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RESEARCH ARTICLE

Stygofaunal inventory of marine caves in Karaburun-Ildır Special Environmental Protected Area (SEPA) (Aegean Sea, Türkiye)

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Abstract

The diversity of stygofauna harboured inside three marine caves (MCs) of Karaburun Ildır Bay Special Environmental Protected Area (KISEPA) was investigated. Overall, 59 stygofaunal taxa are reported inside the MCs with Porifera (37.29%), Chordata (20.34%) and Annelida (13.56%) being the most prevalent phyla. Ecological data extracted from online databases (WoRMS, IUCN, Sealifebase, OBIS, EASIN, EUNIS) highlighted that communities inside the MCs were made of filter feeders (64.29%) with an omnivorous diet (73.21%). The present study added 21 new stygofaunal taxa to the list of species harboured inside the MCs in Türkiye, raising the total diversity to 216 taxa. Composition of marine stygofauna in Türkiye was made of chordates (30.09%), sponges (27.31%) and cnidarians (9.26%), which includes 23 non-indigenous species and 25 species protected under international laws. Contrasting biodiversity patterns inside MCs were observed between the Aegean and Mediterranean Seas. High numbers of protected species were reported in the Central Aegean Sea, while the Mediterranean Sea was dominated by alien species. KISEPA can be considered a biodiversity hotspot for marine stygofaunal communities, confirming the role of the region as a biogeographic barrier for Aegean ecosystems conservation.

Keywords: Marine caves, stygofauna, biodiversity, inventory, SEPA

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Introduction

Marine caves (MC) are well known for harbouring assemblages typical of dark habitats and are famous for being fragile refuges, reservoirs, and hotspots for biodiversity, especially of sponges (Riedl 1966; Derrien *et al.* 2024). MCs enable the preservation of endemic species such as the red coral *Corallium rubrum* and the eastern Mediterranean subpopulation of Mediterranean monk seal *Monachus monachus,* listed as endangered in the Mediterranean Sea, according to the IUCN Red List of Threatened Species (Garrabou *et al.* 2015; Karamanlidis *et al.* 2019).

According to our most recent estimation from an unpublished review and based on open sources (Barraud *et al*. 2024), the diversity of biota inhabiting Mediterranean marine caves (MedMCs) does not exceed 2,747 species. Overall, the diversity is made of Animalia (78.52%), Chromista (11.97%), Plantae (7.64%), Bacteria (1.67%) and other small kingdoms (Fungi, Protozoa, Archaea, and other unclassified taxa). If only MCs within Türkiye's territorial waters are considered, 195 species were reported so far in the Aegean and Mediterranean Seas, which is representative of at least 7.09% of the total MedMCs diversity.

Based on previously mentioned unpublished review by Barraud *et al*. (2024), two major points can be highlighted about MCs biota in Türkiye: (i) diversity assessment efforts in MCs are still ongoing in Türkiye and (ii) marine stygobiota in both the Marmara and Black Seas remains to be investigated through multitaxa approaches although some preliminary data is already available in Topaloğlu (2019). Therefore, both regions are excluded from the present study as research efforts are still pending.

Marine Protected Areas (MPAs) are important tools to preserve marine diversity against anthropogenic threats. However, MPAs of different countries must be interconnected across the Mediterranean region to be more effective. Creating, extending and continuous monitoring on a long-term basis for these MPAs are keys to the conservation of marine wildlife, in accordance with the Kunming Montreal Global Biodiversity Framework. This framework sets the international commitment of MPAs coverage for global oceans at 30% by 2030 (Stephens 2023).

The main issues are the lack of implementation of regulations and adaptive governance. Without them, MPAs are meaningless. The generation of robust databases enables efficient management, which furthers the completion rate of AICHI Targets (Maxwell *et al.* 2020; Giakoumi *et al.* 2024). Different types of MPAs were established in Türkiye, such as Special Environmental Protected Areas (SEPAs), which were defined according to the Turkish legislation by Article 9 (d) of the Environment Law No 2872 (Öztürk *et al.* 2025).

Among the 13 SEPAs designated along Türkiye's coastline, the Karaburun Ildır Bay SEPA (KISEPA) is viewed as a biogeographic barrier, as its proximity to adjacent MPAs in the Aegean Sea (Öztürk 2009) could heavily impact the efficiency of marine ecosystems conservation (Keskin *et al.* 2023). However, not much is known about MCs' stygofaunal communities in the KISEPA.

MCs are considered as priority habitats to be protected by the EU Habitat Directive 92/83/EEC and under the "Dark Habitats Action Plan" of the Barcelona Convention (Giakoumi *et al.* 2013; UNEP-MAP 2013; UNEP-MAP-RAC/SPA 2016a, b; UNEP-SPA/RAC-MAP-OCEANA 2017). By following the recommendations of this action plan, the present study aims to investigate the diversity of stygofauna found within the underwater MCs of KISEPA. The present study aims to gauge the importance of KISEPA for MCs conservation in the Aegean Sea along Turkish coastlines.

Materials and Methods

Region of study

The Karaburun Ildır Bay was designated as a SEPA by Türkiye (decision No 823) via the Turkish Ministry of Environment, Urbanization, and Climate Change on March 15th, 2019 (Türkiye Republic Official Gazette No 30715). This recognition means that this region is officially and legally recognised for its ecological importance in Türkiye, as it was underlined in the past by Veryeri *et al.* (2003). It covers 946.56 km^2, of which 53.16% is dedicated to marine areas (Tosun *et al.* 2024). The marine habitat extends up to 95 m depth, salinity ranges from 38.4 to 39.4 PSU, and sea temperature varies between 16 and 24 °C (Eronat and Sayin 2014). KISEPA is also recognised for supporting local marine biodiversity by providing spawning, breeding and nursing grounds for commercial, endangered, and protected species (Keskin *et al.* 2011, 2023; Mavruk *et al.* 2024).

Stations

There are five MCs located in the KISEPA according to Barraud *et al.* (2024). However, only three were viable as sampling stations due to several reasons. The sampled caves were Eşendere cave (Ec), Ayı Balığı cave (ABc) and Yatak Odası cave (YOc). ABc is located near Mordoğan and is famous for being one of the main breeding caves in the area for *M. monachus* (Kiraç and Veryeri 2009; Sariçam and Erdem 2010) but was affected by anthropogenic disturbances. Both Ec and YOc are well-known as spots for local diving clubs, each located respectively near Eşendere and Çeşme (Figures 1 and 2, Table 1).

In addition to these three MCs with known coordinates, there are two more caves mentioned in the area. Both of them were either not properly georeferenced or theirs whereabouts were unknown, even to most of local diving clubs. The first MC called "Ildırı Reef" might be, hypothetically speaking, a complex cave located at 21 m depth with 3 entrances and 2 chimney like structures near Çeşme (Diving spots 2013). The second MC is allegedly located at 19 m depth near Karaburun. Being located at greater depths and less accessible, these MCs with unknown coordinates were excluded from the sampling for the safety of SCUBA divers.

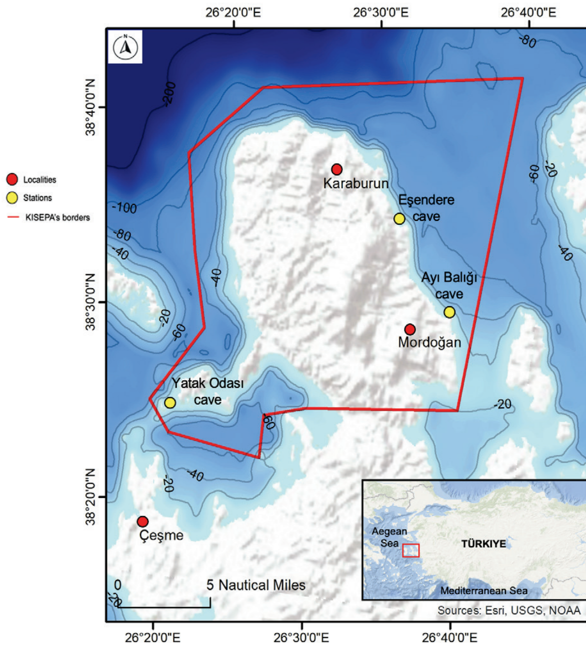


Figure 1. Location of underwater marine caves within Karaburun Ildır Bay Special Environmental Protected Area

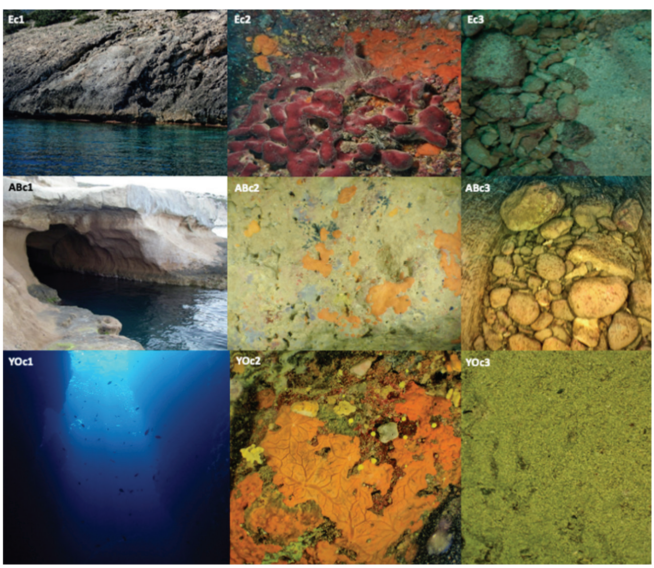


Figure 2. Characteristics of Eşendere cave (Ec), Ayı Balığı cave (ABc) and Yatak Odası cave (YOc) with the number 1 for the cave's entrance, 2 for cave's wall and 3 for cave's floor

Table 1. Descriptive summary of marine caves' geomorphologies in Karaburun Ildır Bay Special Environmental Protected Area

Characteristics of marine caves	Eşendere	Ayı Balığı	Yatak Odası
Proximity to seagrasses meadows	Yes	Yes	No
Presence of monk seals	No	Yes	No
Depth of the main entrance (m)	7.90	3.70	10.00
Height of the main entrance (m)	3.20	8.40	4.30
Width of the main entrance (m)	9.60	5.20	3.90
Number of entrances	3	>2	1+1
Length (m)	13.50	14.70	11.80
Submersion state in the seawater	Partial	Partial	Complete
Geomorphology	Blind-ended	Tunnel	Blind-ended
Bedrock	Rocky	Sedimentary	Rocky
Presence of sandy bottoms	Yes	No	Yes
Averaged internal depth (m)	5.76	2.26	8.52

Sampling strategies
The qualitative assessment of biodiversity was performed via SCUBA diving based on photographic evidence. A total of 7 dives were made inside YOc, ABc and Ec, between 2021 and 2023 (April-June) onboard the research vessel YUNUS-S. The following gear was used: underwater housing for digital camera (TG-5 model No IM005; Olympus Corporation, Tokyo, Japan) and light settings (Sola Video 3800, Light Motion Corporation, Marina, Canada). Diving parameters ranged from 3 to 10 m depth, and seawater temperature was between 19 and 26°C. Taxa, whose taxonomical levels were difficult to determine with pictures only, were directly and parsimoniously sampled and fixed in 4% formaldehyde. Specimens were later brought to the laboratory to be identified to the lowest taxonomic level.

Great caution was applied before entering the marine caves where *M. monachus* had been sighted in the past (Dede and Tonay 2019). As intended by the Turkish Ministry of Environment, Urbanization, Climate Change and the Marine Biology Department of Istanbul University's agreement, the research project aimed at determining the floral/faunal marine biodiversity inside KISEPA by mapping rare/endemic/endangered species and identifying possible threats and possible conservation measures.

Extraction of ecological/qualitative data from online databases
For each of the species recorded from the MCs in the KISEPA, we gathered ecological information from internationally recognized databases such as WoRMS (World Register of Marine Species), IUCN (International Union for Conservation of Nature), Sealifebase, OBIS (Ocean Biodiversity Information System), EASIN (European Alien Species Information Network), EUNIS (European Nature Information System) and WoRCS (World Register of marine

Cave Species). Extracted variables were categorized according to their sources (EASIN 2024; EUNIS 2024; Gerovasileiou *et al.* 2024; IUCN 2024; OBIS 2024; Palomares and Pauly 2024; WoRMS 2025):

- WoRMS: kingdom, phylum, class, order, family, genus, species, authority, feeding guild, functional group, AMBI (AZTI Marine Biotic Index), importance of the species for the fisheries (FAO – ASFIS or Food and Agriculture Organization – Aquatic Sciences and Fisheries Information System) and the conservation status of the species for the EU Habitat Directive.
- OBIS: trophic guild.
- Sealifebase: functional group.
- EASIN: conservation status of the species for the Barcelona Convention, Bern Convention and CITES (Convention on International Trade in Endangered Species of Wild Fauna and Flora).
- EUNIS: status in Mediterranean Sea (alien or cryptogenic).
- WoRCS: presence of the reported species from the present study in the database.
- IUCN: conservation status in the Red List and conservation effort.

Results

Karaburun Ildır Bay Special Environmental Protected Area's marine caves overall biodiversity

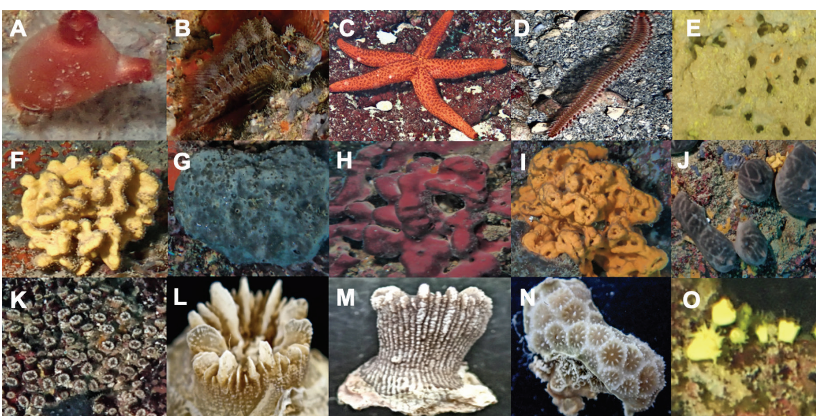


Figure 3. Pictures of organisms found in marine caves within Karaburun Ildır Bay Special Environmental Protected Area. A: red sea squirt *Halocynthia papillosa*, B: tompot blenny *Parablennius gattorugine*, C: the red starfish *Echinaster (Echinaster) sepositus*, D: the beard fireworm *Hermodice carunculata*, E: the date mussel's holes *Lithophaga lithophaga*, F: the crumpled duster sponge *Axinella damicornis*, G: the variable loggerhead sponge *Ircinia variabilis*, H: the stony sponge *Petrosia (Petrosia) ficiformis*, I: the Maltese sponge *Agelas oroides*, J: the chicken liver sponge *Chondrosia reniformis*, K-L: the Weymouth carpet coral *Hoplangia durotrix*, M: the carnation coral *Caryophyllia (Caryophyllia) inornata*, N: the star coral *Madracis pharensis* and O: the sunset cup coral *Leptopsammia pruvoti*.

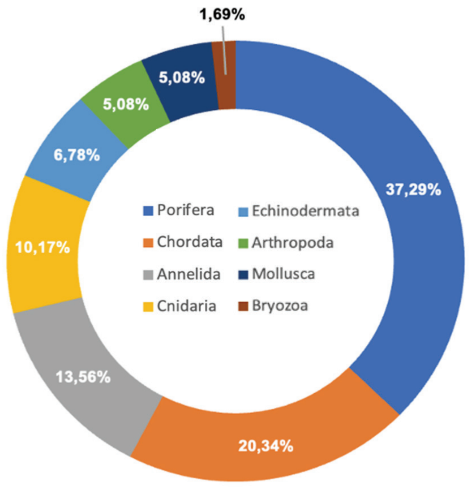


Figure 4. Composition of benthic fauna inside Karaburun Ildır Bay Special Environmental Protected Area's marine caves

Overall, 69 taxa were described inside the underwater MCs in the KISEPA: 2 kingdoms, 11 phyla, 19 classes, 39 orders and 47 families. The diversity of the observable stygobiota was divided between Animalia and Plantae (85.51% and 14.49%). Among the stygofauna (Figure 3), 59 taxa were reported with sponges (37.29%) being the most dominant, followed by chordates (20.34%), annelids (13.56%), cnidarians (10.17%), echinoderms (6.78%), crustaceans (5.08%), molluscs (5.08%) and finally bryozoans (1.69%) as shown in Figure 4. The prevailing class was Demospongiae (21 taxa), followed by Teleostei (11 species), Polychaeta (7 taxa), Hexacorallia (4 species), Echinoidea and Thecostraca (2 species each). The remaining taxonomic groups, i.e., Tunicata, Scyphozoa, Asteroidea, Holothuroidea, Malacostraca, Bivalvia, Cephalopoda, Gastropoda and Gymnolaemata had one species each. In addition, one cnidarian (Cn1), one poriferan (Po1), and one annelid (An1) species were identified at the class level and two taxa (*Pseudosuberites* sp. and *Filograna* sp.) at the genus level. Three non-identified taxa (Cn1 from Eşendere cave, Po1 from Ayı Balığı cave, and An1 from Yatak Odası cave) are not included in the inventory (Table 2), but their presences were taken into account for the statistical analyses.

Moreover, biostalactites were observed in the innermost part of one of the MC. These peculiar biogenic speleothems are known to be composed of metazoan microbial associations (serpulids, brachiopods, sponges, bryozoans, foraminifers, and bacteria) (Guido *et al.* 2013; Jimenez *et al.* 2019; Montefalcone *et al.* 2022). Approximately 35 of these bioconstructions were counted, and the tallest one reached 60 cm in length. It is highly likely that the future study of these bioconcretions will increase the importance of the MCs in the KISEPA (Figure 5).

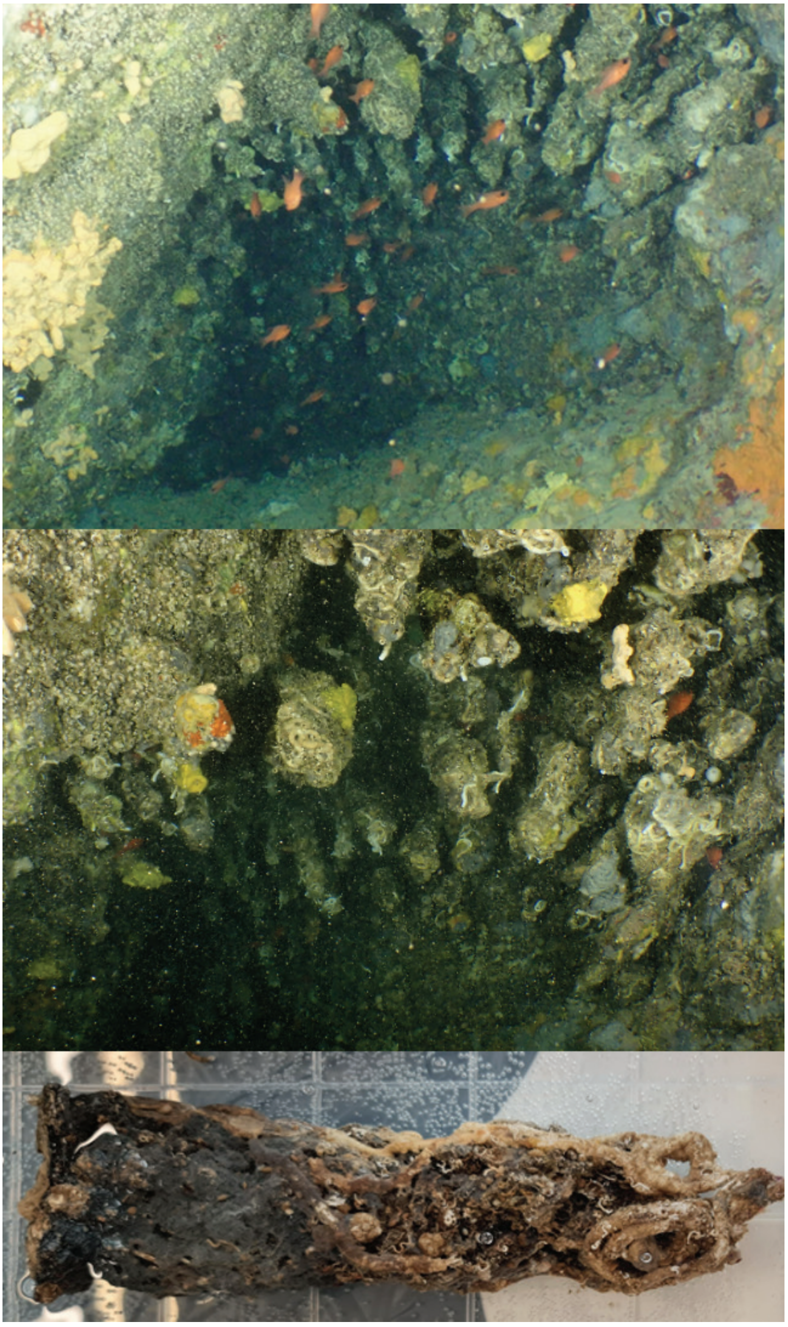


Figure 5. *Apogon imberbis* or cardinal fish schools are harboured between biostalactites

Table 2. Inventory of Karaburun Ildır Bay Special Environmental Protected Area's marine stygofauna in the present study (X: presence)

Phylum	Class	Species	Yatak Odası	Eşen-dere	Ayı Balığı
Annelida					
	Polychaeta				
		Eupolymnia nebulosa (Montagu, 1819)	X	X	
		Filograna sp. Berkeley, 1835	X	X	X
		Hermodice carunculata (Pallas, 1766)	X	X	X
		Metavermilia multicristata (Philippi, 1844)	X		X
		Pileolaria militaris Claparède, 1870	X	X	
		Protula tubularia (Montagu, 1803)	X	X	
		Serpula vermicularis Linnaeus, 1767	X	X	
Arthropoda					
	Malacostraca				
		Dromia personata (Linnaeus, 1758)		X	
	Thecostraca				
		Acasta spongites (Poli, 1791)		X	X
		Semibalanus balanoides (Linnaeus, 1767)			X
Bryozoa					
	Gymnolaemata				
		Reteporella grimaldii (Jullien, 1903)	X	X	
Chordata					
	Teleostei				
		Apogon imberbis (Linnaeus, 1758)	X	X	
		Blennius ocellaris Linnaeus, 1758		X	
		Chromis chromis (Linnaeus, 1758)	X	X	
		Diplodus vulgaris (Geoffroy Saint-Hilaire, 1817)	X	X	
		Muraena helena Linnaeus, 1758	X	X	
		Parablennius gattorugine (Linnaeus, 1758)		X	
		Parablennius zvonimiri (Kolombatovic, 1892)		X	
		Serranus scriba (Linnaeus, 1758)	X	X	
		Symphodus roissali (Risso, 1810)	X	X	
		Thalassoma pavo (Linnaeus, 1758)	X	X	
		Tripterygion tripteronotum (Risso, 1810)			X

Table 2. Continued.

Phylum	Class	Species	Yatak Odası	Eşen-dere	Ayı Balığı
	Tunicata				
		Halocynthia papillosa (Linnaeus, 1767)		X	
Cnidaria					
	Hexacorallia				
		Caryophyllia (Caryophyllia) inornata (Duncan, 1878)	X	X	X
		Hoplangia durotrix Gosse, 1860		X	X
		Leptopsammia pruvoti Lacaze-Duthiers, 1897	X		
		Madracis pharensis (Heller, 1868)	X	X	
	Scyphozoa				
		Nausithoe punctata Kölliker, 1853	X	X	X
Echinodermata					
	Asteroidea				
		Echinaster (Echinaster) sepositus (Retzius, 1783)		X	
	Echinoidea				
		Arbacia lixula (Linnaeus, 1758)		X	X
		Psammechinus microtuberculatus (Blainville, 1825)		X	
	Holothuroidea				
		Parastichopus regalis (Cuvier, 1817)		X	
Mollusca					
	Bivalvia				
		Lithophaga lithophaga (Linnaeus, 1758)	X		X
	Cephalopoda				
		Sepia officinalis Linnaeus, 1758		X	
	Gastropoda				
		Peltodoris atromaculata Bergh, 1880		X	
Porifera					
	Demospongiae				
		Acanthella acuta Schmidt, 1862		X	
		Agelas oroides (Schmidt, 1864)	X	X	
		Axinella cannabina (Esper, 1794)		X	
		Axinella damicornis (Esper, 1794)	X	X	
		Axinella polypoides Schmidt, 1862		X	
		Chondrosia reniformis Nardo, 1847		X	X
		Haliclona (Halichoclona) fulva (Topsent, 1893)		X	X
		Haliclona (Reniera) cinerea (Grant, 1826)		X	X

Table 2. Continued.

Phylum / Class / Species	Yatak Odası	Eşen-dere	Ayı Balığı
Porifera			
Demospongiae			
Haliclona (Reniera) mediterranea Griessinger, 1971		X	
Haliclona (Rhizoniera) rosea (Bowerbank, 1866)	X	X	X
Haliclona (Rhizoniera) sarai (Pulitzer-Finali, 1969)	X		X
Halisarca dujardinii Johnston, 1842		X	X
Ircinia variabilis (Schmidt, 1862)	X	X	
Mycale (Mycale) lingua (Bowerbank, 1866)	X	X	X
Penares helleri (Schmidt, 1864)		X	
Petrosia (Petrosia) ficiformis (Poiret, 1789)		X	X
Phorbas plumosus (Montagu, 1814)	X	X	X
Phorbas tenacior (Topsent, 1925)	X	X	X
Pseudosuberites sp. Topsent, 1896	X	X	X
Spirastrella cunctatrix Schmidt, 1868		X	X
Terpios gelatinosus (Bowerbank, 1866)		X	X

The inventory for KISEPA's marine stygofauna is available in Table 2. As shown in Figures 6, 7, and 8, the overall diversity was highest at Ec (51 taxa), followed by YOc (30 taxa) and ABc (25 taxa). Some taxa were common between stations. The highest similarity was reported between Ec and YOc (25 shared taxa), followed by Ec and ABc (19 shared taxa), YOc and ABc (12 shared taxa), and finally all stations combined (7 shared taxa found in Ec, YOc and ABc). Some taxa were specific to a single station, with Ec possessing 16 specific taxa, 3 taxa for ABc and 2 taxa for YOc.

At the level of phyla, the diversity assessment is reported as follows. For sponges, 20 species were reported in Ec (40.00%), 14 taxa in ABc (54.17%) and 9 species in YOc (31.03%). As for chordates, 11 species in Ec (22.00%), 7 species in YOc (24.14%) and 1 species in ABc (4.17%) were observed. Regarding annelids, 8 taxa in YOc (24.14%), 6 taxa in Ec (12.00%) and 3 taxa in ABc (12.50%) were described. Concerning cnidarians, 5 taxa in Ec (8.00%), 4 species in YOc (13.79%) and 3 species in ABc (12.50%) were identified. Inventory of echinoderms outlined the presence of 4 species in Ec (8.00%) and of 1 species in ABc (4.17%). The presence of arthropods was confirmed in Ec (4.00%) and in ABc (8.33%), with 2 species for each station. Additionally, for molluscs, 2 species were seen in Ec (4.00%) while 1 species was observable in YOc (3.45%) and ABc (4.17%). Finally, Bryozoa accounted for only 1 species in Ec (2.00%) and YOc (3.45%).

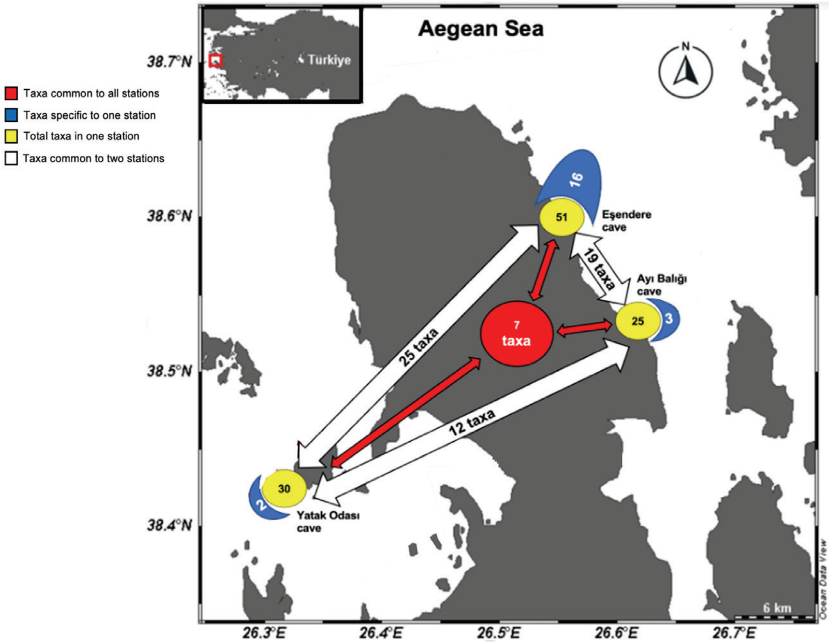


Figure 6. Stygofaunal biodiversity patterns for Karaburun Ildır Bay Special Environmental Protected Area's marine caves

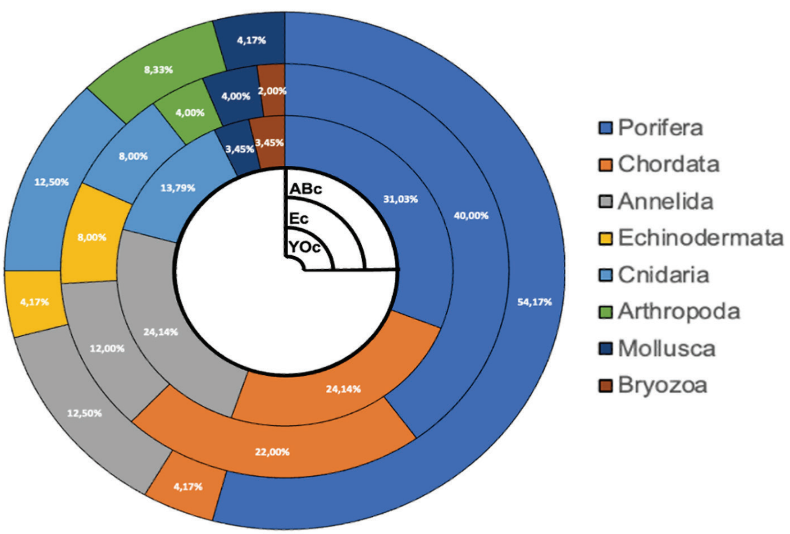


Figure 7. Comparison of biodiversity or the number of identified taxa inside Karaburun Ildır Bay Special Environmental Protected Area's marine caves depicted in the shape of a doughnut chart (ABc for the 1st external layer, Ec for the 2nd middle layer and YOc for the 3rd internal layer)

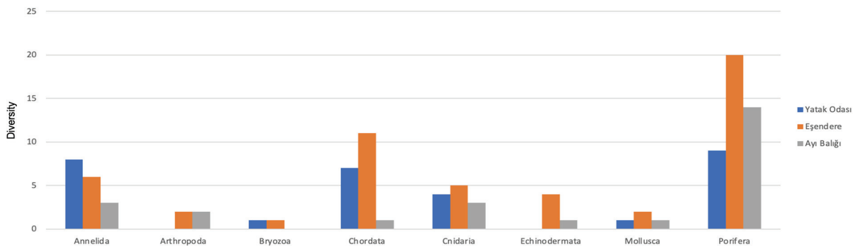


Figure 8. Biodiversity or the number of identified taxa inside Karaburun Ildır Bay Special Environmental Protected Area's marine caves represented in the shape of a clustered columns chart

Protection status, the interest in fisheries for statistical purposes and other ecological data about the species found in the MCs of the KISEPA were gathered from the previously mentioned databases (Figure 9). In terms of feeding and trophic guilds, most of the taxa harboured inside marine caves were 64.29% filter feeders, followed by 28.57% predators and 7.14% deposit feeders. Furthermore, organisms had either omnivorous (73.21%) or carnivorous (26.79%) diets. A higher complexity was highlighted for functional groups amidst stygofaunal species, with the most dominant category being macrobenthos (50.00%), followed by benthos (19.64%), reef-associated (14.29%), demersal (10.71%) and finally 5.37% of minor groups such as hosts (ectoparasites), pelagic and bentho-pelagic (1.79% each respectively). In term of protection status, 39 species (69.64%) of marine stygofauna in the KISEPA was found to be Not Evaluated, 16 species (28.57%) were considered as Least Concern for marine conservation and finally one species (1.79%) of marine caves diversity was acknowledged as Data Deficient. Among the species of commercial interest, both the IUCN and Sealifebase databases agreed that 30.51% of stygofauna (18 species) being of statistical interest for fisheries purposes. As soft bottoms were present in several marine caves, 19.65% of KISEPA's stygofaunal species were considered as indicators to assess the quality of soft bottom benthic macroinvertebrate communities through the AMBI (AZTI Marine Biotic Index). Among these biological indicators, 8.93% were deemed as very sensitive (5 species), 7.14% were considered as indifferent (4 species), and 3.57% were determined to be tolerant (2 species) to anthropogenic disturbances. The presence of KISEPA's species was investigated in WoRCS. As a result, 27.12% of KISEPA's marine stygofauna (16 species) reported in the present study were found to be absent from the WoRCS database.

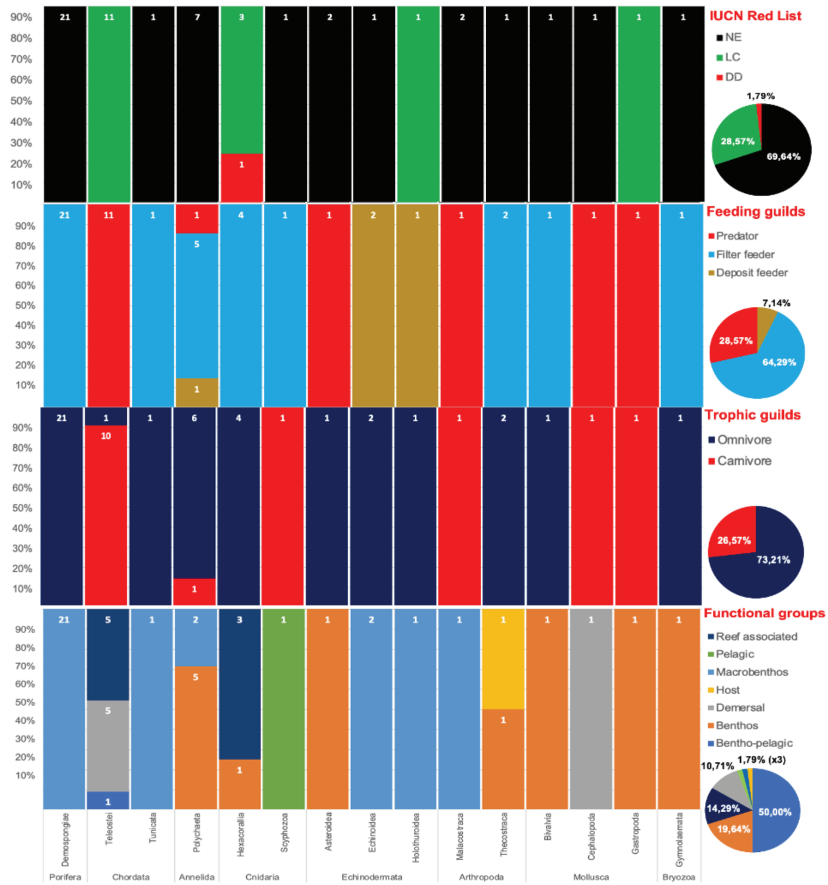


Figure 9. Comparisons of qualitative data between taxonomical groups of marine stygofauna in the Karaburun Ildır Bay Special Environmental Protected Area from different ecological perspectives. Information about the diversity, feeding/trophic guilds, functional groups, species status in the IUCN Red List, species used for statistical purposes in fisheries by FAO-ASFIS, species used as AMBI indicators and species presence inside the WoRCS database were all depicted in the shapes of stacked area, percentage stacked column and pie charts.

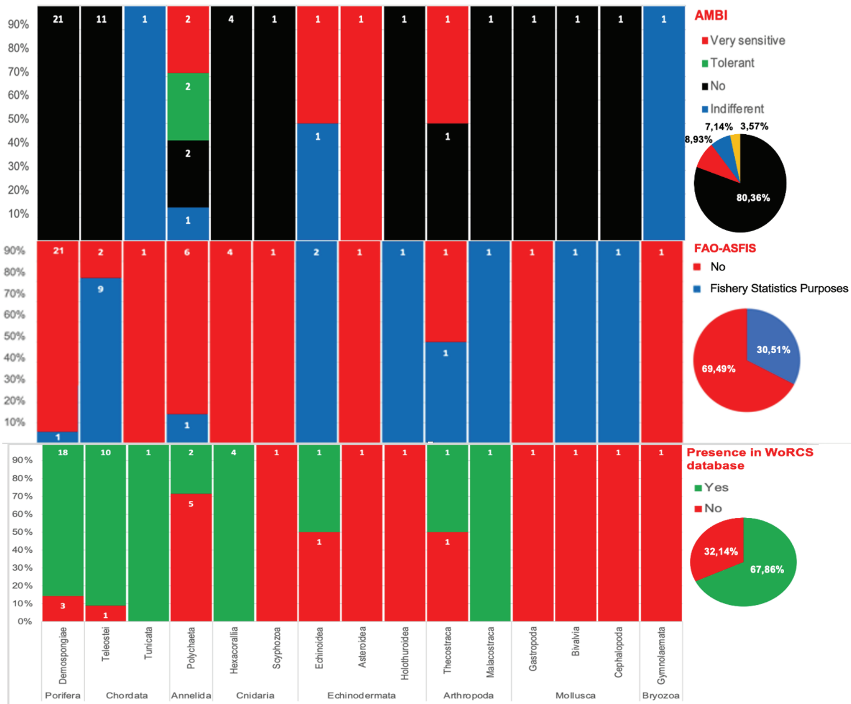


Figure 9. Continued.

Discussion

Karaburun Ildır Bay Special Environmental Protected Area's marine caves biodiversity

KISEPA's MCs were dominated by sponges and annelids, if only macro-invertebrates are considered. Demosponges and serpulids were the most dominant taxonomical groups inside KISEPA's MCs (teleosts excluded). Among the sessile stygofauna, demosponges and serpulids are well known for being one of the major components of diversity pools within semi-dark and dark areas of Mediterranean MCs (Vacelet 1969; Corriero *et al.* 2000; Manconi *et al.* 2013; Montefalcone *et al.* 2022; Schiavo *et al.* 2024).

Demospongiae is one of the richest classes within the Porifera phylum with approximately 8,000 recognized species (Lavrov *et al.* 2023). They can display a wide variety of morphological plasticity in terms of shape, size, colour, and texture through their skeletons made of silicious spicules or collagenic matrices (Van Soest *et al.* 2012). Commercial sponges (Spongiidae), deep-sea sponges (Astrophorida), boring sponges (Clionaidae), rock sponges with (Lithistida *incertae sedis*) and carnivorous poriferans (Cladorhizidae) are all peculiar groups of demosponges (Pomponi 1980; Vacelet and Boury-Esnault 1995; Kelly 2007; Voultsiadou *et al.* 2008; Van Soest *et al.* 2012).

As for serpulids, they are sedentary annelids capable of producing calcareous tubes where their vermiform body is kept hidden out of sight and plugged with a chitinous/calcareous operculum (Bianchi 1981; Bastida-Zavala and Sanchez-Ovando 2021; Montefalcone *et al.* 2022). Under the right environmental conditions, aggregations of serpulids can lead to reef like constructions (Bosence 1979; Ten Hove 1979).

The success of these sessile bioconstructors inside KISEPA's MCs under oligotrophic conditions can be explained through the optimal foraging theory. This hypothesis stipulates that organism capable of preserving their fitness by spending the least amount of energy to meet their nutritional requirements have the highest survival chance (Hughes 1980; McMurray *et al.* 2016). High filtration rates also enable demosponges to filter up to 900 times of their body volume in water per hour (Ludeman *et al.* 2017). As a result, demosponges and serpulids are secondary producers fulfilling vital ecosystemic services through highly complex three-dimensional microhabitats (Benzoni *et al.* 2003; Muricy *et al.* 2024). Demosponges and serpulids modulate the effect of benthic competition (Ten Hove and Van den Hurk 1993; Gonzalez-Murcia *et al.* 2023), with sponges capable of showcasing greater overgrowth in 77.00% of corals-sponges interactions (Murcia *et al.* 2025). Both bioconstructors provide refuges against predators (Ruzicka and Gleason 2009; Perry *et al.* 2020), with up to 69.00% of sponges containing chemical deterrent against fish predation, according to Pawlik *et al.* (1995) in the Caribbean region. Serpulids and demosponges may shelter diurnal species (Jimenez *et al.* 2019; Palmer *et al.* 2022; George *et al.* 2023) and maintain populations of commercial species (Gökalp *et al.* 2019; Palmer *et al.* 2022). Both engineer species regenerate and reinforce themselves via colonisation resets leading to denser/stable structures (Bianchi and Morri 2001; Montefalcone *et al.* 2022). Sponges were reported to regenerate 22 to 2900 times faster than their own growth rates (Ayling 1983), while serpulid growth rate can reach up to 1.5 mm/day (Kim and Yu 2025). Finally, both demosponges and serpulids constitute a major biotope for sciaphilic communities (Hogg *et al.* 2010; Sanfilippo *et al.* 2017).

Demosponges and serpulids also ensure constant trophodynamic (Lindeman 1942; Whitfield *et al.* 2021) through filtration of the confined seawater by actively depleting particulate organic/inorganic matter via suspensivory (Ramos and San Martin 1999; Paoli *et al.* 2016; Mortimer *et al.* 2023). This characteristic contributes to the decrease of eutrophication effects (Pan and Marcoval 2014; Varamogianni-Mamatsi *et al.* 2021). Clearance rates can reach 210 $ml.h^{-1}.g^{-1}$ for sponges (Stabili *et al.* 2006) and 15.7 $ml.h^{-1}.mg^{-1}$ for serpulids (Riisgård *et al.* 2002). Both bioconstructors also participate to the prevention of blooms through top-down control (Bruschetti *et al.* 2008; Pawlik *et al.* 2018) and the enrichment in dissolved O_2 content of a small pocket of seawater column (Bezuidenhout and Robinson 2020; Whitfield *et al.* 2021; Marzuki *et al.* 2023). Finally, demosponges and serpulids enable the generation of trophic/respiratory eddies responsible for the modulation of hydrodynamic factors such as seawater residence time/turbulence (Carling 1992; Hashempour and Kolahdoozan 2023) and the remineralisation of phosphorus and other nutrients, which in turn stabilise the whole ecosystem metabolism (Herman and Scholten 1990; Bianchi and Morri 1996; Colman 2015; Montefalcone *et al.* 2022; Engelberts *et al.* 2023).

Karaburun Ildır Bay Special Environmental Protected Area's marine caves' protected species

Table 3. List of Karaburun Ildır Bay Special Environmental Protected Area's marine caves protected species according to international conventions/agreements and their conservation status (CITES: Convention on International Trade in Endangered Species of Wild Fauna and Flora; NE: non-evaluated species; N/A: non available information)

Protected species	EU Habitat Directive	Barcelona Convention	Bern Convention	CITES	IUCN Red List	Conservation effort (IUCN)
Axinella cannabina	NE	Annexe II	NE	NE	NE	N/A
Axinella polypoides	NE	Annexe II	Annexe II	NE	NE	N/A
Caryophyllia (Caryophyllia) inornata	NE	NE	NE	Appendix II	LC	N/A
Hoplangia durotrix	NE	NE	NE	Appendix II	DD	N/A
Leptopsammia pruvoti	NE	NE	NE	Appendix II	LC	N/A
Lithophaga lithophaga	Appendix IV	Annexe II	Annexe II	Appendix II	NE	N/A
Madracis pharensis	NE	NE	NE	Appendix II	LC	Yes

Overall, seven species from KISEPA's MCs were reported (Table 3) to be protected under regional or international agreements such as the EU Habitat Directive (92/43/EEC) (Loos *et al.* 2021), Barcelona Convention (Lizinska and Guerin 2021), Bern Convention (Elvan *et al.* 2021), CITES (Heid and Marquez-Ramos 2023) and IUCN Red List (IUCN 2024). The common antler sponge *A. polypoides*, *A. cannabina*, the carnation coral *C. (Caryophyllia) inornata*, the Weymouth carpet coral *H. durotrix*, the sunset cup coral *L. pruvoti*, the date mussel *L. lithophaga* and the star coral *M. pharensis* are considered as protected species, but not to the same degree, depending on the International Environmental Agreements or IEAs (Mitchell *et al.* 2020). Even though *L. lithophaga* is protected under all IEAs; this bioeroder remains Not Evaluated by the IUCN.

While CITES placed most of KISEPA's MCs stygofauna under its protective regulation, other IEAs showcased a substantial lack of information concerning the reported species. Finally, all species listed as protected (except for *M. pharensis*) lack a conservation plan (IUCN 2024). The global decline of biodiversity and the possible extinction of species motivated the creation of IEAs, which are tasked with the preservation of endangered species (Barrett 1992). Within the IUCN Red List, at least 20% of Mediterranean marine species are threatened with extinction (Klaoudatos *et al.* 2024). However, for an IEA to be effective in its functions, flawless and transparent cooperation between member countries that signed the convention is paramount (Zeeuw 2015).

Consequently: (i) the vague implication of parties (Karp and Sakamoto 2018), (ii) lack of reinforcement and implementation of detailed regulation on numerous species by national authorities (Kilduff 2019) and finally (iii) the syndrome of "paper parks" are problematic. Paper parks are MPAs with mitigated conservation prowess, where decreed protection is in name only, due to insufficient management, design, enforcement or resources (Rife *et al.* 2023). More than 90% of Mediterranean MPAs are weakly enforced (Jane *et al.* 2016). All these issues contribute to weakening and delaying the commitments to reach the AICHI Targets by 2030 (Matz-Lück and Fuchs 2014; Lemieux *et al.* 2019). Among these flaws, the lack of standardisation between different agreements is the most glaring one (Seelarbokus 2014), which is visible in the present study.

Overview of stygofaunal inventories in Türkiye

As notified by Ertek (2019), "only" a small fraction of MCs was reported in Türkiye in comparison to their terrestrial counterparts, with only 57 MCs against 800 terrestrial caves. The most recent catalogue of MCs in Turkish territorial waters (unpublished data) highlighted the presence of 161 MCs, with 47 in the Aegean and 114 in the Mediterranean Seas. Among them, the number of MCs subjected to a complete marine faunal diversity assessment is even less.

With the inclusion of the present study, 12 articles have been published on the faunal diversity of Turkish marine caves. Among these publications, four are multitaxa inventories (Cinar *et al.* 2019; Özalp 2019; Turan *et al.* 2019; present study), two are preliminary multitaxa investigations (Öztürk *et al.* 2019; Topaloğlu 2019), five are observations of singular species (Yokes and Galil 2006; Rastorgueff *et al.* 2014; Chevaldonné *et al.* 2015; Filiz and Sevingel 2015; Çelikok 2019), and one is a monotaxa checklist (Bilecenoglu 2019).

However, despite being scarce, these studies are surprisingly evenly distributed on the coastline of Türkiye, with 6 articles for the Aegean Sea and 6 articles for the Mediterranean Sea. Nevertheless, several subregions remain severely under-investigated due to the heterogeneous distribution of MCs along the Turkish coastline and the difficult accessibility inherent to these dark habitats (Emecan and Yalgin 2019; Sümen and Aktaş 2019).

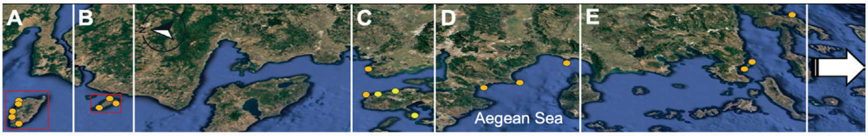
Diversity patterns of marine stygofauna across Turkish coastlines
After gathering all the data along the Mediterranean and Aegean coastlines of Türkiye (216 animal taxa from 12 articles), the overall diversity of MCs stygofauna in Türkiye was estimated to be composed of 30.09% of chordates, 27.31% of sponges, 9.26% of cnidarians, 8.33% of annelids, 7.87% of echinoderms, 7.41% of arthropods, 6.48% of molluscs, 2.31% of bryozoans and 0.93% of brachiopods.

Stygofaunal inventories were considered for the following regions: Turkish territorial waters inside the Aegean (193 taxa) and the Mediterranean (51 taxa) Seas. Borders between Turkish seas were defined according to the delimitations of Bengil and Mavruk (2018). The Northern Aegean Sea extends from the Saros Bay to the 38°16'00.0"N latitude, while the Southern Aegean Sea's border starts at the same latitude down to Marmaris, in front of the Rhodes Island.

Diversity assessments were depicted for each region (Figure 10). Throughout the book entitled "Marine Caves of the Eastern Mediterranean Sea. Biodiversity, Threats and Conservation" (Öztürk 2019), a modern synthesis on the diversity of Türkiye stygofauna was made possible by Turkish experts. In total, 23 species were reported as alien/cryptogenic species (21 alien and 2 cryptogenic species) and 25 species as protected species under diverse IEAs inside Türkiye MCs.

Alien/cryptogenic species were divided among Chordata (12 species), Arthropoda/Annelida (3 species each), Echinodermata/Mollusca (2 species each) and Cnidaria (1 species) phyla. Most alien/cryptogenic species were found in the Mediterranean Sea (15 species in region F) while the lowest count of alien/cryptogenic species was reported in the Northern Aegean Sea (2 and 1 species in regions A and B). The increase in alien/cryptogenic species followed an eastern-western gradient within the Mediterranean Sea and a northern-southern gradient inside the Aegean Sea. These differences observed inside MCs also corroborate with the findings described by Cinar *et al.* (2021), where most alien species reported along Türkiye's coastline originated from the Red Sea (58.00%) due to the proximity of the Suez Canal, mainly through shipping activities.

Protected species were made of cnidarians (8 species), poriferans (7 species), chordates (4 species), echinoderms (3 species), arthropods (2 species) and molluscs (1 species). Compared to alien/cryptogenic species, protected species showed different distribution patterns with the highest value of species reported around the central part of the Aegean Sea (16 species in region D) and to some extend in the Northern Aegean Sea (12 species respectively in region A-B). Even though the number of protected species was lower in the Mediterranean Sea compared to the Aegean Sea, most of protected taxa were observed in the western part of the Mediterranean Sea (5 species in region F). Clusters of protected species harboured inside MCs along Türkiye coastline were reported to be located at the north edge of each Aegean Sea's subregions.



Phylum	A	B	C	D	E	F	G	Γ	Protected
Annelida	3	3	15	10	0	3	0	1+2	0
Arthropoda	2	1	4	4	0	6	2	3	2
Brachiopoda	0	0	2	1	0	0	0	0	0
Bryozoa	1	1	2	1	0	2	0	0	0
Chordata	13	9	26	25	12	15	8	12	4
Cnidaria	8	9	7	10	0	1	4	1	8
Echinodermata	5	4	6	7	1	3	3	2	3
Mollusca	4	1	3	7	1	1	0	2	1
Porifera	18	21	40	40	0	4	0	0	7
Total	54	49	105	105	14	35	17	**Total** 23	25
Γ	1+1	0+1	1+2	3+1	7	15	7		
Protected	12	12	9	16	0	5	3		

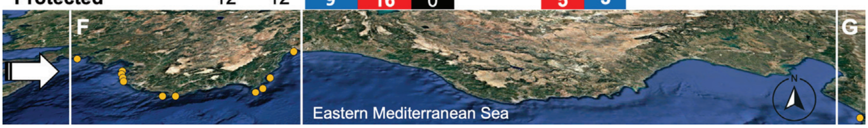


Figure 10. Matrix of stygofaunal diversity sorted by taxonomical groups (9 phyla), regions (Northern Aegean Sea = A + B + C; Southern Aegean Sea = D + E; Mediterranean Sea = F + G) and species status (total; Γ or zeta = alien + cryptogenic; protected). Maxima (red colour) and minima (blue colour) were depicted in function of regions and species status. Black colour depicts the absence of species.

Overall, diversity followed the same trend as protected species, with maxima in the central region of the Aegean Sea, including KISEPA and its surrounding areas (105 species each in regions C and D). The lowest value was reported in the south edge of the Aegean Sea (14 species in region E). Although the overall diversity was lower in the Mediterranean Sea compared to the Aegean Sea, a maximum was reached in the western part of the Mediterranean Sea (35 species in F region). The distribution trends of stygofaunal species along Türkiye coastlines highlighted the importance of the central region of the Aegean Sea, in particular of KISEPA and its adjacent areas as biodiversity hotspots.

As previously mentioned, 12 articles were found in the scientific literature. Using them as a baseline, stygofaunal dominance patterns across different marine regions in Türkiye were synthesised (Figure 11 and Table 4). From Gökçeada Island to Marmaris, sponges were the most dominant phylum inside Aegean MCs (from 33.73% to 59.09% of species, except for some caves near the border of the Mediterranean Sea where chordates were dominant with 85.71%). This trend increased along the latitudinal gradient. However, changes started to occur in the ranking with other major stygofaunal groups.

Chordates were the second most dominant in the Northern Aegean Sea, ranging from 21.57% to 25.45% in terms of diversity (except for Ayı Balığı cave, where chordate dominance fell to 4.17%). Once the border between Northern and Southern Aegean Seas was crossed, the Chordata phylum became a minor group in Southern Aegean MCs (ranging from 2.27% to 2.53%).

Even though cnidarians were the third most encountered stygofaunal group in Northern Aegean MCs with a representativity varying from 12.50% to 16.04% in term of diversity (except for Eşendere and Yatak Odası caves where Cnidaria phylum's rank dropped to 4th place), the same tendencies were not observed inside the Southern Aegean Sea where cnidarians had lower dominances (from 9.09% to 11.39%).

Another notable observation is the particularity of KISEPA within the Northern Aegean Sea's MCs, where annelids were more prevalent (from 11.76% to 18.52% of diversity), while they amount only to 5.45% to 5.66% in Gökçeada and Bozcaada Islands. In this aspect, KISEPA shares a peculiar trait with Southern Aegean MCs where the Annelida phylum's prevalence ranged from 11.39% to 18.18% in terms of diversity.

More biodiversity inventories are needed to reach equidistributional reliability to encompass all Aegean MCs in Turkish territorial waters, as only three studies were undertaken inside Southern Aegean MCs (Bilecenoglu 2019; Cinar *et al.* 2019; Öztürk *et al.* 2019) while six studies were performed inside their northern counterparts (Filiz and Sevingel 2015; Bilecenoglu 2019; Cinar *et al.* 2019; Özalp 2019; Topaloğlu 2019; present study).

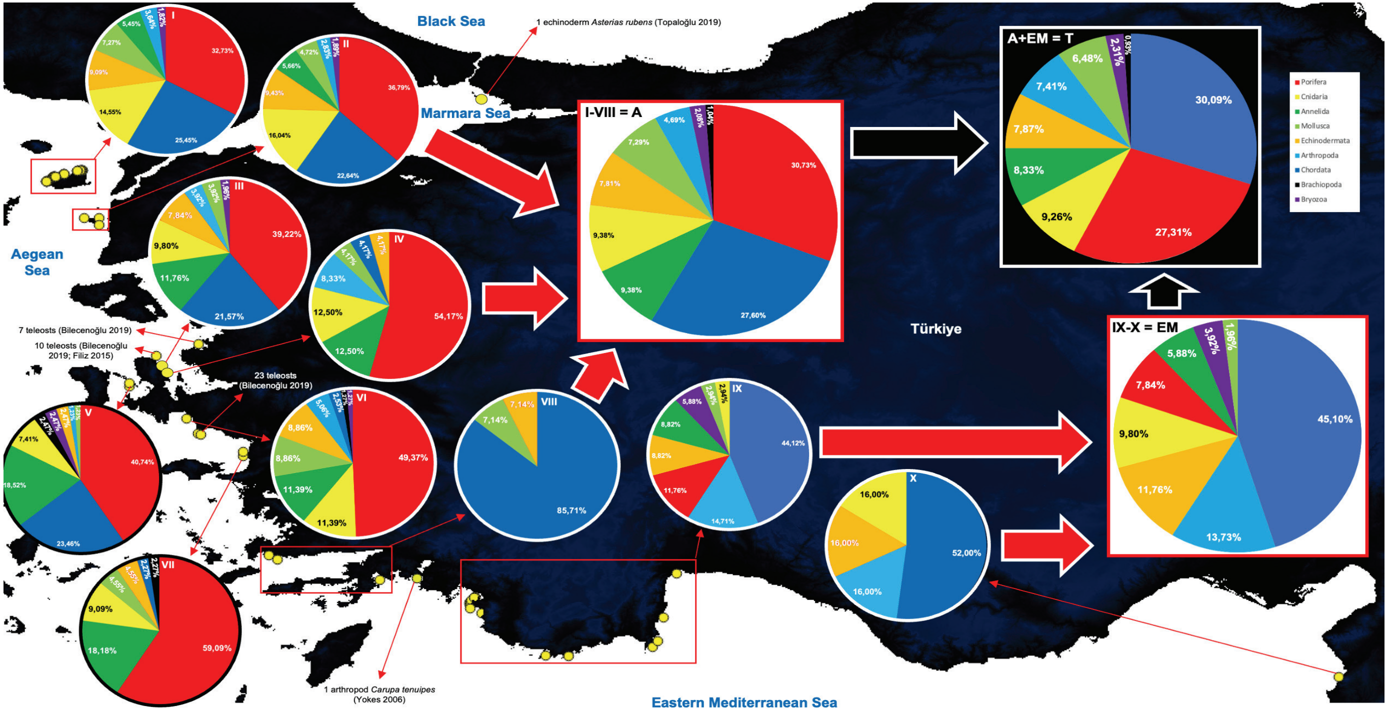


Figure 11. Complete map of marine caves stygofaunal inventories inside Turkish territorial waters. The codes (I-X) are explained in Table 4.

Table 4. Codes of sources used in Figure 11

Code	References	Region
I	Topaloğlu (2019) Özalp (2019)	Aegean Sea (A)
II	Özalp (2019)	
III	Present study	
IV	Present study	
V	Cinar *et al.* (2019) Bilecenoğlu (2019) Present study	
VI	Cinar *et al.* (2019)	
VII	Cinar *et al.* (2019)	
VIII	Öztürk *et al.* (2019)	
IX	Rastorgueff *et al.* (2014) Chevaldonné *et al.* (2015) Öztürk *et al.* (2019) Çelikok (2019)	Eastern Mediterranean Sea (EM)
X	Turan *et al.* (2019)	

Contrasting features became even more apparent between MCs from the Aegean and Mediterranean Seas within Turkish territorial waters. Overall, the Aegean stygofaunal diversity was defined by communities dominated by Porifera (30.73%) followed by Chordata (27.60%) and Annelida (9.38%), in opposition to the Mediterranean stygofaunal diversity which was composed mainly of Chordata (45.10%), Arthropoda (13.73%) and Echinodermata (11.76%) phyla. Another specificity was also underlined with the exclusive presence of the Brachiopoda phylum inside Aegean MCs and its absence in Mediterranean MCs. Glaring differences in stygofaunal composition can be linked to varying levels of research efforts between MCs. Multitaxa inventories provide the highest degree of taxonomical identification, while observations of singular species allow only incremental contributions to the baseline knowledge.

Conservation measures for KISEPA's MCs

The overview of stygofaunal diversity in Türkiye underlined the importance of KISEPA. Similarly, to MCs individualities, conservation measures have to be tailor-made for each MC to enable effective protection. The region is experiencing rapid coastal development, resulting in poor urbanisation planning and coordination (Salata *et al.* 2022). As a consequence, all illegal constructions located in a 100m radius (setback zone) around MCs should be removed, in accordance to the Protocol on Integrated Coastal Zone Management (ICZM) of the Barcelona Convention. The measure is especially designed for ABc to fight against disturbances of *M. monachus* breeding site (Kiraç and Veryeri 2009; Sariçam and Erdem 2010) and the negative impact of *L. lithophaga* harvesting (Devescovi *et al.* 2005). Citizen science coupled with SCUBA diving clubs will enable better protection of endangered species inside YOc and Ec by killing two birds with one stone through the regulation of recreational diving and continuous monitoring of marine species (Lucrezi *et al.* 2018; Giglio *et al.* 2020).

Conclusion

Need of further studies about stygofaunal diversity in Türkiye

The present study provides, in addition to KISEPA's MCs inventory, for the first time an updated overview of the stygofaunal diversity reported inside Türkiye MCs. It also outlined the gap in our knowledge of Aegean and Mediterranean MCs. Although Türkiye's coastlines harbour 161 MCs, most of them remain severely understudied. This lack of research effort is obviously depicted by the contrasting counts of stygofaunal species and MCs between Aegean and Eastern Mediterranean regions. While 193 taxa were reported in Aegean MCs, only 51 taxa are known to reside inside Eastern Mediterranean MCs, even though 70.63% of Turkish MCs are located in the Eastern Mediterranean Sea. Hence, there is a dire need to extend our research effort to encompass the whole Turkish coastline to effectively protect dark habitats like MCs.

Importance of quantitative assessments of marine caves communities

Increasing the level of MCs' conservation goes hand in hand with refining the available database. By transitioning from an inventory based on qualitative data to a fully comprehensive quantitative assessment of diversity, meta-analysis of MCs' communities in relation to their environmental variables would be possible. The necessity and urgency to obtain further data is also reinforced by the fact that MCs are highly susceptible to disturbances such as coastal development, tourism, sediment burial, oil spills, mucilage, ghost fishing, alien species, intensive recreational diving, pleasure boats, natural storms, heat waves, spearfishing, waste outflows, littering, overfishing and acidification (Giakoumi *et al.* 2013; Öztürk *et al.* 2019; Gerovasileiou and Bianchi 2021; Türetken 2023). Hence, as the climate crisis continues, there is a dire need for quantitative studies of MCs' biota, which is especially vital to assess any potential damages and measure any dramatic changes in species composition. As a result, diversity trends of marine stygofauna in Turkish territorial waters remain understudied, with many unresolved questions concerning the variability of these communities.

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Karaburun-Ildır Özel Çevre Koruma Bölgesi'ndeki (ÖÇKB) deniz mağaralarının stygofaunal envanteri (Ege Denizi, Türkiye)

Öz

Karaburun-Ildır Körfezi Özel Çevre Koruma Bölgesi'nde (KIOÇKB) üç deniz mağarasında (DM) stygofauna çeşitliliği araştırılmıştır. Genel olarak, DM'lar içerisinde Porifera (%37.29), Chordata (%20.34) ve Annelida (%13.56)'nın baskın filumlar olduğu 59 stygofaunal takson bildirilmiştir. Çevrimiçi veri tabanlarına göre, DM'lar içerisindeki toplulukların süzerek beslenenlerden (%64.29) ve omnivorlardan (%73.21) oluşmaktadır (WoRMS, IUCN, Sealifebase, OBIS, EASIN, EUNIS). Mevcut çalışma, Türkiye DM türlerine 21 yeni takson ekleyerek toplam hayvan taksonunu sayısı 216'ya çıkarmıştır. Türkiye'deki stygofauna, 23 yerli olmayan ve 25 uluslararası yasalar kapsamında korunan türler de dahil olmak üzere kordalılar (%30.09), süngerler (%27.31) ve knidliler (%9.26) tarafından baskındır. Ege Denizi ve Akdeniz'in Türkiye kıyılarında DM'lar içinde zıt biyoçeşitlilik kalıpları gözlemlenmiştir. Ege Denizi'nin orta bölgesinde yüksek sayıda faunal ve korunan tür bulunurken Akdeniz'de yerli olmayan türler yaygındır. Sonuç olarak, KIOÇKB stygofauna için bir biyoçeşitlilik merkezi olarak kabul edilebilir ve Ege ekosistemlerinin korunması için biyocoğrafik eşik rolünü doğrulamaktadır.

Anahtar kelimeler: Deniz mağaraları, stygofauna, biyoçeşitlilik, envanter, OÇKB

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