granada (Mar de Alborán). Zoologica baetica 11, 51–65.

O'Higgins, T.G., DeWitt, T.H., Lago, M., 2020. Using conceptual tools of socio ecological systems and ecosystem services to advance the practice of ecosystem-based management. In: O'Higgins, T., Lago, M., DeWitt, T.H. (Eds.), Ecosystem-based Management, Ecosystem Services and Aquatic Biodiversity: Theory, Tools, and Applications. Springer, Amsterdam, pp. 3–16. https://doi.org/10.1007/978-3-030-45843-0.

Parravicini, V., Guidetti, P., Morri, C., Montefalcone, M., Donato, M., Bianchi, C., 2010. Consequences of sea water temperature anomalies on a Mediterranean submarine cave ecosystem. Estuar. Coast. Shelf Sci. 86, 276–282.

Peña, L., Sánchez Tocino, L., 2013. Peces serránidos de la Costa Tropical. Concejalía de Medio Ambiente del Ayuntamiento de Motril.

Pérès, J.M., Picard, J., 1964. Nouveau manuel de bionomie benthique de la Mer Méditerranée. Recueil des Travaux de la Station Marine d'Endoume 47, 3–137.

Pergent, G., Aguilar, R., Ballesteros, E., Bazairi, H., Bianchi, C.N., Bitar, G., Borg, J., Chevaldonné, P., Daniel, B., Gerovasileiou, V., Harmelin, J.-G., Mastrototaro, F., Ouerghi, A., Perez, T., Pergent-Martini, C., Sartoretto, S., Schembri, P., Tilot, V., Tunesi, L., Vacelet, J., 2015. Action Plan for the Conservation of Habitat and Species Associated with Seamounts, Underwater Caves and Canyons, Aphotic Hard Beds and Chemo-synthetic Phenomena in the Mediterranean Sea. Dark Habitats Action Plan. United Nations Environment Programme / Mediterranean Action Plan (UNEP/MAP) – Regional Activity Centre for Specially Protected Areas (RAC/SPA), Tunis.

Personnic, S., Boudouresque, C.F., Astruch, P., Ballesteros, E., Blouet, S., Bellan-Santini, D., Bonhomme, P., Thibault-Botha, D., Feunteun, E., Harmelin-Vivien, M., Pergent, G., Pergent-Martini, C., Pastor, J., Poggiale, J.C., Renaud, F., Thibaut, T., Ruitton, S., 2014. An ecosystem-based approach to assess the status of a mediterranean ecosystem, the *Posidonia oceanica* seagrass meadow. PLoS One 9 (6). https://doi.org/10.1371/journal.pone.0098994.

Radolović, M., Bakran-Petricioli, T., Petricioli, D., Surić, M., Perica, D., 2015. Biological response to geochemical and hydrological processes in a shallow submarine cave. Mediterr. Mar. Sci. 16, 305–324.

Rastorgueff, P.A., Harmelin-Vivien, M., Richard, P., Chevaldonné, P., 2011. Feeding strategies and resource partitioning mitigate the effects of oligotrophy for marine cave mysids. Mar. Ecol. Prog. Ser. 440, 163–176. https://doi.org/10.3354/meps09347.

Rastorgueff, P.A., Bellan-Santini, D., Bianchi, C.N., Bussotti, S., Chevaldonné, P., Guidetti, P., Harmelin, J.G., Montefalcone, M., Morri, C., Perez, T., Ruitton, S., Vacelet, J., Personnic, S., 2015. An ecosystem-based approach to evaluate the ecological quality of Mediterranean undersea caves. Ecol. Indic. 54, 137–152. https://doi.org/10.1016/j.ecolind.2015.02.014.

Real, R., Gofas, S., Altamarino, M., et al., 2021. Chapter 11: biogeographical and macroecological context of the Alboran Sea. In: Báez, J.C., Vázquez, J.T., Camiñas, J. A., Malouli, M. (Eds.), Alboran Sea - Ecosystems and Marine Resources. Springer Nature Switzerland AG, pp. 431–457. https://doi.org/10.1007/978-3-030-65516-7_11.

Remón, J.M., Moreno, D., Barrajón Domenech, A., Fernández-Casado, M., Arroyo, M.C., Mallofret, E., de la Linde, A., Carreto, T., Vivas, S., 2024. Caracterización de los Hábitats marinos en la Red Natura marina de Andalucía. PARTE I. HIC 8330 Cuevas marinas sumergidas o semisumergidas. LIFE IP INTEMARES Gestión integrada, innovadora y participativa de la Red Natura 2000 en el medio marino español. Agencia de Medio Ambiente y Agua de Andalucía/Consejería de Sostenibilidad y Medio Ambiente y Economía Azul/Junta de Andalucía, Sevilla, 61 pp.

Rodriguez, V., Bautista, B., Blanco, J.M., Figueroa, F.L., Cano, N., Ruiz, J., 1994. Hydrological structure, optical characteristics and size distribution of pigments and particles at a frontal station in the Alboran Sea. In: Rodriguez, J., Li, W.K.W. (Eds.), The Size Structure and Metabolism of the Pelagic Ecosystem, vol. 58. Scientia Marina, pp. 31–41.

Rowell, D.A., Arafeh-dalmau, N., Fuller, R.A., Possingham, H.P., 2022. Efficient small-scale marine reserve design requires high-resolution biodiversity and stakeholder data. Ocean Coast. Manag. 223, 106152. https://doi.org/10.1016/j.ocecoaman.2022.106152.

Rueda J.L., Gofas S., Aguilar, R., de la Torriente A., García Raso, J. E., Lo Iacono C., Luque, A. A., Marina, P., Mateo-Ramírez Á., Moya-Urbano E., Moreno D., Navarro-Barranco C., Salas C., Sánchez-Tocino L., Templado J. y Urra J. (2021). Benthic fauna of littoral and deep-sea habitats of the Alboran Sea a hotspot of biodiversity. En Báez J.C. et al. (Ed.). Alboran Sea - Ecosystems and Marine Resources, Chapter 9. Springer Nature Switzerland AG 285-358 pp, https://doi.org/10.1007/978-3-030-65516-7_9.

Sala, E., Garrabou, J., Zabala, M., 1996. Effects of diver frequentation on Mediterranean sublittoral populations of the bryozoan *Pentapora fascialis*. Mar. Biol. 126, 451–459.

Sarhan, T., García-Lafuente, J., Vargas, M., Vargas, J.M., Plaza, F., 2000. Upwelling mechanisms in the northwestern Alboran Sea. J. Mar. Syst. 23 (4), 317–331. https://doi.org/10.1016/S0924-7963(99)00068-8.

Sempere-Valverde, J., Lorenzo, Á.S., Espinosa, F., Gerovasileiou, V., Sánchez-Tocino, L., Navarro-Barranco, C., 2019. Taxonomic and morphological descriptors reveal high benthic temporal variability in a Mediterranean marine submerged cave over a decade. Hydrobiologia 839 (1), 177–194. https://doi.org/10.1007/s10750-019-04005-2.

Sempere-Valverde, J., Ostalé-Valriberas, E., Maestre, M., Aranda, R.G., Bazairi, H., Espinosa, F., 2021. Impacts of the non-indigenous seaweed *Rugulopteryx okamurae* on a Mediterranean coralligenous community (Strait of Gibraltar): the role of long-term monitoring. Ecol. Indic. 121, 107135. https://doi.org/10.1016/j.ecolind.2020.107135.

Terrón-Sigler, A., León-Muez, D., Peñalver-Duque, P., Torre, F.E., 2016. The effects of SCUBA diving on the endemic Mediterranean coral *Astroides calycularis*. Ocean Coast. Manag. 122, 1–8. https://doi.org/10.1016/j.ocecoaman.2016.01.002.

Thibaut, T., Blanfuné, A., Boudouresque, C.F., Personnic, S., Ruitton, R., Ballesteros, E., Bellan-Santini, D., Bianchi, C.N., Bussotti, S., Cebrián, E., Cheminée, A., Culioli, J.M., Derrien-Courtel, S., Guidetti, P., Harmelin-Vivien, M., Hereu, B., Morri, C., Poggiale, J.C., Verlaque, M., 2017. An ecosystem-based approach to assess the status of Mediterranean algae-dominated shallow rocky reefs. Mar. Pollut. Bull. 117, 311–329. https://doi.org/10.1016/j.marpolbul.2017.01.029.

Trygonis, V., Sini, M., 2012. PhotoQuad: a dedicated seabed image processing software, and a comparative error analysis of four photoquadrat methods. J. Exp. Mar. Biol. Ecol. 424–425, 99–108. https://doi.org/10.1016/j.jembe.2012.04.018.

Zabala, M., Riera, T., Gili, J.M., Barangé, M., Lobo, A., Peñuelas, J., 1989. Water flow, trophic de-pletion, and benthic macrofauna impoverishment in a submarine cave from the western Mediterranean. Mar. Ecol. 10, 271–287. https://doi.org/10.1111/j.1439-0485.1989.tb00478.x.