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An ecosystem-based index for Mediterranean coralligenous reefs: A protocol to assess the quality of a complex key habitat

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ABSTRACT

Coralligenous reefs are among the most diverse Mediterranean ecosystems, particularly in the circalittoral zone. Shaped by calcified red algae, sponges, cnidarians, and bryozoans, they create a complex three-dimensional structure providing shelter for diverse fauna. These reefs develop either on steep rocky walls or as bioherms when calcified algae are the dominant organisms. Their structure and composition vary with location, depth, substrate, and environmental conditions.

Assessing the status of such a complex ecosystem poses significant challenges. Ecosystem-based quality indices (EBQI) have already been applied successfully to various coastal Mediterranean habitats. Using a similar methodology, a new index, the Coralligenous Ecosystem-Based Quality Index (Cor-EBQI), was developed to assess the ecological status of the coralligenous ecosystem. The index incorporates the main functional compartments of these reefs, with each compartment weighted according to its importance in ecosystem functioning. Suitable descriptors were then selected to define five status classes for each compartment. A confidence index was also created to estimate data quality based on criteria such as methodology and expert judgement.

Data from 63 sites along the French Mediterranean coast, including the Gulf of Lions, Provence, the French Riviera, Corsica, and Monaco, were analyzed. The ecological status ranged from bad to high, influenced by

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environmental conditions, geomorphology, anthropogenic pressures, and management practices. The Cor-EBQI is designed to meet the objectives of both the Habitats and Marine Strategy Framework Directives of the European Union. As such, it offers a practical tool for future monitoring networks across the Mediterranean Sea.

1. Introduction

1.1. Description of the coralligenous ecosystem

The conservation of the Mediterranean coralligenous ecosystem is of paramount importance in the current global change and climate crisis (Ballesteros, 2006; Garrabou et al., 2022). Research on the coralligenous has been carried out since the late 19th century (Marion, 1883; Pruvot, 1894, 1895; Bianchi, 2001). Following the development of SCUBA diving, Mediterranean coralligenous reefs have been extensively studied since the 1950s (e.g., Bacci, 1947; Rossi, 1958, 1965; Tortonesi, 1958; Molinier, 1960; Parenzan, 1960; Pérès and Picard, 1964; Laborel, 1961; Laubier, 1966; True, 1970; Hong, 1980; Ferrigno et al., 2024), but a clear definition of this ecosystem remains a matter of debate (Ballesteros, 2006). Moreover, marked biogeographical differences have been highlighted linked with nutrient availability, depth range and temperature (Piazzi et al., 2021a; Pinna et al., 2021; Casoli et al., 2024).

According to Ballesteros (2006), coralligenous constructions are Mediterranean formations of biogenic origin produced by calcareous algae in dim light conditions hosting diverse communities, including outstanding and key species. Their complex and heterogeneous structure is driven by environmental factors such as light, water movement and sedimentation rates. Their growth is primarily attributed to sciaphilic calcareous algae (Ballesteros, 1992; Sartoretto, 1996). The slow dynamics of coralligenous reefs suggests that they are likely adapted to low nutrient concentration in sea water, as increased nutrient availability greatly affects the specific composition, inhibits bioconstruction, and favours the activity of borers (Hong, 1980).

Calcareous sessile fauna such as scleractinians, serpulids, bryozoans and bivalves may also play a role in the edification of the bioherm (i.e., biogenic concretion) (Laubier, 1966; Hong, 1980; Casoli et al., 2020), but their skeletons and tests are more easily eroded by boring organisms (e.g., clionid sponges, bivalves, polychaetes, microborers) than calcified algal thalli, so that they remain of secondary importance (Hong, 1980; Cerrano et al., 2001). Sediment, mostly of organic origin, fills the interstices and also contributes to the construction (Laubier, 1966; Hong, 1980). Bioherms constitute the basis of a very diverse reef represented by: (i) structuring long-lived sessile fauna (Teixidó et al., 2011); (ii) the so-called animal forests constituted by gorgonians, erect sponges and bryozoans (Bertolino et al., 2013; Longo et al., 2018; Casoli et al., 2020); (iii) associations of perennial and seasonal macroalgae (Ballesteros et al., 1993; Boudouresque et al., 2017; Ingrosso et al., 2018; Gennaro et al., 2020); (iv) associated benthic fauna favoured by various sizes of habitats, including infauna (Laubier, 1966; Hong, 1980); and (v) mobile fauna (e.g., teleost fishes, crustaceans, echinoderms, cephalopods, gastropods) that permanently or temporarily use the bioherm framework as a shelter, a trophic source, a place for breeding or feeding, and a nursery, or that transit from neighbouring ecosystems (Laubier, 1966; Gómez-Gras et al., 2021). Altogether, Ballesteros (2006) estimated that ≥ 1666 species are found in coralligenous reefs.

Laborel (1961) described several coralligenous reef types: 'cave and overhang concretions, wall concretions, concretions at the base of submarine walls, concretions over flat rocky surfaces and coralligenous platform', simplified by Pérès and Picard (1964) as two categories: (i) 'deep littoral rock coralligenous', and (ii) 'coralligenous banks or platforms' (see also Sarà, 1968, 1969; Hong, 1982; Harmelin, 1994; Piazzi et al., 2022), similar to those defined by Ballesteros (2006) (see also Bracchi et al., 2017).

Boudouresque et al. (2017) distinguished four communities within coralligenous reefs: (i) the blade-forming calcareous algae, i.e., the

autogenous ecosystem engineers; (ii) the so-called 'pre-coralligenous' macroalgae (e.g., *Flabellia petiolata*); (iii) the seaweed forests (e.g., *Cystoseira* sensu lato, *Sargassum* spp.); and (iv) the animal forests (e.g., gorgonians, large erect porifera, and erect bryozoans). The authors grouped all these categories together as they are closely 'intertwined into a mosaic of patches and successional stages', so that in the frame of an ecosystem-based approach, they constitute one ecosystem.

For the purposes of this study, we will hereafter refer to the coralligenous as an ecosystem formed by the three-dimensional growth of epibiotic organisms (e.g., calcareous algae and other algae, cnidarians, bryozoans) on steep rocky walls or forming a bioherm, especially when coralline algae are particularly abundant. This definition is derived from existing literature and will facilitate the assessment of the coralligenous at ecosystem level.

1.2. Ecological functions and related ecosystem services

The complexity of the coralligenous ecosystem led Laubier (1966) to consider it as an eco-ethological crossroad with numerous interactions with neighbouring ecosystems from infralittoral (e.g., *Posidonia oceanica* seagrass meadow, shallow rocky reefs), circalittoral (e.g., coastal and deep detrital bottoms) and bathyal zones (e.g., bathyal muddy bottoms and reefs) (Fourt et al., 2014; Boudouresque et al., 2021; Astruch et al., 2023). The resulting natural capital of the coralligenous reef ecosystem provides important ecosystem services (Chimienti et al., 2017; Paoli et al., 2017; Thierry de Ville and d'Avray, 2018; Tonin, 2018; Thierry de Ville et al., 2019; Buonocore et al., 2020; Langlois et al., 2021), including: (i) halieutic resources for artisanal fishery (Canessa et al., 2017); (ii) attractive sites for recreational divers (Chimienti et al., 2017); (iii) cultural heritage and aesthetic value (Tribot et al., 2016; Zunino et al., 2020; Langlois et al., 2021); and (iv) long-term carbon sequestration (Martin et al., 2014; van Der Heijden and Kamenos, 2015; Zunino et al., 2019).

1.3. Threats

The coralligenous suffers major stress and disturbances (Gatti et al., 2012, 2015a; Montefalcone et al., 2017; Bevilacqua et al., 2018; Azzola et al., 2023):

- i). **Degradation by waste water and industrial pollution** (Bellan-Santini, 1980; Cormaci et al., 1985; Arnoux et al., 1992; Harmelin and Capo, 2001; Piazzi et al., 2011).
- ii). **Sediment deposition:** related to terrigenous input, coastal development, urbanisation and land reclamations (Airoldi, 2003; Balata et al., 2005, 2007; Gatti et al., 2012; Ponti et al., 2011, 2014; Harmelin, 2009; Casoli et al., 2017). However, sediment deposition can also be of natural origin (e.g., river input; see Hong, 1983).
- iii). **Colonization by invasive and/or harmful species:** the Rhodophyta *Womersleyella setacea* (Ballesteros, 2006), *Lophocladia trichoclados* (Boudouresque et al., 2022, 2024a), the chlorophyta *Caulerpa cylindracea* and *C. taxifolia* (Meinesz, 1999; Piazzi et al., 2007; Baldaconi and Corriero, 2009; Morri et al., 2019), mucilage (i.e., a multi-species complex of native and non-indigenous brown filamentous macroalgae including *Acinetospora crinita*, *Nematochryopsis marina* and *Chrysonephus lewisii*) (Piazzi et al., 2018; Bianchi et al., 2019a, 2019b), recently, the Phaeophyceae *Rugulopteryx okamurae* (Navarro-Barranco et al., 2021; Ruitton et al., 2021a; Sempere-Valverde et al., 2021).

- iv). **Harvesting and degradation by fishing activities:** non-intentional trawling is the most destructive fishing method for hard substrate habitats (Palanques et al., 2001). Recreational and artisanal fisheries also affect the coralligenous by reducing abundance and diversity of target species (Bell, 1983; Garcia-Rubies and Zabala, 1990; Harmelin, 1990). The coralligenous structure is also damaged by fishing gears (especially longlines and plastic lines) from artisanal fisheries (Thibaut et al., 2015, 2016; Ferrigno et al., 2018, 2021; Consoli et al., 2019; Enrichetti et al., 2019a; Ruitton et al., 2019; Azzola et al., 2021; Navarro-Barranco et al., 2023).
- v). **Degradation induced by recreational SCUBA diving:** the impact of recreational divers on the coralligenous has been investigated by several authors (Harmelin and Marinopoulos, 1994; Garrabou et al., 1998; Linares et al., 2010; Ceccherelli et al., 2017), in particular on erect bryozoans (e.g., *Pentapora fascialis*; Sala et al., 1996; Casoli et al., 2017; Harmelin, 2017) and gorgonians (Linares et al., 2010). In many cases, this impact is far from being obvious, likely due to relatively low pressure from visits by divers, natural conditions that may explain the absence of certain indicator species (e.g., erect bryozoans), or because the impact is masked by pressures from other activities such as fishing, anchoring or the consequences of climate change (see below).
- vi). **Climate change and warming of the Mediterranean Sea:** Marine Heat Waves (MHW) are increasing in frequency and triggering epizootic outbreaks and mass mortality events (Pérez et al., 2000; Garrabou et al., 2009, 2022; Ponti et al., 2014; Ceccherelli et al., 2020; Piazzzi et al., 2021a; Estaque et al., 2023; Grenier et al., 2023; Boudouresque et al., 2024b). Climate change is also conducive to an increase in the occurrence and intensity of extreme events (Teixidó et al., 2013; Gómez-Gras et al., 2021), acidification (Linares et al., 2015; Zunino et al., 2019; Teixidó et al., 2024) and the spread and establishment of non-indigenous species (see paragraph iii) and references therein). Pinna et al. (2024) suggest that warming and mechanical abrasion will also impact Crustose Coralline Algae following future climate scenarios.

1.4. Management and ecological indicators

Various indices allow the assessment of coastal waters, marine habitats or ecosystems, but each of them serves a distinct purpose (Kipson et al., 2011; Boudouresque et al., 2020a, 2020b, 2020c; Bianchi et al., 2022; Pausch et al., 2024). Specific descriptors can assess the ecological status linked with the water quality (Water Framework Directive (WFD 2000/60/EC); e.g., Borja et al., 2000, 2003; Ballesteros et al., 2007; Gobert et al., 2009; Lopez y Royo et al., 2010; Deter et al., 2012a; Piazzzi et al., 2021b), the ecosystem functioning (descriptor 1 of the Marine Strategy Framework Directive (MSFD 2008/56/EC); e.g., Personnic et al., 2014; Giakoumi et al., 2015; Montefalcone et al., 2015), the seafloor integrity (descriptor 6 of the MSFD; e.g., Montefalcone et al., 2007; Gatti et al., 2015b; Enrichetti et al., 2019b; Piazzzi et al., 2019), the conservation status of natural habitats (Habitat Directive (HD 92/43/EEC); e.g., Maciejewski et al., 2016; Sartoretto et al., 2017). Some others target the putative effects of natural and anthropogenic stressors (Holon et al., 2015; Quemmerais-Amice et al., 2020). The Barcelona Convention (BC) was established in 1976 in order to protect the marine environment in the Mediterranean. The BC recognizes the significance of the coralligenous as an essential component of the Mediterranean Sea. Through its protocols and action plans (e.g., UNEP/MAP: Mediterranean Action Plan within United Nations Environment Program), the BC promotes measures to safeguard the coralligenous reef habitat from anthropogenic threats, ensuring its conservation and sustainable use (UNEP-MAP/SPA-RAC, 2011). In the framework of the HD, coralligenous is part of the Reef '1170' habitat of European Interest

(Bensettiti et al., 2004; Maciejewski et al., 2016). Consequently, considering the EUR27 typology, upper circalittoral reefs have been defined as 'coralligenous reefs', corresponding to different types, facies and associations fitting with Natura 2000 criteria.

Numerous ecological indices dealing with the coralligenous have been developed, published and implemented. They have adopted different approaches focussing on species composition, seascape structure or other metrics (Bavestrello et al., 2016). The purposes, methods and metrics of 16 of these indices have been recently reviewed by Di Camillo et al. (2023). The CAI (Coralligenous Assemblages Index; Deter et al., 2012a, 2012b) is currently applied along the French Mediterranean coast. It proposes a suitable method to quickly assess several descriptors of the coralligenous structure (biobuilders, sediment cover, animal forests) using standardized photoquadrats. The MACS index (Enrichetti et al., 2019b) aims at assessing mesophotic reefs (including coralligenous reefs) fitting with MSFD descriptors 1, 6 and 10. The CBQI (Coralligenous Bioconstructions Quality Index; Ferrigno et al., 2017) aims at assessing the coralligenous reef quality based on the assessment of structuring communities, bottom abiotic factors and anthropic stress level. The COARSE index (COralligenous Assessment by ReefScape Estimate; Gatti et al., 2015b) is a rapid visual assessment method to evaluate the seafloor integrity and the health of the coralligenous. The ISLA (Integrated Sensitivity Level of Coralligenous Assemblages; Montefalcone et al., 2017) aims at assessing the ecological status of coralligenous assemblages considering the sensitivity of the resident communities to disturbance and stress. INDEX-COR (Sartoretto et al., 2017) considers three metrics: i) the sensitivity of the taxa to organic matter and sediment deposition; ii) the observable taxonomic richness; and iii) the structural complexity of the assemblages. ESCA and ESCA-TA (Cecchi et al., 2014; Piazzzi et al., 2017, 2021c) consider the cover of sensitive taxa, the diversity (α -diversity) and the heterogeneity (β -diversity). ESCA and INDEX-COR have been tested with regard to an anthropization index. The STAR (STAndardized coralligenous evaluation procedure; Piazzzi et al., 2019, 2025) encompasses several existing indices to allow impact assessment on coralligenous reefs. Most of these methods support monitoring activities at regional (EU Directive) and/or local scale, highlighting the need for proper management measures and protection of the coralligenous (Piazzzi et al., 2016). The main conclusion of the Di Camillo et al. (2023) review was that integrated approaches and a common methodology are needed at the Mediterranean basin scale for the proper monitoring of coralligenous reefs. The OCI index by Paoli et al. (2016), for instance, combines both extensive and intensive structural and functional metrics, including exergy, throughput, and information, to estimate overall ecological complexity. Given the conceptual differences that underlie all those approaches, Bavestrello et al. (2016) called for an intercalibration of the ecological indices currently available.

1.5. The ecosystem-based approach

Coastal management policies need an appropriate combination of the most relevant descriptors in an integrated index (Bond, 2001; Pikaver et al., 2004; Paoli et al., 2016; Borja et al., 2021; Oprandi et al., 2021, 2023). In this context, the aim of the ecosystem-based approach is to achieve a better understanding of ecosystem functioning as a basis for more suitable management strategies (Laffoley et al., 2004; Boudouresque et al., 2020a, 2020b, 2020c). Ecosystem-Based Quality Indices (EBQIs) have been already defined for a number of Mediterranean coastal marine ecosystems, namely *Posidonia oceanica* seagrass meadows (Personnic et al., 2014; Boudouresque et al., 2015), underwater caves (Rastorgueff et al., 2015), shallow rocky reefs (Thibaut et al., 2017; Jacob et al., 2024), and coastal detrital bottoms (Astruch et al., 2023). Other indices apply an ecosystem-based approach, such as the MACS index (Enrichetti et al., 2019b), designed to assess 'mesophotic reefs' using video transects carried out by ROV (Remote Operating Vehicle), or the ECOfast index (Kytinou et al., 2023), implemented in the eastern

Mediterranean Sea for shallow rocky reefs.

Proposing an easy assessment method for one of the most complex ecosystems of the Mediterranean Sea (Boudouresque, 2004; Ballesteros, 2006; Paoli et al., 2016; Boudouresque et al., 2017; Pérez, 2024) is challenging and requires a pragmatic and robust approach based on updated knowledge. The present paper aims at proposing an original ecosystem-based quality index adapted to the coralligenous (hereafter Cor-EBQI), inspired by EBQIs developed for other ecosystems and by other existing indices designed for the coralligenous. The effectiveness of this novel index was tested along the coasts of the French Mediterranean Sea (Gulf of Lions, western and eastern Provence, French Riviera and Corsica) and Monaco with regard to the level of pressure, management, habitat geomorphology and local specificities.

2. Material and methods

A workshop involving experts on coralligenous reefs was held on November 28th, 2013. Workshop participants are the authors of the preliminary work by Ruitton et al. (2014). A DELPHI approach was implemented (Rowe and Wright, 1999) to discuss and validate: i) a conceptual model of the coralligenous reef composed by its main functional compartments (boxes); ii) the descriptors to assess each box; and iii) the weighting of each box to design the Cor-EBQI.

2.1. Conceptual model of the coralligenous

A simplified conceptual model of the functioning of coralligenous reefs is illustrated hereafter (Fig. 1). Its aim is to describe an easy way to understand the main fluxes of organic matter, mainly by trophic interactions, between functional compartments. Fifteen compartments are

defined and ten are considered in the Cor-EBQI scoring.

2.2. Box description

The lists of characteristic taxa of coralligenous reefs used for boxes 1, 2, 3 and 5 are taken from UNEP-MAP-RAC/SPA (2011) and completed with literature data and authors' expert judgement.

1) Builders.

Sessile biota, both vegetal and animal, growing in the three dimensions are the fundamental component of the coralligenous reef ecosystem. Among them, builders play a crucial role. The quality of this functional compartment is a keystone of the whole ecosystem functioning. Corallinales and Hapalidiales are the main photosynthetic bio-builders of the frameworks (Ballesteros, 2006; Bracchi et al., 2022). *Mesophyllum alternans*, a tolerant species, is the main calcareous alga contributing to the building of the basal concretion (Sartoretto et al., 1996). Different *Mesophyllum* species merged into *M. alternans* in past research (E. Ballesteros, unpublished data). *Mesophyllum expansum* can be observed with foliated thalli. *Lithophyllum stictiforme* constitutes a species complex (De Jode et al., 2019; Pezzolesi et al., 2019), which includes from 8 to 11 'cryptic species' such as *L. cabiochiai* and *L. stictiforme*. *Lithophyllum incrustans* is a mainly infralittoral tolerant encrusting species which can be abundant in low water quality conditions (Boudouresque, 1984). Calcified Peyssonneliaceae have a much lower building capacity than *Lithophyllum* spp. or *Mesophyllum* spp. (Sartoretto, 1996). Identification of Peyssonneliaceae at the species level is not possible in situ, sampling being necessary. Animal builders are also numerous and allow the enhanced complexity of the coralligenous framework (Laubier, 1966; Hong, 1980; Ballesteros, 2006). The characteristic species considered for box 1 are listed in Table 1 (Péres and

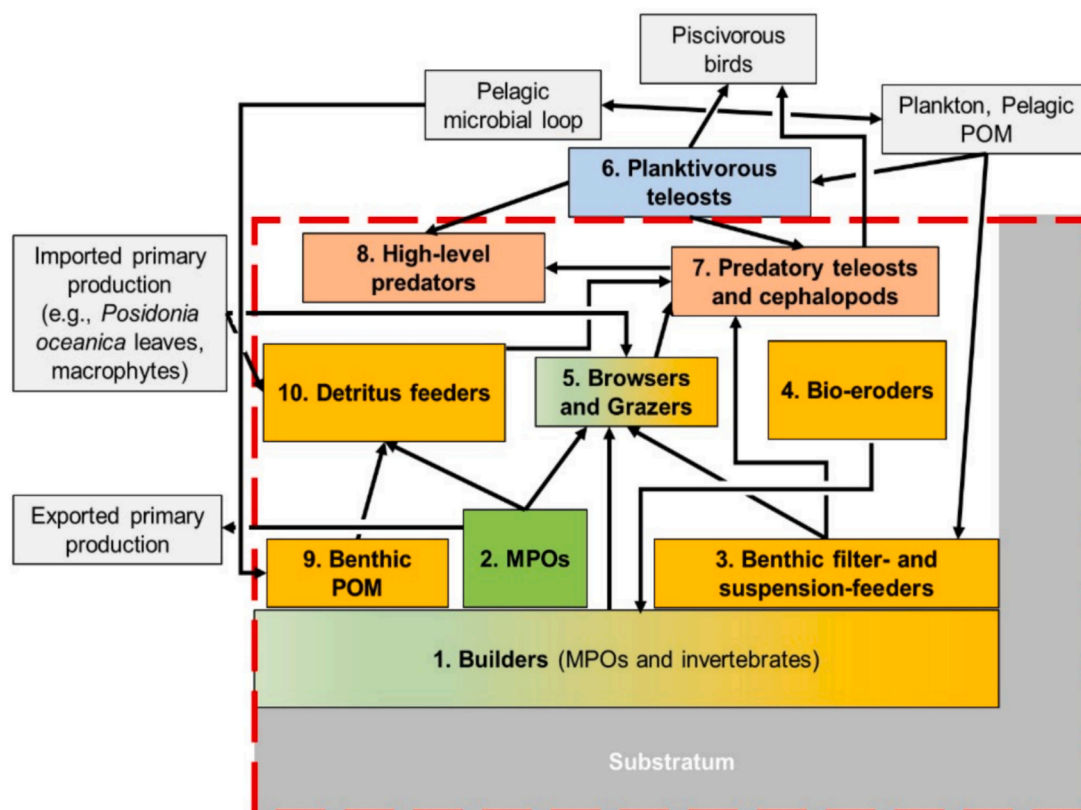


Fig. 1. Conceptual model of the functioning of the coralligenous ecosystem, modified from Ruitton et al. (2014, 2017). The coralligenous proper functional compartments are included within the red dotted rectangle. MPOs: Multicellular Photosynthetic Organisms; POM: Particulated Organic Matter; DOM: Dissolved Organic Matter. See text for the description of the boxes. Box colours are related to the trophic level: green for MPOs and herbivores, orange for detritivores, bioeroders and filter and suspension feeders, light red for carnivores and blue for planktivores. Boxes in light gray and without numbers are not included for Cor-EBQI calculation. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1

Taxa considered for boxes 1 (builders), 2 (MPOs), 3 (BFSF) and 5 (browsers and grazers). The box 5 list corresponds to taxa observed during the survey and is not predefined.

Box	Phylum	Scientific name	Authority		
1 - Builders	Rhodophyta	<i>Lithophyllum stictiforme</i>	(J.E. Areschoug) Hauck		
		<i>Mesophyllum alternans</i>	(Foslie) Cabioch & M.L.Mendoza (Philippi)		
		<i>Mesophyllum expansum</i>	Cabioch & M.L. Mendoza		
		<i>Mesophyllum macedonis</i>	Athanasiadis		
		<i>Mesophyllum macroblastum</i>	(Foslie) W.H. Adey		
		<i>Peyssonnelia heteromorpha</i>	Athanasiadis		
		<i>Peyssonnelia rosamarina</i>	Boudouresque & Denizot		
		Annelida	<i>Filograna</i> sp. / <i>Salmacina</i> sp.	Berkeley, 1835 / Claparède, 1870	
			<i>Protula</i> spp.	Risso, 1826	
			<i>Serpula</i> spp.	Linnaeus, 1758	
			<i>Spirobranchus</i> spp.	Blainville, 1818	
			<i>Spirorbinae</i> spp.	Chamberlin, 1919	
	Bryozoa	<i>Adeonella calveti</i>	Canu & Bassler, 1930		
		<i>Cellepora pumicosa</i>	(Pallas, 1766)		
		<i>Celleporina mangnevellana</i>	(Lamouroux, 1816)		
		<i>Dentiporella sardonica</i>	(Waters, 1879)		
		<i>Myriapora truncata</i>	(Pallas, 1766)		
		<i>Parasmittina</i> spp.	Osburn, 1952		
		<i>Pentapora fascialis</i>	(Pallas, 1766)		
		<i>Reteporella</i> spp.	Busk, 1884		
		<i>Schizomavella</i> spp.	Canu & Bassler, 1917		
		<i>Schizoretepora serratimargo</i>	(Hincks, 1886)		
		Cnidaria	<i>Smittina cervicornis</i>	(Pallas, 1766)	
			<i>Caryophyllia (Caryophyllia) inornata</i>	(Duncan, 1878)	
			<i>Caryophyllia (Caryophyllia) smithii</i>	Stokes & Broderip, 1828	
			<i>Hoplangia durotrix</i>	Gosse, 1860	
			<i>Leptopsammia pruvoti</i>	Lacaze-Duthiers, 1897	
	<i>Phyllangia americana mouchezii</i>		Lacaze-Duthiers, 1897		
	<i>Polycyathus muellerae</i>		(Abel, 1959)		
	Foraminifera		<i>Miniacina miniacea</i>	(Pallas, 1766)	
			Chlorophyta	<i>Codium coralloides</i>	(Kützing) P.C. Silva
				<i>Flabellia petiolata</i>	(Turra) Nizamuddin
2 - MPOs	Chordata	<i>Halimeda tuna</i>	(J.Ellis & Solander) J.V. Lamouroux		
		<i>Pseudochlorodesmis furcellata</i>	(Zanardini) Borgesen		
		<i>Valonia macrophysa</i>	Kützing (Naccari)		
		Prasinodermatophyta	<i>Palmophyllum crassum</i>	Rabenhorst	
			Phaeophyceae	<i>Arthrocladia villosa</i>	(Hudson) Duby
	<i>Cystoseira sensu lato</i>	C.Agardh			
	<i>Dictyopteris polypodioides</i>	(A.P.De Candolle) J.V. Lamouroux			
	<i>Dictyota</i> spp.	J.V.Lamouroux			
	<i>Ericaria funkii</i>	(Schiffner ex Gerloff &			

Table 1 (continued)

Box	Phylum	Scientific name	Authority	
3 - Benthic filter- and suspension feeders	Annelida	<i>Ericaria zosteroides</i>	Nizamuddin Molinari & Guiry (C.Agardh)	
		<i>Gongolaria montagnei</i> var. <i>compressa</i>	Molinari & Guiry (Ercegović) Verlaque, Blanfuné, Boudouresque & Thibaut	
		Bryozoa	<i>Halopteris filicina</i>	(Grateloup) Kützing
			<i>Nereia filiformis</i>	(J.Agardh) Zanardini
		Chordata	<i>Phyllariopsis brevipes</i>	(C.Agardh) E.C. Henry & G.R. South
			<i>Sargassum</i> spp.	C.Agardh
		Cnidaria	<i>Spatoglossum solieri</i>	(Chauvin ex Montagne) Kützing
			<i>Sporochnus pedunculatus</i>	(Hudson) C. Agardh
			<i>Zanardinia typus</i>	(Nardo) P.C.Silva
			<i>Zonaria tournefortii</i>	(J.V.Lamouroux) Montagne
	<i>Chrysymenia ventricosa</i>		(J.V.Lamouroux) J.Agardh	
	<i>Felicinia marginata</i>		(Roussel) Manghisi, Le Gall, Ribera, Gargiulo & Morabito	
	<i>Gloiocladia repens</i>		(C.Agardh) N. Sánchez & Rodríguez-Prieto	
	<i>Gulsonia nodulosa</i>		(Ercegovic) Feldmann & G. Feldmann	
	<i>Halymenia</i> spp.		C.Agardh	
	<i>Nemastoma</i> spp.		J.Agardh	
	<i>Osmundaria volubilis</i>	(Linnaeus) R.E. Norris		
	Cnidaria	<i>Phyllophora crispa</i>	(Hudson) P.S. Dixon	
		<i>Platoma cyclocolpum</i>	(Montagne) F. Schmitz	
		<i>Plocamium cartilagineum</i>	(Linnaeus) P.S. Dixon	
		<i>Sebdenia</i> spp.	(J.Agardh) Berthold	
		<i>Sphaerococcus coronopifolius</i>	Stackhouse	
<i>Sabella spallanzanii</i>		(Gmelin, 1791) (Hincks, 1887)		
<i>Chartella tenella</i>		(Lamarck, 1816)		
<i>Margaretta cereoides</i>		(Ellis & Solander, 1786)		
<i>Turbicellepora avicularis</i>		(Hincks, 1860)		
<i>Aplidium</i> spp.		Savigny, 1816		
<i>Diazona violacea</i>	Savigny, 1816			
<i>Halocynthia papillosa</i>	(Linnaeus, 1767)			
<i>Microcosmus</i> spp.	Heller, 1877			
<i>Pseudodistoma cyrnusense</i>	Pères, 1952			
Cnidaria	<i>Alcyonium acaule</i>	Marion, 1878		
	<i>Alcyonium coralloides</i>	(Pallas, 1766)		
	<i>Corallium rubrum</i>	(Linnaeus, 1758)		
	<i>Eunicella cavolini</i>	(Koch, 1887)		
	<i>Eunicella singularis</i>	(Esper, 1791)		
	<i>Leptogorgia sarmentosa</i>	(Esper, 1791)		
	<i>Paramuricea clavata</i>	(Risso, 1827)		
	<i>Parazoanthus axinellae</i>	(Schmidt, 1862)		

(continued on next page)

Table 1 (continued)

Box	Phylum	Scientific name	Authority	
5 - Browsers and grazers	Echinodermata	<i>Savalia savaglia</i>	(Bertoloni, 1819)	
		<i>Antedon mediterranea</i>	(Lamarck, 1816)	
		<i>Astrospartus mediterraneus</i>	(Risso, 1826)	
	Mollusca	<i>Arca noae</i>	Linnaeus, 1758	
		<i>Lima</i> sp.	Bruguière, 1797	
		<i>Mimachlamys</i> sp.	Iredale, 1929	
		<i>Pteria hirundo</i>	(Linnaeus, 1758)	
		Porifera	<i>Acanthella acuta</i>	Schmidt, 1862
			<i>Agelas oroides</i>	(Schmidt, 1864)
			<i>Aplysina cavernicola</i>	(Vacelet, 1959)
			<i>Axinella damicornis</i>	(Esper, 1794)
			<i>Axinella polypoides</i>	Schmidt, 1862
			<i>Axinella verrucosa</i>	(Esper, 1794)
	<i>Chondrosia reniformis</i>		Nardo, 1847	
	<i>Clathrina</i> sp.		Gray, 1867	
	<i>Crambe crambe</i>		(Schmidt, 1862)	
	<i>Dysidea</i> sp.		Johnston, 1842	
	<i>Haliclona (Reniera) mediterranea</i>		Griessinger, 1971	
	<i>Haliclona (Soestella) mucosa</i>		(Bowerbank, 1874)	
	<i>Hemimycale columella</i>		(Schmidt, 1864)	
	<i>Ircinia oros</i>		(Schmidt, 1862)	
	<i>Ircinia variabilis</i>		Vosmaer, 1884	
	<i>Oscarella</i> sp.		(Poiret, 1789)	
	<i>Petrosia (Petrosia) ficiformis</i>		(Topsent, 1925)	
	<i>Phorbis tenacior</i>		(Schmidt, 1862)	
	<i>Scalarispongia scalaris</i>		Schmidt, 1868	
	<i>Spirastrella cunctatrix</i>		(Schulze, 1879)	
	<i>Spongia (Spongia) lamella</i>	Linnaeus, 1759		
	<i>Spongia (Spongia) officinalis</i>	(Philippi, 1845)		
	Echinodermata	<i>Centrostephanus longispinus</i>	Lamarck, 1816	
		<i>Echinus melo</i>	Gray, 1840	
		Mollusca	<i>Hacelia attenuata</i>	(Delle Chiaje, 1841)
			<i>Antiopella cristata</i>	(Laurillard, 1832)
			<i>Berghia coerulescens</i>	J. E. Gray, 1847
			<i>Bittium</i> sp.	(Linnaeus, 1758)
			<i>Bolinus brandaris</i>	(Linnaeus, 1767)
			<i>Calliostoma zizyphinum</i>	(Linnaeus, 1758)
			<i>Calmella cavolini</i>	(Vérany, 1846)
			<i>Caloria elegans</i>	(Alder & Hancock, 1845)
			<i>Cerithium</i> spp.	Bruguière, 1789
			<i>Charonia lampas</i>	(Linnaeus, 1758)
		<i>Charonia variegata</i>	(Lamarck, 1816)	
		<i>Clanculus corallinus</i>	(Gmelin, 1791)	
		<i>Cratena peregrina</i>	(Gmelin, 1791)	
		<i>Dendrodoris</i> spp.	Ehrenberg, 1831	
		<i>Diaphorodoris</i> sp.	Iredale & O'Donoghue, 1923	
		<i>Candiella striata</i>	(Haefelfinger, 1963)	
		<i>Edmundsella pedata</i>	(Montagu, 1816)	
		<i>Euthria cornea</i>	(Linnaeus, 1758)	
	<i>Felimare cantabrica</i>	(Bouchet & Ortea, 1981)		
<i>Felimare fontandraui</i>	(Pruvot-Fol, 1951)			
<i>Felimare gasconi</i>	(Ortea, 1996)			
<i>Felimare orsinii</i>	(Vérany, 1846)			

Table 1 (continued)

Box	Phylum	Scientific name	Authority
		<i>Felimare picta</i>	(R. A. Philippi, 1836)
		<i>Felimare tricolor</i>	(Cantraine, 1835)
		<i>Felimida binza</i>	(Ev. Marcus & Er. Marcus, 1963)
		<i>Felimare villafranca</i>	(Risso, 1818)
		<i>Felimida krohni</i>	(Vérany, 1846)
		<i>Felimida luteorosea</i>	(Rapp, 1827)
		<i>Flabellina affinis</i>	(Gmelin, 1791)
		<i>Haliotis</i> sp.	Linnaeus, 1758
		<i>Hexaplex trunculus</i>	(Linnaeus, 1758)
		<i>Jujubinus</i> spp.	Monterosato, 1884
		<i>Linatella caudata</i>	(Gmelin, 1791)
		<i>Lomanotus genei</i>	Vérany, 1846
		<i>Luisella babai</i>	(Schmekel, 1972)
		<i>Luria lurida</i>	(Linnaeus, 1758)
		<i>Monoplex durbanensis</i>	(E. A. Smith, 1899)
	<i>Monoplex parthenopeus</i>	(Salis Marschlin, 1793)	
	<i>Naria spurca</i>	(Linnaeus, 1758)	
	<i>Nemesignis banyulensis</i>	(Portmann & Sandmeier, 1960)	
	<i>Paraflabellina gabinierii</i>	(Vicente, 1975)	
	<i>Paraflabellina ischitana</i>	(Y. Hirano & T. E. Thompson, 1990)	
	<i>Peltodoris atromaculata</i>	Bergh, 1880	
	<i>Phyllidia flava</i>	Aradas, 1847	
	<i>Pleurobranchus testudinarius</i>	Cantraine, 1835	
	<i>Simnia</i> sp.	Risso, 1826	
	<i>Thuridilla hopei</i>	(Vérany, 1853)	
	<i>Tritonia</i> sp.	Cuvier, 1798	
	<i>Tylocladia perversa</i>	(Gmelin, 1791)	
	<i>Umbraculum umbraculum</i>	([Lightfoot], 1786)	
	Platyhelminthes	<i>Prostheceraeus giesbrechtii</i>	Lang, 1884
		<i>Prostheceraeus roseus</i>	Lang, 1884
<i>Pseudobiceros splendidus</i>		(Lang, 1884)	

Picard, 1951; Laubier, 1966; Harmelin, 2017; Casoli et al., 2020).

2) Multicellular Photosynthetic Organisms (MPOs, no builders).

This box includes both perennial and seasonal macroalgae that are not involved in the building process. The main characteristic taxa considered here are listed in Table 1. All, except *Halimeda tuna*, are not calcified but several of them may have a heavy cover of small calcified epiphytes. All the furoids (*Cystoseira* sensu lato and *Sargassum* spp.) are found dwelling on the rocky part of the coralligenous when foliaceous calcareous algae are absent. Stress-tolerant species such as *Codium bursa* and *C. vermilara* and non-indigenous species (e.g., *Caulerpa cylindracea*, *C. taxifolia*, *Womersleyella setacea*, *Acrothamnion preissii*, *Rugulopteryx okamurae*, *Asparagopsis taxiformis*, *Lophocladia trichoclados*), are not taken into account in this box: non-indigenous species are not considered as part of the ecosystem but rather as stressors.

3) Benthic filter- and suspension-feeders (BFSF).

Box 3 encompasses taxa that are not significantly involved in the building process of the coralligenous framework, even if some of them harbour calcareous structures. Benthic filter- and suspension-feeders (BFSF) are mainly represented by sponges, cnidarians, annelids, bryozoans, ascidians, echinoderms, crustaceans and molluscs. The main characteristic species are listed in Table 1.

4) Bioeroders.

Bioeroders or borers play a major role by influencing the dynamic and the complexity of the framework. Feldmann (1937) was the first to

describe their role in coralligenous reefs. Among the complex and diverse community of bioeroders, the sponges *Cliona viridis* and *C. celata* are the most powerful destructive species (Rosell et al., 1999). *C. viridis* is more abundant in areas rich in organic matter (Hong, 1983; Cerrano et al., 2001) and can be related to an unbalanced condition of the coralligenous functioning and construction, shifting from builder-dominated to borer-dominated communities (Turicchia et al., 2022). The boring bivalves *Rocellaria dubia* and *Lithophaga lithophaga* and sipunculids also contribute to bioerosion (Hong, 1980; Gennaro et al., 2020; Turicchia et al., 2022). The sea urchin *Sphaerechinus granularis*, by grazing calcareous algae, contributes to the wearing down of the basal bioconcretion (Sartoretto, 1996, 1998; Sartoretto and Francour, 1997; Boudouresque et al., 2017).

5) Browsers and grazers.

The diversity and abundance of browsers and grazers reflects the complexity and diversity of assemblages associated with the

coralligenous framework. Some grazers are associated with sessile invertebrates (e.g., *Peltodoris atromaculata* eating *Petrosia ficiformis*; *Flabellina* spp. on *Eudendrium* spp.). This box is mainly represented by echinoderms and gastropods, including numerous opisthobranchs (Table 1).

6) Planktivorous teleosts.

Planktivorous teleosts *Anthias anthias* and *Apogon imberbis* are considered as nocturnal feeders in coralligenous, while *Chromis chromis*, *Spicara maena*, *S. smaris* and *Boops boops*, use at least partially coralligenous reefs, feeding in the water column during the day and resting in the coralligenous outcrops at night. They can form schools of over several thousand individuals, providing a substantial resource for high-level predators (box 8) and importing organic matter from the pelagic to the benthic system (e.g., *C. chromis*; Pinnegar and Polunin, 2006). Other occasional planktivorous species, less dependent on benthic habitats, can be observed: e.g., *Engraulis encrasicolus*, *Sardina pilchardus*,

Table 2

List of the main teleost fish species found during visual census on the coralligenous (non-exhaustive), corresponding trophic group (box), authority, a and b Length/Weight coefficients, source of the data (Fishbase or Ecocen), LSID.

Box	Scientific name	Authority	Coeff a	Coeff b	Source	
6 - Planktivorous teleosts	<i>Anthias anthias</i>	(Linnaeus, 1758)	0.023	2.8292	Ecocen	
	<i>Apogon imberbis</i>	(Linnaeus, 1758)	0.01245	3.1079	Ecocen	
	<i>Atherina</i> spp.	Linnaeus, 1758	0.0075	3.023	Fishbase	
	<i>Boops boops</i>	(Linnaeus, 1758)	0.0161	2.8121	Ecocen	
	<i>Chromis chromis</i>	(Linnaeus, 1758)	0.02625	2.7534	Ecocen	
	<i>Engraulis encrasicolus</i>	(Linnaeus, 1758)	0.00654	2.98087	Ecocen	
	<i>Oblada melanurus</i>	(Linnaeus, 1758)	0.013	3.058794	Ecocen	
	<i>Sardina pilchardus</i>	(Walbaum, 1792)	0.00594	3.0766	Ecocen	
	<i>Spicara maena</i>	(Linnaeus, 1758)	0.004	3.037	Ecocen	
	<i>Spicara smaris</i>	(Linnaeus, 1758)	0.013	2.987	Ecocen	
	7 - Predatory teleosts, omnivores and cephalopods	<i>Centrolabrus melanocercus</i>	(Risso, 1810)	0.00977	3.04	Fishbase
		<i>Coris julis</i>	(Linnaeus, 1758)	0.00685	3.0311	Ecocen
		<i>Ctenolabrus rupestris</i>	(Linnaeus, 1758)	0.0123	3	Fishbase
		<i>Diplodus annularis</i>	(Linnaeus, 1758)	0.01648	2.9859	Ecocen
<i>Diplodus cervinus</i>		(Lowe, 1838)	0.01479	3.079	Ecocen	
<i>Diplodus puntazzo</i>		(Walbaum, 1792)	0.01479	3.079	Ecocen	
<i>Diplodus sargus</i>		(Linnaeus, 1758)	0.01479	3.079	Ecocen	
<i>Diplodus vulgaris</i>		(Geoffroy Saint-Hilaire, 1817)	0.01423	3.0288	Ecocen	
<i>Mola mola</i>		(Linnaeus, 1758)	0.0454	3.05	Fishbase	
<i>Mullus surmuletus</i>		Linnaeus, 1758	0.00972	3.0746	Ecocen	
<i>Pagellus acarne</i>		(Risso, 1827)	0.0049	3.3	Ecocen	
<i>Pagellus erythrinus</i>		(Linnaeus, 1758)	0.0168	3.06	Fishbase	
<i>Pagrus pagrus</i>		(Linnaeus, 1758)	0.0152	3.005	Fishbase	
<i>Sciaena umbra</i>		Linnaeus, 1758	0.00826	3.05876	Ecocen	
<i>Scorpaena notata</i>		Rafinesque, 1810	0.02237	2.9194	Ecocen	
<i>Scorpaena porcus</i>		Linnaeus, 1758	0.01667	3.0179	Ecocen	
<i>Serranus cabrilla</i>		(Linnaeus, 1758)	0.01661	2.8246	Ecocen	
<i>Serranus hepatus</i>		(Linnaeus, 1758)	0.01117	3.1233	Ecocen	
<i>Serranus scriba</i>		(Linnaeus, 1758)	0.01368	2.9707	Ecocen	
<i>Sparus aurata</i>		Linnaeus, 1758	0.0136	3.04	Ecocen	
<i>Spondylisoma cantharus</i>		(Linnaeus, 1758)	0.0091	2.948	Ecocen	
<i>Symphodus cinereus</i>		(Bonnaterre, 1788)	0.01007	3.1328	Ecocen	
<i>Symphodus doderleini</i>		Jordan, 1890	0.00835	3.1967	Ecocen	
<i>Symphodus mediterraneus</i>		(Linnaeus, 1758)	0.02121	2.8798	Ecocen	
<i>Symphodus ocellatus</i>		(Linnaeus, 1758)	0.00911	3.1708	Ecocen	
<i>Symphodus rostratus</i>		(Bloch, 1791)	0.01769	2.8019	Ecocen	
<i>Symphodus tinca</i>		(Linnaeus, 1758)	0.0102	3.0738	Ecocen	
<i>Thalassoma pavo</i>		(Linnaeus, 1758)	0.0069	3.0806	Ecocen	
<i>Trachurus</i> spp.		Rafinesque, 1810	0.00719	3.03271	Ecocen	
<i>Trisopterus</i> sp.		Rafinesque, 1814	0.00752	3.15	Fishbase	
8 - High-level predators		<i>Conger conger</i>	(Linnaeus, 1758)	0.00022	3.50886	Ecocen
		<i>Dentex dentex</i>	(Linnaeus, 1758)	0.011	3.06	Ecocen
	<i>Epinephelus costae</i>	(Steindachner, 1878)	0.00832	3.01	Fishbase	
	<i>Epinephelus marginatus</i>	(Lowe, 1834)	0.024322	2.971	Ecocen	
	<i>Labrus merula</i>	Linnaeus, 1758	0.0102	3.0738	Ecocen	
	<i>Labrus mixtus</i>	Linnaeus, 1758	0.0048	3.318	Ecocen	
	<i>Labrus viridis</i>	Linnaeus, 1758	0.0102	3.0738	Ecocen	
	<i>Muraena helena</i>	Linnaeus, 1758	0.00022	3.50886	Ecocen	
	<i>Mycteroperca rubra</i>	(Bloch, 1793)	0.01072	3.01	Fishbase	
	<i>Phycis phycis</i>	(Linnaeus, 1766)	0.00513	3.074	Ecocen	
	<i>Sarda sarda</i>	(Bloch, 1793)	0.0082	3.13	Fishbase	
	<i>Scorpaena scrofa</i>	Linnaeus, 1758	0.0218	2.9392	Ecocen	
	<i>Sphyraena viridensis</i>	(Linnaeus, 1758)	0.031	2.32	Ecocen	

Sardinella aurita (Table 2).

7) Predatory teleosts, omnivores and cephalopods.

This compartment includes meso- and macro-carnivorous and omnivorous species whose diet consists of invertebrates such as annelids, crustaceans, echinoderms, and molluscs, e.g., *Scorpaena porcus*, *Phycis phycis*, *Diplodus puntazzo*, *D. vulgaris*, *D. sargus*, *Pagellus* spp., *Spondyliosoma cantharus*, *Symphodus* spp., *Coris julis*, *Labrus mixtus*, *L. merula* (Table 2). This category also includes cephalopods (e.g., *Octopus vulgaris*, *Sepia officinalis*, *Loligo vulgaris*).

8) High-level predators (piscivorous teleosts).

The abundance of high-level predators (i.e., piscivores) is considered as a good indicator of the quality of fish assemblages with regard to the management of fishing activities (Astruch et al., 2018; Oprandi et al., 2023). *Dentex dentex*, *Epinephelus marginatus*, *Scorpaena scrofa*, *Muraena helena*, *Pagrus pagrus*, *Sphyrna viridensis*, *Seriola dumerilii* and *Conger conger* are among the main species found (Table 2).

6–8) Specific Relative Diversity Index (SRDI).

The specific richness of fish assemblages is a good descriptor of the status of fish assemblages, complementary to the mean biomass per trophic group (Oprandi et al., 2023).

9) Benthic Particulate Organic Matter (POM).

This compartment comprises particulate organic matter settled on the substrate as well as detrital litter. The particulate matter is composed of both organic and mineral matter; however, it is not possible to distinguish between the two in situ. Detrital litter consists of organic debris, from both plants and animals, imported from adjacent ecosystems (Belloni et al., 2019). The cover of sediment on the substrate can be a good proxy of the sedimented POM. Dead leaves and broken rhizomes of *Posidonia oceanica*, originating from the infralittoral zone (Boudouresque et al., 1990, 2023), could have been included in this box. However, we have classified them under 'Imported primary production,' an external box that contributes to box 10 (detritus-feeders) (Fig. 1).

10) Detritus-feeders.

Detritus-feeders constitute a complex compartment contributing to the degradation of organic matter (Purcell et al., 2016; Lee et al., 2018). Here we have chosen to consider the abundance of Holothuroidea and *Bonellia viridis* as proxies of this compartment, these taxa being easy to identify in situ.

2.3. Functional compartments not considered in the assessment

The Pelagic POM, the Pelagic Microbial Loop, Dissolved Organic Matter and Phyto- and Zooplankton communities and imported primary production are also part of coralligenous ecosystem functioning (Fig. 1) but are not considered in the Cor-EBQI calculation. A 'Piscivorous birds' compartment could have been considered as for *P. oceanica* meadows (Personnic et al., 2014) and shallow rocky reefs (Thibaut et al., 2017), but its main taxon (e.g., *Phalacrocorax* spp.) is known to feed mostly on seagrass meadows and pelagic fish species (Morat et al., 2011). For this reason, this compartment has not been assessed for the Cor-EBQI.

2.4. Weighting

The weighting of each functional compartment has been determined via a DELPHI process among the experts participating in the workshop. Builders (box 1), filter- and suspension-feeders (box 3) and borers (box 4) get the highest weighting (5), as these boxes are considered the most important in the ecosystem functioning; other compartments, such as planktivorous teleosts (box 6), predators of invertebrates (box 7), benthic POM (box 9) and detritus-feeders (box 10), get a lower weighting (1–2) (see Table 4).

2.5. Synthesis

Table 4 presents for each box the corresponding descriptors and status (from 0 to 4).

2.6. Cor-EBQI calculation

The Cor-EBQI is then calculated using the following formula (Eq. 1):

$$\text{Cor-EBQI} = \left[\frac{\sum_{i=1}^{11} (W_i \times S_i)}{\sum_{i=1}^{11} (W_i \times S_{\max})} \right] \times 10 \quad \text{Eq. 1}$$

W_i is the weight of the box, S_i the status of the box and S_{\max} the maximum status possible (4, in this case). A score between 0 and 10 is obtained, and an ecological status is defined according to the resulting score (Personnic et al., 2014; Table 3). The ecological status limits are similar to those defined for *Posidonia oceanica* seagrass meadow (Personnic et al., 2014), shallow rocky reefs (Thibaut et al., 2017), and coastal detrital bottoms (Astruch et al., 2023).

A confidence index (CI) was used to assess the quality of the data (suitable protocol, recent data, expert judgement) (Eq. 2), scored between 0 and 4 (Table 5). The CI allows the assessment of the quality of the survey according to recommended methods. If a survey does not combine all the suitable methods, it will still be possible to calculate an EBQI with a low CI (e.g., data available with other protocols, expert judgement). Of course, to calculate the Cor-EBQI, all compartments must have an assessment, even without field data or expert judgement. In this case, the score attributed to a neighbouring site (under the same environmental conditions, management, anthropogenic pressure level) can be used, implying the attribution of the lowest score for CI (0).

$$\text{CI} = \left[\frac{\sum_{i=1}^{11} (W_i \times CI_i)}{\sum_{i=1}^{11} (W_i \times CI_{\max})} \right] \quad \text{Eq. 2}$$

2.7. Data collection

The survey must be carried out between June and August, when most of the macrophytes are well developed (Feldmann, 1937) and water temperature is suitable for assessing fish assemblages. If the survey is done in a different period, a reduction in the confidence index of the most sensitive compartments must be applied, considering the seasonal sensitivity of such functional compartments (Table 6). Surveys should take place in the shallowest zone of the coralligenous reefs (i.e., above 50 m depth), where anthropogenic pressures and the consequences of climate change are the highest (Garrabou et al., 2009). In addition, this zone is more accessible to scuba divers for regular monitoring.

The number of species among a predefined list of taxa (Table 1) is estimated on the basis of in situ observations, seascape photographs and photoquadrats for boxes 1, 2 and 3. The number of strata of builders (descriptor 1b) is defined using the same classes as the COARSE index (Gatti et al., 2015b), also used by Sartoretto et al. (2017). Descriptors of boxes 2, 3 and 9 (% cover) are surveyed using 30 subhorizontal (<45°) 0.5 m × 0.5 m photographic quadrats along a 40-m long transect (Deter et al., 2012a, 2012b) corresponding to a total surface area of 7.5 m². After having implemented the photoquadrats, the observers cover the site taking photographs at wide-angle and macro-scale in order to identify rare species that would not be observed in the photoquadrats to complete the list of taxa for boxes 1, 2, 3, 4 and 5.

Descriptors of boxes 6, 7, 8 and 6–8 (Specific Relative Diversity Index SRDI) are surveyed by underwater visual census (UVC, Harmelin-Vivien et al., 1985, 2008). As far as possible, the survey must be carried out when the thermocline is deeper than the survey depth. Along 25-m long

Table 3
Ecological status according to Cor-EBQI score.

Colour code	Ecological status	Cor-EBQI score
	High	EBQI ≥ 7.5
	Good	7.5 > EBQI ≥ 6
	Intermediate	6 > EBQI ≥ 4.5
	Poor	4.5 > EBQI ≥ 3.5
	Bad	EBQI < 3.5

Table 4
Selected descriptors to assess each functional compartment of coralligenous reef ecosystem for Cor-EBQI calculation. W: weighting.

Functional compartments	W	Descriptors	Status (S)				
			4	3	2	1	0
1- Builders (macrophytes and invertebrates)	5	1a. Nb. of building species (30 listed)	≥ 25	15 to 24	10 to 14	6 to 9	≤ 5
		1b. Nb. of strata	3 strata with the highest >50 % cover	3 strata with the highest <50 % cover	2 strata	1 stratum	0 stratum
2- MPOs	3	2a. Nb. of species (33 listed)	≥ 25	15 to 24	10 to 14	6 to 9	≤ 5
		2b. Cover (%)	≥ 50	≥ 30 to <50	≥ 10 to <30	≥ 1 to <10	< 1
		2c. Nb. of strata (arborescent, shrubby, grazing, encrusting)	4 strata	3 strata	2 strata	1 stratum	0 stratum
3- Benthic filter- and suspension- feeders	5	3a. Nb. of species (48 listed)	≥ 30	20 to 29	12 to 19	6 to 11	≤ 5
		3b. Cover (%)	≥ 50	≥ 30 to <50	≥ 10 to <30	≥ 1 to <10	< 1
4- Bioeroders	5	4a. Boring sponges (Clionaidae)	Rare papillas	Sparse papillas	Moderately abundant papillas	Abundant papillas	Massive specimens
		4b. Density of <i>Sphaerechinus granularis</i> (individuals.25 m ⁻²)	< 1.0	≥ 1.0 to <3.0	≥ 3.0 to <8.0	≥ 8.0 to <12.0	≥ 12.0
5- Browsers and grazers	3	Nb of species	≥ 10	7 to 9	4 to 6	3 to 2	≤ 1
6- Planktivorous teleosts	2	Biomass (kg _{WM} .100 m ⁻²)	≥ 4.0	≥ 2.0 to <4.0	≥ 1.0 to <2.0	≥ 0.5 to <1.0	< 0.5
7- Predatory teleosts, omnivores and cephalopods	2		≥ 5.0	≥ 3.0 to <5.0	≥ 1.0 to <3.0	≥ 0.5 to <1.0	< 0.5
8- High-level predators (piscivorous teleosts)	4		≥ 6.0	≥ 2.0 to <6.0	≥ 0.4 to <2.0	≥ 0.1 to <0.4	< 0.1
6-8- Specific Relative Diversity Index (SRDI)	3	Nb of species per transect	≥ 10	≥ 8 to <10	≥ 5 to <8	≥ 3 to <5	< 3
9- Benthic POM	2	Cover (%)	< 10	≥ 10 to <25	≥ 25 to <50	≥ 50 to <75	≥ 75
10- Detritus-feeders (<i>Holothuria</i> spp. and <i>Bonellia viridis</i>)	1	Density (individuals.25 m ⁻²)	< 1.0	≥ 1.0 to <3.0	≥ 3.0 to <8.0	≥ 8.0 to <12.0	≥ 12.0

Table 5
Confidence index (CI) related with data quality or expert judgement (criteria from Personnic et al., 2014).

CI	Criteria
4	Field data available, recent, and suitable with the recommended methods
3	Field data recent, partially completed with expert judgement
2	No quantitative field data but recent expert judgement
1	No quantitative field data but ancient expert judgement
0	No quantitative field data and no suitable expert judgement

Table 6
Seasonal sensitivity of the functional compartments of coralligenous reef ecosystem (modified from Ruitton et al., 2017).

Functional compartments	Seasonal sensitivity	Suitable period	CI degrading
1- Builders (macrophytes and invertebrates)	None	All year	=
2- MPOs	High	May–August	-1
3- Benthic filter- and suspension-feeders	None	All year	=
4- Bioeroders	None	All year	=
5- Browsers and grazers	None	All year	=
6- Planktivorous teleosts	High	May–October	-1
7- Predatory teleosts, omnivores and cephalopods			
8- High-level predators (piscivorous teleosts)			
9- Benthic POM	Low	May–August	-1
10- Detritus-feeders	None	All year	=

and 4-m wide random transects, the observer counts the number and estimates the size (with a 2-cm accuracy) of each teleost species. In total, teleost fish survey covers a surface area of 1000 m². Using the following formula (Eq. 3), the mean wet mass (kg_{WM}.100 m⁻²) can be estimated for each compartment (6, 7, 8). The Specific Relative Diversity Index (SRDI) is the mean number of species per transect. For these boxes, at least 6 replicates should be taken per site but, when the site is large

enough (i.e., enough space to deploy all the transects), we recommend surveying 10 replicates.

$$WM = a \cdot L^b \tag{Eq. 3}$$

WM corresponds to the wet mass, a and b are the Bayesian length-mass values, which are defined for each species and can vary according to biogeographical regions (see fishbase.org), L is the total length of the teleost species (see Table 2).

Cliona spp. abundance (descriptor 4a) is assessed semi-quantitatively at the scale of the survey site with in situ photoquadrats). The descriptors 4b (bioeroders) and 10 (detritus-feeders) are assessed along the 25-m long and 1-m wide transects by counting *Sphaerechinus granularis*, *Bonellia viridis* and *Holothuria* spp. density. For convenience, the same transect can be used, but not simultaneously, for teleost (boxes 6, 7, 8, SRDI), bioeroders (box 4b) and detritus-feeders (box 10). The assessment of the whole set of compartments needs 1 or 2 dives with 4 observers, depending on depth (Table 7).

2.8. Survey strategy

Surveys were carried out between 2014 and 2024 at 63 sites along the French and Monaco Mediterranean coast (Fig. 2, Table 8). Depth ranged from 10 to 46 m; the shallower sites were located in the Gulf of Lions while the deepest were located in Corsica.

2.9. Data analysis

The management level was considered to test its influence on the Cor-EBQI score. Four categories were considered: i) No-Take Zone within Marine Protected Areas (MPA-NTZ); ii) Multi-Use Management regulation (MPA-MUM; Astruch et al., 2018; Boudouresque et al., 2019); iii) Natura 2000 (EU Habitats Directive) sites; and iv) No Regulation (NR) (see Thibaut et al., 2017 for more details). The influence of the management level was tested on Cor-EBQI scores and circularity values through PERMANOVA analysis, using Euclidean distance and 999 permutations (Anderson, 2001). It is worth noting that, while several authors emphasize the fact that many MPAs, in the Mediterranean and

Table 7

Methods per descriptor of each functional compartment of coralligenous reef ecosystem. Time per dive is indicative and depends on site depth.

Functional compartments	Descriptors	Protocol	Time per dive	Dive organisation
1- Builders (macrophytes and invertebrates)	Nb of species	In situ observations, seascape photographs and photoquadrats	20–30 min	1 dive with 2 observers
2- MPOs				
3- Benthic filter- and suspension-feeders				
4a- Bioeroders (<i>Cliona</i> spp.)				
5- Browsers and grazers				
1- Builders (macrophytes and invertebrates)	Nb of strata	In situ observations, seascape photographs and photoquadrats		
2- MPOs				
2- MPOs	Cover (%)	30 photographic subhorizontal (<45°) 50-cm × 50-cm quadrats		
3- Benthic filter- and suspension-feeders				
9- Benthic POM				
4b- Bioeroders (<i>Sphaerechinus granularis</i>)	Density (individuals·25 m ⁻²)	6 to 10 random-transects of 25-m long and 1-m wide	25–40 min	1 or 2 dives with 2 observers
10- Detritus-feeders				
6- Planktivorous teleosts	Biomass (kgWM·100 m ⁻²)	6 to 10 random-transects of 25-m long and 4-m wide		
7- Predatory teleosts, omnivores and cephalopods				
8- High-level predators (piscivorous teleosts)				
6-8- Specific Relative Diversity Index (SRDI)	Number of species per transect			

worldwide, are ‘paper parks’ (i.e., they exist on maps and in the legislation but offer little real protection) (e.g., Sale et al., 2010; Pieraccini et al., 2016; Dorigatti et al., 2022; Simantiris et al., 2024), within the study area, MPA regulations are fully implemented.

The relative level of pressure (LP) has been estimated following and adapting the methods of Gobert et al. (2009) and Sartoretto et al. (2017). Four pressure categories were defined: i) sedimentation/eutrophication (linked with coastal development, wastewater inputs, etc.); ii) mechanical abrasion by scuba diving and anchoring; iii) mechanical abrasion and harvesting by fishing activities; and iv) cover of the substrate by marine litter. For each category, a score was attributed to each site on the basis of the authors’ expert judgement and field observations (0: not concerned; 1: low pressure; 2: moderate pressure; 3 high pressure). The LP corresponds to the sum of the four category scores, ranging between 0 (no pressure) and 12 (highest level of human pressure).

The habitat geomorphology (HG) has been assessed qualitatively on the basis of the rugosity (size and number of blocks) and the heterogeneity of the slope observed for each survey site to consider their geomorphologic specificities. A score has been attributed between 0 and 3 for both rugosity (0: very low rugosity; 1: low rugosity; 2: moderate rugosity; 3: high rugosity) and the slope (0: subhorizontal homogenous slope; 1: low changes in slope; 2: heterogenous slope mostly between 0 and 45°; 3: numerous changes of the slope between 0 and 90°). The HG ranges between 0 and 6 (see Jacob et al., 2024).

Spearman correlation test was used to analyse the link between Cor-EBQI, LP, HG, Longitude and Latitude and between Cor-EBQI and box status. Principal Component Analysis (PCA) was used without standardization to show the relation between boxes and Cor-EBQI sites scores. Supplementary variables (latitude, longitude, management level, level of pressure and habitat geomorphology) were added to the PCA. The robustness of the Cor-EBQI has been tested with regard to the ecological status per box and the weight per box. A robustness analysis involving 1000 simulations with 25 and 100 % probability of perturbation of ± 1 or ± 2 (of each ecological status per box and each weighting per box) has been tested. The analysis recalculates the EBQI score considering the corresponding perturbation (± 1 or ± 2) and the probability of perturbation (25 or 100 %). Box status has been plotted on radar charts and the uniformity of box status has been assessed through the circularity of polygons representing those charts. Circularity is the ratio between the polygon area and the area of a circle having a circumference equal to the polygon perimeter (Oprandi et al., 2021). Perimeter and area have been calculated using ArcGIS Pro 3.0®.

Spearman correlation test was performed to compare the Cor-EBQI with existing indices already applied at similar sites (CAI: Deter et al., 2012b; RECOR, 2024; COARSE: Gatti et al., 2015b; INDEX-COR: Sartoretto et al., 2017; Sartoretto pers. comm.; see also Gatti et al., 2016). Sub-descriptors, used for the calculation of the indices, were also considered for comparison with functional compartment descriptors: Sedimentation (% cover) and Builder cover (%) for CAI, Taxonomic Sensitivity (TS), Observable Taxonomic Richness (OTR) and Structural Complexity (SC) for INDEX-COR and basal, intermediate and high layers (semi-qualitative criteria, see Gatti et al., 2015b) for COARSE. Compiled data from the different indices are presented in Supplementary Material.

P-value threshold was set at 5 % for all tests. Analyses were performed with R software (R core team, 2024).

3. Results

3.1. Cor-EBQI score

The Cor-EBQI score ranges from 2.82 (Banc de Vendres Nord C14) to 8.18 (Sec de la Gabinière C37). Among the 63 study sites, 4 exhibit a high status, 22 exhibit a good status, 19 moderate, 13 poor and 5 bad. The CI is high, ranging from 69 % to 100 %, 97 % on average. Good and high scores are found mostly in Corsica, Provence (western and eastern) and French Riviera while poor and bad scores are located in the Gulf of Lions and western Provence (Table 8, Fig. 3).

The Principal Component Analysis (PCA), displaying sites according to box status, shows a strong gradient along the first axis which explains 41.7 % of the variability, while 13.3 % is explained by the second axis. Good and high scores are mostly influenced by boxes 2a (MPOs), 4a (Bioeroders), 6, 7, 8, SRDI (fish assemblages) and 9 (Sedimented POM) (Fig. 4). Additional variables (LP, HG, Longitude, Latitude, Management) show strong correlations with site distribution along the first axis. LP is linked with poor and bad sites while good and high sites correspond to higher longitudes. HG seems to have an influence on the distribution but at a lower level together with Management.

Cor-EBQI score varies strongly according to the management level (permanova; $p < 0.001$). Natura 2000 site scores (mean 4.76) are significantly lower than NTZ (mean 6.58) and MUM (mean 5.85) (pairwise test: $p = 0.001$ and 0.005 respectively); so are NR (mean 3.54) (pairwise test: $p = 0.010$ and 0.005 respectively); NTZ and MUM also show differences (pairwise test: $p = 0.032$), unlike NR and Natura 2000 (pairwise test: $p = 0.245$) (Fig. 5A). Differences in LP are evidenced

Table 8

Survey sites per region, geographical position (WGS84), depth range (m), year of the survey and management level, Cor-EBQI score, confidence index (CI in %), Status, Level of Pressure (LP) and Habitat Geomorphology (HG). DD: Decimal Degree; MUM: Multi-Use Management regulation; NTZ: No-Take Zone within Marine Protected Areas; NR: No Regulation. Monaco site C52 'Roche Saint Nicolas' is included in French Riviera region.

Code	Region	Site	Longitude E (DD)	Latitude N (DD)	Depth (m)	Year	Management	CI (%)	Cor-EBQI	Status	LP	HG
C01	French Catalonia	Cerbère	3.17949	42.44197	25 - 27	2021	Natura 2000	100	4.50	Moderate	5	4
C02		Cap Peyrefite	3.16883	42.45695	20 - 23	2021	MUM	100	5.32	Moderate	5	4
C03		Sec Rederis	3.16894	42.46642	26 - 30	2021	NTZ	100	6.18	Good	1	5
C04		Les 3 Moines	3.15422	42.47381	20 - 23	2021	MUM	100	5.00	Moderate	5	2
C05		Cap l'Abeille	3.15559	42.47539	18 - 25	2021	MUM	100	4.86	Moderate	4	6
C06		Oullestrell	3.13842	42.50082	22 - 22	2021	Natura 2000	100	4.86	Moderate	5	3
C07		Sainte Catherine	3.13802	42.51264	20 - 23	2021	Natura 2000	100	5.11	Moderate	5	5
C08		Cap Bear	3.14079	42.51513	19 - 23	2019	Natura 2000	96	3.54	Poor	5	4
C09		Port-Vendres	3.11965	42.52361	18 - 23	2021	Natura 2000	100	4.61	Moderate	7	5
C10		La Moulade	3.08424	42.53201	21 - 21	2021	Natura 2000	100	4.14	Poor	6	4
C11		Roches du Large	3.08150	42.76842	30 - 30	2021	Natura 2000	100	3.75	Poor	6	2
C12		Leucate	3.06915	42.91974	19 - 19	2021	Natura 2000	100	3.82	Poor	6	4
C13	Northern Gulf of Lions	Banc de Vendres Sud	3.25771	43.19419	18 - 19	2022	Natura 2000	100	4.18	Poor	9	2
C14		Banc de Vendres Nord	3.26694	43.20463	17 - 19	2022	Natura 2000	100	2.82	Bad	9	2
C15		Les Casiers Nord	3.49881	43.24940	18 - 19	2020	Natura 2000	79	3.50	Poor	7	4
C16		Les Langoustiers	3.51487	43.25035	19 - 20	2020	Natura 2000	69	3.07	Bad	7	4
C17		Corasi	3.78062	43.40710	12 - 14	2022	Natura 2000	100	3.82	Poor	7	1
C18		Porquières Sud	3.98268	43.51116	12 - 15	2022	Natura 2000	100	4.07	Poor	4	2
C19		Les Guérites	3.99350	43.51527	12 - 14	2022	Natura 2000	100	3.00	Bad	8	2
C20	Western Provence	Le Pic	4.04911	43.53558	10 - 11	2022	Natura 2000	100	3.79	Poor	8	1
C21		Centre Fos	4.94731	43.39131	15 - 16	2023	NR	100	3.11	Bad	10	2
C22		Ponteau	5.00917	43.35065	20 - 21	2023	Natura 2000	100	4.75	Moderate	7	3
C23		Aiguilles de Carro	5.02809	43.32134	25 - 30	2023	Natura 2000	100	6.89	Good	7	6
C24		Carro	5.03600	43.32228	27 - 27	2019	Natura 2000	96	3.46	Bad	8	4
C25		Couronne	5.05408	43.32038	26 - 27	2019	NTZ	100	6.61	Good	2	4
C26		Méjean	5.22262	43.32818	25 - 30	2018	MUM	100	5.11	Moderate	6	5
C27		Tiboulén Frioul	5.28587	43.27967	26 - 33	2020	MUM	100	4.68	Moderate	7	5
C28		Cap Caveau	5.28962	43.26057	26 - 32	2019	MUM	100	5.79	Moderate	7	5
C29		Ile Maire	5.30916	43.21022	25 - 28	2019	MUM	85	4.39	Poor	6	4
C30		Moyades	5.37145	43.17812	26 - 34	2018	NTZ	98	6.25	Good	4	6
C31		Plane Nord	5.38730	43.18817	24 - 30	2020	NTZ	100	5.54	Moderate	4	4
C32	Grand Congloue	5.40292	43.17625	30 - 30	2018	NTZ	100	6.21	Good	4	6	
C33	Pointe de la Cride	5.75917	43.11083	34 - 35	2023	Natura 2000	75	4.11	Poor	5	4	
C34	La Plate aux mérours	5.75100	43.08044	34 - 34	2023	Natura 2000	75	4.75	Moderate	4	4	
C35	Eastern Provence	Fourmignes de Giens	6.06913	43.03793	28 - 32	2023	MUM	100	7.32	Good	5	5
C36		Escampobariou	6.09565	43.02644	28 - 33	2023	MUM	100	6.04	Good	5	5
C37		Sec de la Gabinière	6.39352	42.98631	32 - 34	2014	NTZ	88	8.18	High	1	6
C38		Gabinière Est	6.39671	42.98743	26 - 36	2022	NTZ	100	7.79	High	2	6
C39		Pointe de la Galère	6.40961	43.02093	24 - 32	2022	NTZ	98	7.46	Good	2	5
C40		Quairrolles	6.63306	43.15382	28 - 34	2022	MUM	100	7.14	Good	3	5
C41		Les Brisés de Taillat	6.65799	43.16757	26 - 32	2022	MUM	100	6.50	Good	3	5
C42	Sèche à huile	6.68997	43.30943	31 - 33	2022	MUM	96	4.93	Moderate	6	4	
C43	French Riviera	Vaquette	6.95425	43.48243	25 - 32	2021	MUM	100	6.14	Good	5	4
C44		La Galère Théoule	6.95970	43.49685	25 - 32	2021	MUM	100	6.54	Good	6	3
C45		Tombant du Bateguier	7.02518	43.52811	26 - 34	2022	Natura 2000	100	6.11	Good	5	4
C46		Tombant de Vengeur	7.06604	43.52341	28 - 35	2022	Natura 2000	100	5.64	Moderate	5	5
C47		Fourmignes d'Antibes	7.08237	43.54013	25 - 32	2021	MUM	100	7.61	High	4	6
C48		L'Enfer de Dante	7.08273	43.53764	25 - 35	2021	MUM	100	6.68	Good	4	6
C49		Rascoui	7.11668	43.54293	26 - 32	2021	MUM	100	5.82	Moderate	5	5
C50		Le Lido	7.32220	43.69217	30 - 38	2022	NR	100	3.96	Poor	7	5
C51		Cap d'Ail	7.40073	43.71020	32 - 37	2022	NTZ	100	5.32	Moderate	4	3
C52		Roche Saint Nicolas	7.42484	43.72794	29 - 34	2023	NTZ	96	6.14	Good	4	4
C53	La Piscine	7.48493	43.74827	22 - 30	2023	MUM	100	5.57	Moderate	6	5	
C54	Corsica	Gorgones noires	7.49027	43.75063	23 - 32	2023	MUM	100	6.43	Good	5	4
C55		Grand Pain de Sucre	9.45957	42.71345	30 - 42	2023	Natura 2000	92	7.39	Good	3	4
C56		Petra Luna	9.46032	42.71393	32 - 40	2024	Natura 2000	79	3.57	Poor	8	2
C57		Griffes de Toro	9.39788	41.50868	35 - 44	2023	NTZ	100	6.79	Good	2	5
C58		Cathédrales	8.79750	41.69330	36 - 45	2023	MUM	100	5.14	Moderate	5	5
C59		Les Sanguinaires	8.56595	41.85613	37 - 40	2023	Natura 2000	100	6.82	Good	2	4
C60		Le Rocher des Orgues	8.55067	42.38007	35 - 46	2018	NTZ	98	6.46	Good	1	5
C61	Chapeau du Gendarme	9.26000	42.71728	30 - 38	2024	Natura 2000	100	6.39	Good	5	5	
C62	Sainte Julie	9.33012	42.78577	38 - 46	2024	Natura 2000	100	7.46	Good	4	5	
C63	Banc de Centuri	9.28853	42.99313	35 - 45	2024	Natura 2000	78	8.14	High	1	6	

Table 9
Spearman correlation between Cor-EBQI and functional compartment status (FCS). The number corresponds to the correlation factor (r_s); ***: $p < 0.001$; **: $p < 0.01$; *: $p < 0.05$; r_s followed by a point ‘:’ : $p < 0.10$. Numbers in bold: $r_s > 0.5$.

FCS	1a	1b	2a	2b	2c	3a	3b	4a	4b	5	6	7	8	SRDI	9	10
Cor-EBQI	0.486***	0.308***	0.653***	0.374**	0.471***	0.168	0.504***	0.759***	0.300*	0.030	0.830***	0.537***	0.726***	0.670***	0.743***	0.272*
1a		0.267*	0.443***	0.081	0.084	0.104	0.618***	0.360**	0.02	0.132	0.321*	0.198	0.052	0.206	0.468***	-0.119
1b			0.281*	0.324**	0.225	0.12	0.284*	0.211	-0.083	0.12	0.1	-0.007	0.032	-0.042	0.290*	-0.054
2a				0.301*	0.529***	0.017	0.383**	0.564***	0.165	0.101	0.426***	0.116	0.416**	0.207	0.678***	-0.082
2b					0.447***	0.024	0.103	0.410***	0.181	-0.153	0.189	0.046	0.156	0.199	0.385**	0.024
2c						0.081	0.212	0.428***	0.270*	-0.048	0.332**	0.0003	0.296*	0.219	0.449***	-0.001
3a							0.244	0.003	0.073	0.148	0.125	-0.067	0.121	-0.119	-0.104	0.017
3b								0.393**	0.107	0.144	0.340**	0.199	0.075	0.2	0.409**	-0.076
4a									0.320*	-0.152	0.580***	0.319*	0.469***	0.432***	0.670***	0.143
4b										-0.074	0.279*	-0.050	0.162	0.263*	0.228	0.129
5											-0.149	-0.223	-0.151	-0.299*	-0.214	-0.102
6												0.496***	0.662***	0.659***	0.604***	0.241
7													0.614***	0.614***	0.317*	0.333*
8													0.459***	0.535***	0.424***	0.213
SRDI															0.517***	0.477***
9																0.120

between management levels (permanova; $p < 0.001$; Fig. 5B). As might be expected, NTZ has a significantly lower LP than other levels (pairwise test: $p < 0.019$) while no differences are exhibited between NR and Natura 2000 (pairwise test: $p = 0.101$) and Natura 2000 and MUM (pairwise test: $p = 0.175$). HG also shows differences according to management level (permanova: $p = 0.007$; Fig. 5C). While NTZ and MUM show the highest mean HG, significant differences are observed only between MUM and Natura 2000 (pairwise test: $p = 0.025$) and between NTZ and Natura 2000 (pairwise test: $p = 0.025$).

Spearman correlations between Cor-EBQI scores and LP, Longitude, HG and Management are highly significant (Fig. 6): LP is negatively correlated with Cor-EBQI, as expected, while HG and Longitude exhibit a positive correlation with Cor-EBQI. Significant correlations are also observed between HG and LP, LP and Longitude and HG and Longitude which can be interpreted by a higher LP when HG is lower, a LP gradient from west to east and a HG gradient, increasing from west to east.

3.2. Descriptors analysis

With regard to functional boxes, Cor-EBQI exhibits highly significant positive correlations (Spearman test: $p < 0.001$; $R > 0.5$), the highest being observed with boxes 3b, 7, 2a, SRDI, 8, 9, 4a and 6. The correlation between boxes can help in assessing the complementarity of the descriptors and the link between functional compartments (Table 9). Boxes 1a, 2a, 4b, 5 and 10 show few significant correlations with other boxes.

Functional boxes have been displayed on radar charts, allowing the calculation of the circularity for each site (see Oprandi et al., 2021). Radar charts for each region (mean values) are presented in Fig. 7.

There is a highly significant positive correlation between Cor-EBQI scores and Circularity (Spearman test: $r_s = 0.73$; $p < 0.001$). In addition, strong differences in Circularity are evidenced between Cor-EBQI statuses (permanova: $p < 0.001$): while Bad and Poor statuses do not show any differences (pairwise test: $p = 0.076$), Intermediate status is significantly different from all the others (pairwise test: $p < 0.034$), Good and High statuses do not differ (pairwise test: $p = 0.180$) and are significantly different from the others (pairwise test: $p < 0.034$). This result shows that high Cor-EBQI scores correspond mostly to high circularity, which means a higher homogeneity of the status per box (Fig. 8).

3.3. Robustness of box descriptors

The robustness of the weighting of Cor-EBQI has been tested by randomly changing the weight of the boxes (± 1 and ± 2) with a probability of 25 % or 100 % on 1000 iterations. It allows us to estimate the percentage of similarity of the Cor-EBQI score after weight perturbation. It remains high with 92 % with a ± 1 perturbation of the weight at 25 % probability. The similarity decreases when increasing the perturbation, reaching 73 % with a ± 2 perturbation of the weight at 100 % of probability (Fig. 9).

The robustness of the Cor-EBQI has been tested as well by randomly changing the status of the boxes (± 1 and ± 2) with a probability of 25 % or 100 % on 1000 iterations. The similarity reaches 81 % with a ± 1 perturbation of the status at a 25 % probability decreases strongly while increasing the perturbation, with only 39 % of similarity with a ± 2 perturbation of the status at 100 % of probability (Fig. 10).

3.4. Comparison between the Cor-EBQI and other ecological indicators

Twenty, sixteen and six sites were common between Cor-EBQI and CAI, INDEX-COR and COARSE respectively (Table 10). Spearman test did not evidence any significant correlation between Cor-EBQI and CAI ($p = 0.598$, $R = 0.13$), INDEX-COR ($p = 0.075$, $R = 0.46$) and COARSE ($p = 0.700$, $R = 0.20$). Only 15 % of the sites share the same ecological status between CAI and Cor-EBQI and 50 % of sites between INDEX-COR

Table 10

Cor-EBQI, CAI, INDEX-COR (IC), COARSE (C) scores and sub-descriptors (Sed.: Sediment cover, Build.: Builders, TS: Taxonomic Sensitivity, OTR: Observable Taxonomic Richness, SC: Structural complexity, basal, intermediate and high layers). Colours correspond to the ecological status (see Table 3, Deter et al., 2012b, Sartoretto et al., 2017).

Code	Site	Cor-EBQI	CAI	Sed.	Build.	IC	TS	OTR	SC	C	Basal	Int.	High
C01	Cerbère	4.50	0.64	38.78	26.89	45.02	20.1	50	1.5	-	-	-	-
C03	Sec Rederis	6.18	-	-	-	43.86	20.2	50	0.8	-	-	-	-
C05	Cap l'Abeille	4.86	-	-	-	48.56	35.5	43	0.4	-	-	-	-
C06	Oullestrell	4.86	-	-	-	40.31	21.1	40	1.9	-	-	-	-
C08	Cap Bear	3.54	0.32	76.46	2.34	32.97	7.3	40	2.6	-	-	-	-
C11	Roches du Large	3.75	0.44	63.65	17.02	-	-	-	-	-	-	-	-
C16	Les Langoustiers	3.07	0.83	40.58	42.36	-	-	-	-	-	-	-	-
C21	Centre Fos	3.11	-	-	-	26.40	7.7	31	1.6	-	-	-	-
C22	Ponteau	4.75	0.53	26.33	66.89	50.70	51.8	28	1.5	-	-	-	-
C23	Aiguilles de Carro	6.89	-	-	-	52.40	48.4	33	1.6	-	-	-	-
C24	Carro	3.46	-	-	-	-	-	-	-	-	-	-	-
C25	Couronne	6.61	-	-	-	37.30	21.3	33	3	-	-	-	-
C26	Méjean	5.11	-	-	-	71.40	48.8	59	2.3	1.8	1.7	1.6	2
C27	Tiboulou Frioul	4.68	0.43	31.93	29.38	90.10	76.1	55	5.3	2.4	1.3	3	3
C28	Cap Caveau	5.79	-	-	-	-	-	-	-	2.6	2	2.8	3
C29	Ile Maïre	4.39	-	-	-	-	-	-	-	-	-	-	-
C30	Moyades	6.25	-	-	-	78.00	55.4	58	4.1	2.7	2.1	3	3
C31	Plane Nord	5.54	-	-	-	55.00	37.7	49	1.1	0.7	0.5	1.3	0.4
C32	Grand Congloue	6.21	0.60	25.78	37.66	74.20	58.8	60	3.4	-	-	-	-
C33	Pointe de la Cride	4.11	0.41	28.53	35.02	-	-	-	-	-	-	-	-
C34	La Plate aux merous	4.75	0.40	21.34	44.45	-	-	-	-	-	-	-	-
C35	Fourmignes de Giens	7.32	-	-	-	59.60	20.1	65	3	1.8	1	3	1.4
C38	Gabinier Est	7.79	0.40	11.60	16.82	-	-	-	-	-	-	-	-
C40	Quairolles	7.14	0.52	14.97	54.43	82.40	58.1	63	3.8	-	-	-	-
C45	Tombant du Bateguier	6.11	0.47	33.40	49.13	-	-	-	-	-	-	-	-
C50	Le Lido	3.96	0.37	36.55	34.89	-	-	-	-	-	-	-	-
C51	Cap d'Ail	5.32	0.43	39.21	46.44	-	-	-	-	-	-	-	-
C53	La Piscine	5.57	0.29	61.61	12.76	-	-	-	-	-	-	-	-
C57	Griffes de Toro	6.79	0.49	20.73	48.85	-	-	-	-	-	-	-	-
C59	Les Sanguinaires	6.82	0.37	14.14	17.60	-	-	-	-	-	-	-	-
C60	Le Rocher des Orgues	6.46	0.50	12.65	21.11	-	-	-	-	-	-	-	-
C62	Sainte Julie	7.46	0.55	11.31	50.32	-	-	-	-	-	-	-	-
C63	Banc de Centuri	8.14	0.59	5.93	60.72	-	-	-	-	-	-	-	-

and Cor-EBQI.

While the CAI score and Builder cover do not correlate with any Cor-EBQI descriptors, the sediment cover is, as expected, positively correlated with descriptor 9 (sedimented POM cover), as well as the density of *Sphaerechinus granularis* (descriptor 4b) and detritivores (descriptor 10). In contrast, significant negative correlations were observed between sediment cover and Cor-EBQI score, MPO diversity (2a), Clionaidae status (4a) planktivorous (descriptor 6) and piscivorous teleost fish (descriptor 8). INDEX-COR is positively correlated with the number of MPO strata (descriptor 2c), the cover of filter- and suspension feeders (3c), the biomass of planktivorous fish (6) and SRDI, while negatively correlated with sedimented POM cover (9), as well as with the TS and SC descriptors. Surprisingly, OTR and SC exhibit negative correlations with the diversity of grazers (5). OTR also shows positive correlations with descriptors 2c, 3a, 3b, 4a and 6 and unexpectedly with the density of detritivores (10). A comparison of COARSE's additional descriptors and the functional compartments of Cor-EBQI reveals no significant correlation, likely due to the limited sample size ($n = 6$) (Fig. 11).

4. Discussion

4.1. Applicability and relevance of Cor-EBQI

The implementation of an original ecosystem-based indicator designed for coralligenous reefs (Cor-EBQI) has enabled us to discriminate various levels of ecological quality along the French Mediterranean coast. The Cor-EBQI fits with operational standards to envisage its implementation in the framework of MSFD and HD monitoring. It is a matter of balance between the relevance of the descriptors chosen and the feasibility of their implementation in the field at low cost in terms of human and financial resources.

Circularity analysis evidenced a higher heterogeneity of box status for both bad and poor Cor-EBQI scores while good and high scores corresponded to more homogenous box status. A good overall ecosystem quality corresponds to intertwined and healthy functioning compartments, justifying the observed homogeneity. The heterogeneity observed in low scores might be explained by (i) functional compartments exhibiting a low status and (ii) others characterised by homogeneous high status (e.g., descriptors 4b and 10) increasing the perimeter of the radar chart and consequently reducing the circularity. When the status deteriorates, this reflects the degradation of some functional

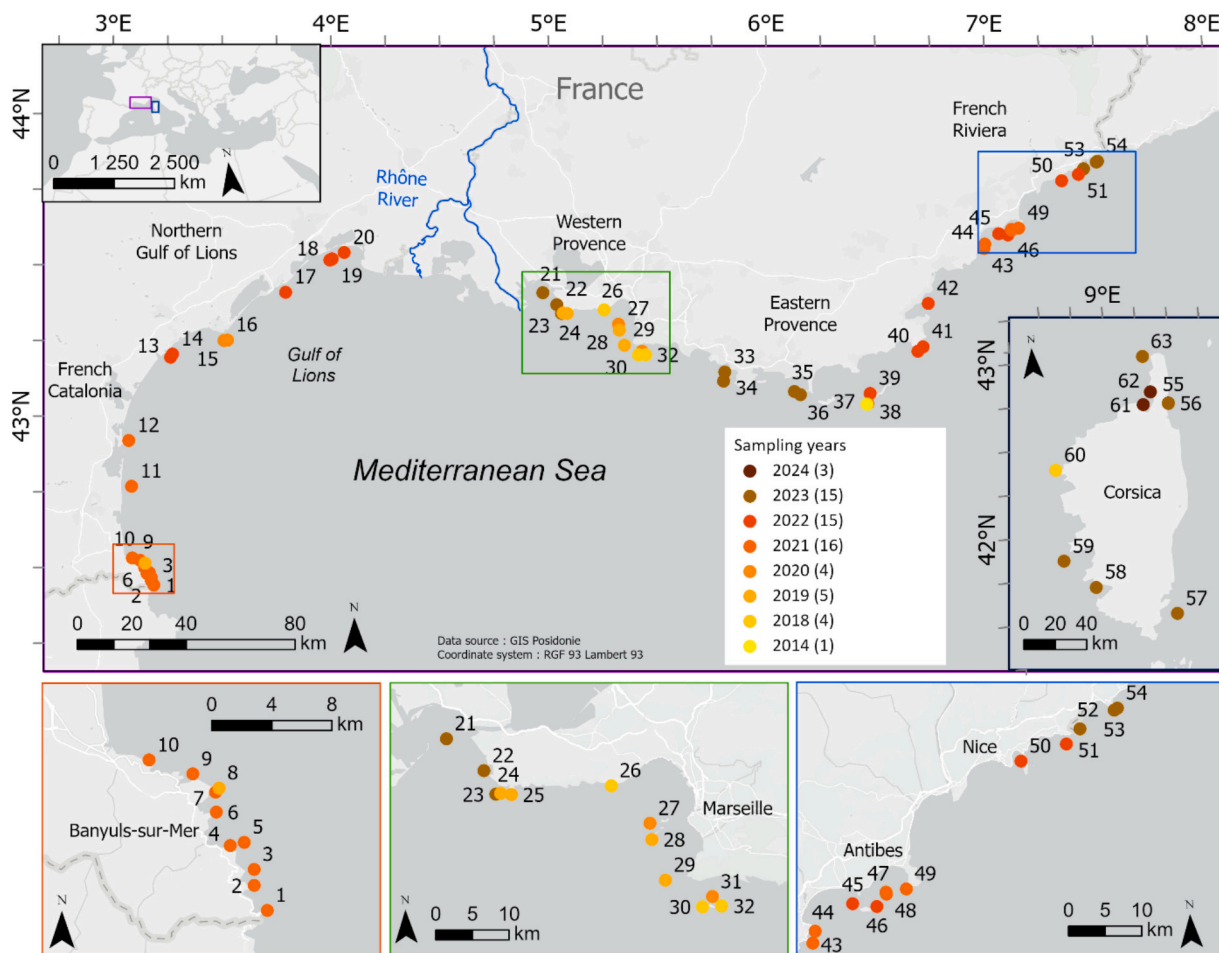


Fig. 2. Location of the study sites according to the survey year; the numbers between brackets correspond to the number of study sites per year.

groups, which are not all as sensitive to pressures, or resistant to these pressures.

Robustness analysis showed a relative stability of Cor-EBQI scores with a moderate perturbation of the weight or the box status (± 1 with 25 % of probability; 82 % of scores similarity after weight perturbation and 82 % after status perturbation). With an increased perturbation (± 2 with 100 % of probability) the similarity decreases dramatically. These results prove that Cor-EBQI assessment remains robust even with a moderate perturbation which could be compared to the potential bias between observers during field surveys. Recent visual surveys of different coralligenous reefs concluded that the variability between observers has little effect on the assessment (Azzola et al., 2022a, 2022b). The higher variability of the scores with major perturbation suggests the suitability of the index to address differences between sites of different quality.

When comparing Cor-EBQI scores with other ecological indices applied in the same area, notable insights emerge. None of the other indices showed significant correlations with Cor-EBQI; however, certain functional compartments exhibited similar trends. The CAI (Deter et al., 2012a, 2012b) was developed to assess water body quality using a set of descriptors based on builder capacities, sediment cover, and the cover of erect bryozoans. Notably, sediment cover, which can reflect local environmental conditions or anthropogenic pressures, was negatively correlated with Cor-EBQI scores. INDEX-COR (Sartoretto et al., 2017) assesses coralligenous assemblages at both taxonomic and structural levels, with methodological similarities to the Cor-EBQI protocol (e.g., lists of characteristic species and bioconstruction characterization), explaining the positive correlation with 2c (MPOs: number of strata) and 3b (cover of benthic filter and suspension feeders) and the observed

positive, albeit non-significant, correlation with Cor-EBQI. The sedimented POM (descriptor 9), assessed in Cor-EBQI by sediment cover, showed a marked negative influence on structural complexity and taxonomic richness in coralligenous communities. COARSE (Gatti et al., 2015b) provides valuable insights into the structure of coralligenous bioconstructions and associated benthic communities through a robust and straightforward protocol. Unfortunately, data limitations precluded a comprehensive and robust comparison. Interestingly, the planktivorous fish compartment was correlated with both CAI and INDEX-COR descriptors. The abundance and biomass of planktivorous fish may serve as effective indicators of habitat quality and complexity provided by coralligenous frameworks. Overall, our results highlight the complementary nature of these indices with regard to their respective objectives, supporting their relevance without undermining their validity.

The Cor-EBQI proposes an integrated approach and meets several of the requirements of Di Camillo et al. (2023): i) it has been designed considering methods already used in existing indices: e.g., COARSE, CAI, INDEX-COR (Deter et al., 2012a, 2012b; Gatti et al., 2015b; Sartoretto et al., 2017); ii) the Cor-EBQI protocol capitalizes on feedback from and the relevance of these indices, resulting in the potential assessment of several indices using one integrated protocol and matching the aims of three EU Directives (WFD, HD, MSFD). In addition, the diversity of descriptors implemented to assess the Cor-EBQI allows for the assessment of metrics to monitor the major anthropogenic pressures and environmental stressors identified by Di Camillo et al. (2023).

The Cor-EBQI allows MPA managers to dispose of a relevant overview of the ecosystem quality with a view to developing an integrated management strategy. For example, results from EBQI assessment in the Marine Nature Park of the Gulf of Lions (French Catalonia, France) have

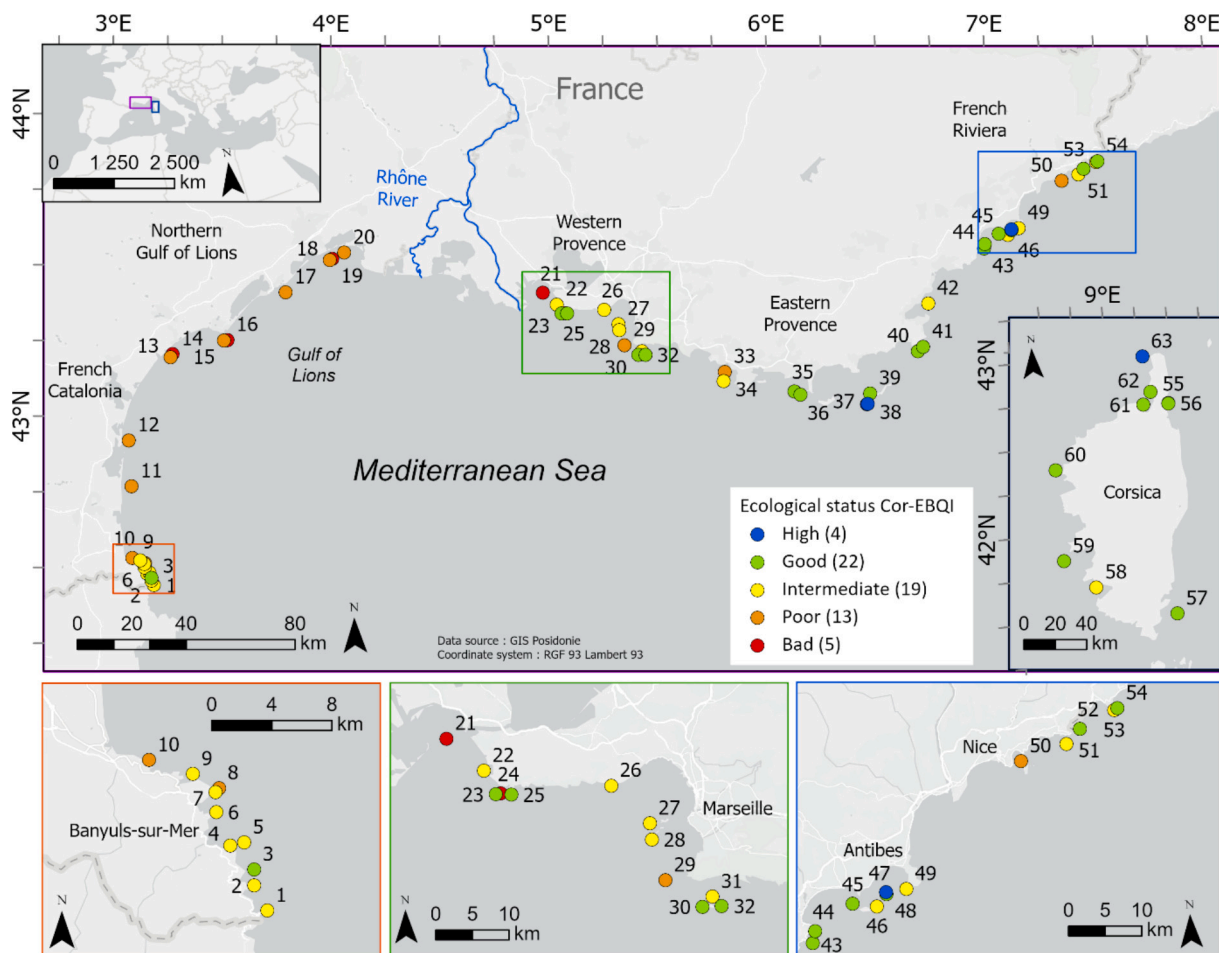


Fig. 3. Location of the survey sites and related Cor-EBQI scores.

been used to promote the need for the extension of the Nature Marine Reserve of Cerbère-Banyuls (Astruch et al., 2022). Managers of both MPAs were trained to apply the Cor-EBQI and were able to implement it in the field by themselves as well as for *Posidonia oceanica* meadows and shallow rocky reef EBQIs (Personnic et al., 2014; Thibaut et al., 2017).

The use of a Confidence Index (CI) is a novelty of the Cor-EBQI, as well as the EBQIs published for other ecosystems. If the CI reaches a value equal to or higher than 75 %, the score can be considered as suitable. If the CI is under 75 %, the first suggestion should be to improve the quality of the assessment. We highlight here that the use of a CI should be recommended for most of the monitoring methods implemented in MPAs.

4.2. Link with anthropogenic pressures

Our work evidenced the influence of anthropogenic pressures on the ecosystem quality through Cor-EBQI scores, although here the pressures were considered in a simplistic way through an anthropization level (Sartoretto et al., 2017). A more detailed approach is needed to assess pressures in order to analyse the links with ecosystem quality and functioning. This notwithstanding, several descriptors showed correlation with the level of pressure. For instance, fish assemblages, particularly high-level predators, were mostly found at sites with a very low level of pressure, such as in highly protected areas with fishing prohibition (NTZ; Harmelin-Vivien et al., 2008; Giakoumi et al., 2017). The current climate change is strongly impacting the upper limit of the circalittoral zone, including the coralligenous ecosystem (Azzola et al., 2024, and references therein). The poor status for the benthic sessile fauna (filter- and suspension-feeders, box 3), may be attributed to past

marine heatwaves and related mass mortality events (Pérez et al., 2000; Linares et al., 2005; Garrabou et al., 2009, 2022; Estaque et al., 2023; Grenier et al., 2023).

Some boxes were less discriminating. The descriptors 4b (*S. granularis* density) and 10 (detritivores density) show mostly good and high status at all sites, corresponding to a very low abundance of *S. granularis* and of *Holothuria* spp. and *Bonellia viridis*, respectively. Class limits for each descriptor were defined according to pre-existing information (Sartoretto and Francour, 1997). This result could be related to the overall improvement of the water quality at French Mediterranean scale. Wastewater treatment plants reduce the availability of organic matter which usually favours sea urchins and detritivores (Savriama et al., 2015; Boudouresque and Verlaque, 2020). This improvement of the quality of the water body mass can have direct consequences on the ecosystems' functioning and quality, as already evidenced for *Posidonia oceanica* meadows (Boudouresque et al., 2021; Bockel et al., 2024). But this trend towards the oligotrophication of northwestern Mediterranean waters is likely conducive to an imbalance in the functioning of coastal ecosystems, as shown by Chen et al. (2022) with the decline in planktivorous fish biomass.

Our results evidenced strong differences according to the management level. NTZ and MUM sites showed the highest scores, while Natura 2000 sites scores were significantly lower. MPA efficiency is obviously linked with effective management measures, implementation of regulations and actual surveillance. The implementation of Natura 2000 marine sites under the EU Habitat Directive provides a large surface area theoretically intended to increase the level of protection of marine habitats. The lack of means reduces the effectiveness of Natura 2000 sites as an MPA tool (Meinesz and Blanfuné, 2015; Guidetti et al., 2019;

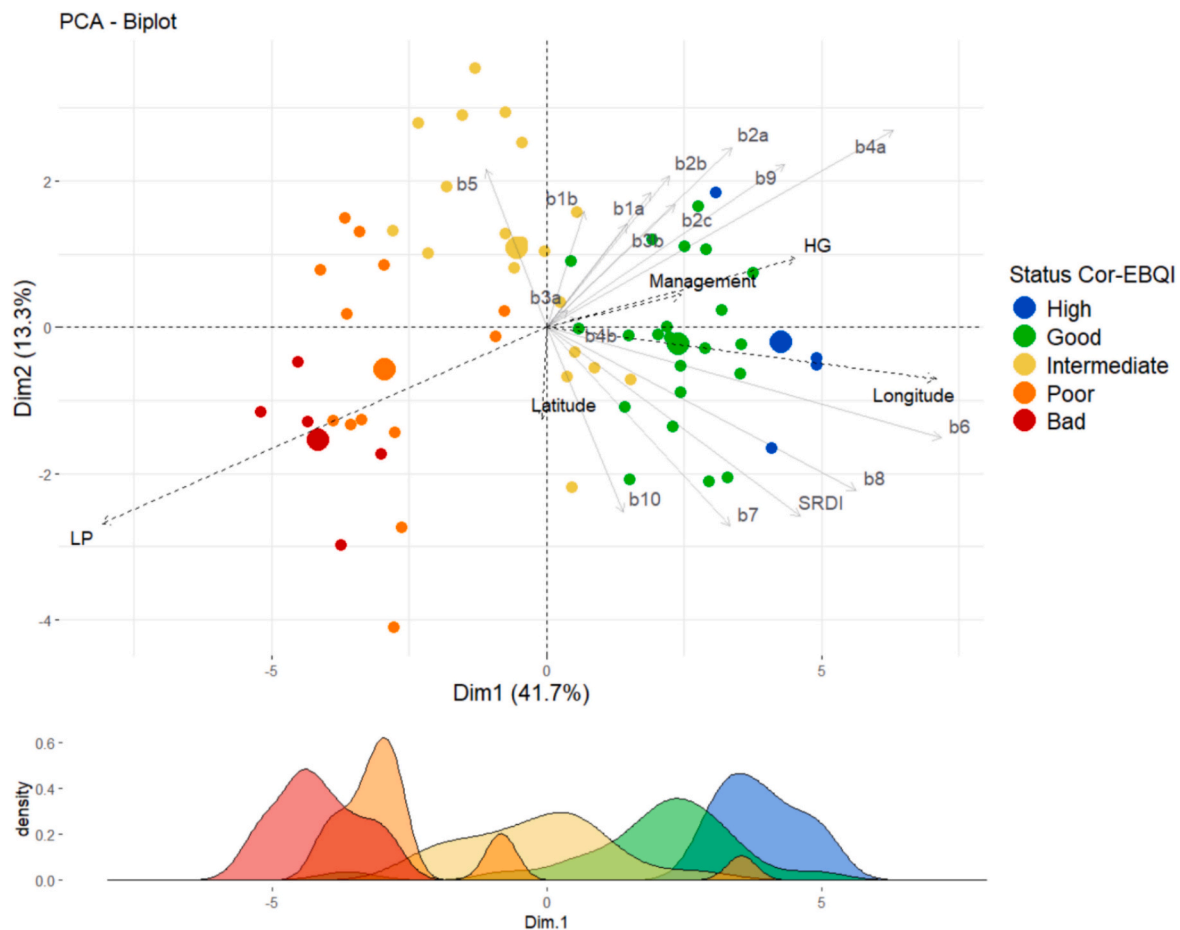


Fig. 4. Principal Component Analysis (PCA) displaying the sites according to boxes b1a through b10 (variables, gray arrows, see Table 3 for box and descriptor correspondence) along the two first dimensions (Dim1 and Dim2). Colours correspond to the Cor-EBQI status, big dots are the barycentres for each Cor-EBQI status. Additional variables (LP: Level of Pressure, HG: Habitat Geomorphology, Longitude, Latitude, Management level) are presented in black dotted lines. The relative density of the sites per Cor-EBQI status is displayed along the first dimension (Dim1) below the PCA.

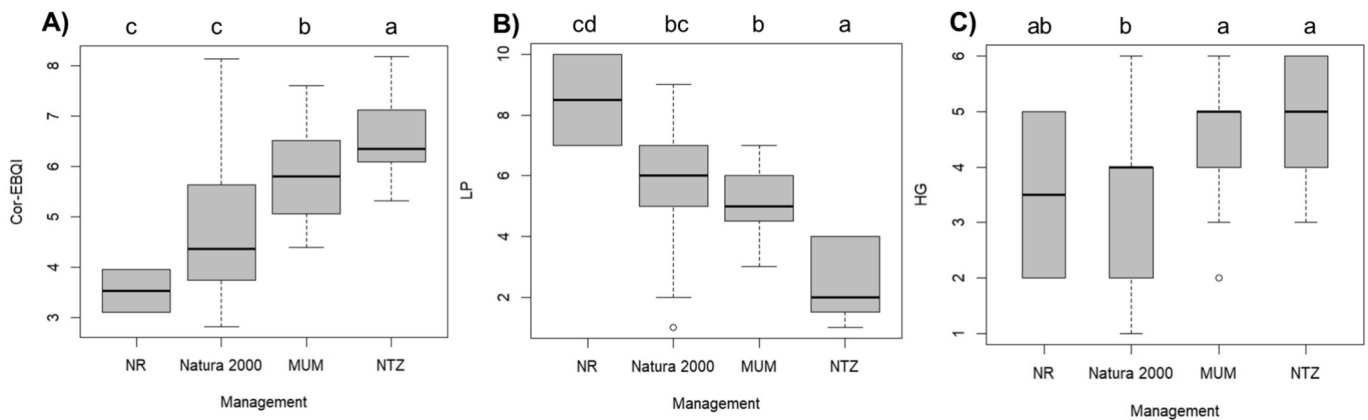


Fig. 5. Boxplots of Cor-EBQI score (A), LP (Level of Pressure) (B) and HG (Habitat Geomorphology) (C) per management level (NR: No regulation; Natura 2000 sites; MUM: Multi-use management; NTZ: No take zone). Boxplots illustrate the distribution of data by displaying the median, interquartile range (IQR), and potential outliers, with whiskers extending to $1.5 \times$ IQR from the first and third quartiles. Letters correspond to the different groups showing statistical differences. The black crossbar corresponds to the mean EBQI score, the gray rectangle corresponds to the standard error, the vertical bars correspond to the 95 % confidence interval.

Claudet et al., 2020; but see Barcelo, 2024). As already highlighted by Thibaut et al. (2017) for shallow rocky reefs, our results showed the ineffectiveness of Natura 2000. Moreover, caution is advised when considering that using management level alone may be deceptive, as its effectiveness and enforcement are often unsatisfactory (Scianna et al.,

2018, 2019).

The Cor-EBQI score showed an increase between two assessments after the removal of a lost fishing net at two of our survey sites C24 (Carro) and C29 (Ile Maire), which moved from 3.46 and 4.39 to 5.11 and 5.00, respectively, thus enabling the ecosystem to exhibit a better

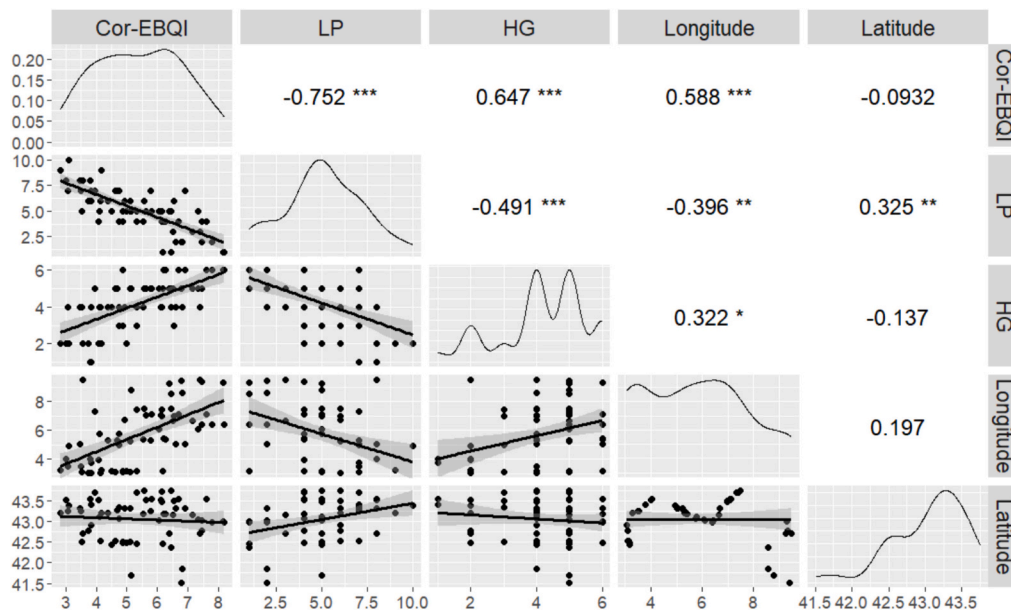


Fig. 6. Spearman correlation matrix between Cor-EBQI, Level of Pressure (LP), Habitat Geomorphology (HG), Longitude and Latitude (in decimal degree). Numbers are correlation coefficients (r); ***: $p < 0.001$; **: $p < 0.01$; *: $p < 0.05$. The plots on the diagonal show the distribution (density) of each parameter.

structure through biobuilders, MPOs, filter-feeders, and consequently improving fish assemblage compartments (Ruitton et al., 2021b).

The Cor-EBQI provides a first insight on the overall quality of a coralligenous ecosystem but is limited in its ability to pinpoint the specific stressors influencing the score. According to management goals and context, further monitoring on specific identified compartments may be needed, as for any ecological index (Bianchi et al., 2022). A proper assessment of anthropogenic pressures is needed, involving if possible quantitative data which is challenging at large scale when considering the whole range of potential stressors. However, caution must be taken in interpreting these results because the level of pressure was estimated rather than calculated directly, following the method of Sartoretto et al. (2017); the lack of weighting for the four pressure categories represents a weakness in this approach. A standardized and more accurate method, considering the synergy between pressures and cumulative impact, is needed (Parravicini et al., 2012; Halpern et al., 2019; Quemmerais-Amice et al., 2020). Here, we highlight the need for defining an anthropogenic pressure index in order to establish the link between the ecosystem status and the different pressures at site scale; such a method should be applicable for all type of ecosystems. The diversity of descriptors required for the calculation of the Cor-EBQI should provide relevant and detailed information to identify specific consequences of the stressors affecting one or several functional compartments.

4.3. Influence of local specificities and inherent habitat complexity

Environmental managers must consider not only the consequences of anthropogenic pressures on marine ecosystems but also local features and geomorphology. Ecosystem-based indices such as the Cor-EBQI propose a broad integrated view of the status of the ecosystem in its own context. The Cor-EBQI highlights the quality of the functioning of CR as an ecosystem. Obviously, local natural specificities, such as low water transparency or excess nutrient level, can strongly impinge on ecosystem functioning and its quality. Our results showed that habitat geomorphology (HG) affects significantly the Cor-EBQI score, suggesting an influence on the quality of the ecosystem functioning. Here, we have only considered qualitative descriptors (rugosity and slope) to define the HG. On hard substrate, the habitat complexity is known to strongly influence benthic and demersal communities, particularly for

fish assemblages (García-Charton and Pérez-Ruzafa, 2001). Habitat features can therefore hide the effect of management measures (García-Charton et al., 2004; Di Franco et al., 2021); for example, most of the existing MPAs with a high level of protection encompass areas with exceptional and complex habitat (e.g., Rédérès within the Marine Nature Reserve of Cerbère-Banyuls, La Gabinière islet within the Port-Cros National Park, Palazzu islet within the Nature Reserve of Scandola). It is mandatory to consider this factor at least with a qualitative assessment and when feasible with a more robust quantitative method (e.g., see García-Charton and Pérez-Ruzafa, 2001). According to Gatti et al. (2015b), the geomorphological characterization should precede the assessment of coralligenous reef status: they distinguished shoals, outcrops, cliffs, landslide deposits, and detrital bottoms, and measured depth, elevation from the seafloor, slope, and compass orientation of the substrate. It would therefore be necessary to remove this habitat effect in order to assess the true impact of anthropogenic pressures and management measures.

Piazzini et al. (2021b) highlighted differences in coralligenous sites around Sardinia (Italy) linked to environmental differences (e.g., current, temperature patterns). Environmental differences among the sites studied along the French Mediterranean coast are much higher than around Sardinia. On one hand, bad and poor Cor-EBQI scores in the Gulf of Lions may not solely be explained by the lack of effective management. The coralligenous habitats assessed in this area were shallower (10–20 m depth), influenced by the inputs from the Rhône River, resulting in high turbidity and sediment resuspension. In addition, the overall habitat complexity of these sites remains low, the coralligenous framework being weak along sub-horizontal substrates, abundance of bioeroders naturally limiting its 3D-development and the settlement of diverse benthic and demersal assemblages. In this area, other indicators such as the PREI for *Posidonia oceanica* seagrass meadow (Gobert et al., 2009) or CARLIT for shallow rocky reefs (Ballesteros et al., 2007) remain low (e.g. mostly Poor or Bad). On the other hand, Corsican waters are characterised by oligotrophic conditions due to very low terrigenous inputs and a resulting high transparency of the water column (Guieu et al., 2010). In addition, the overall level of anthropogenic pressure is relatively low compared to the Gulf of Lions, Provence and French Riviera. Consequently, Cor-EBQI scores in Corsica are moderate to high. French Riviera, eastern and western Provence are in a more balanced configuration: with a contrasted level of pressure (e.g., from the heavily

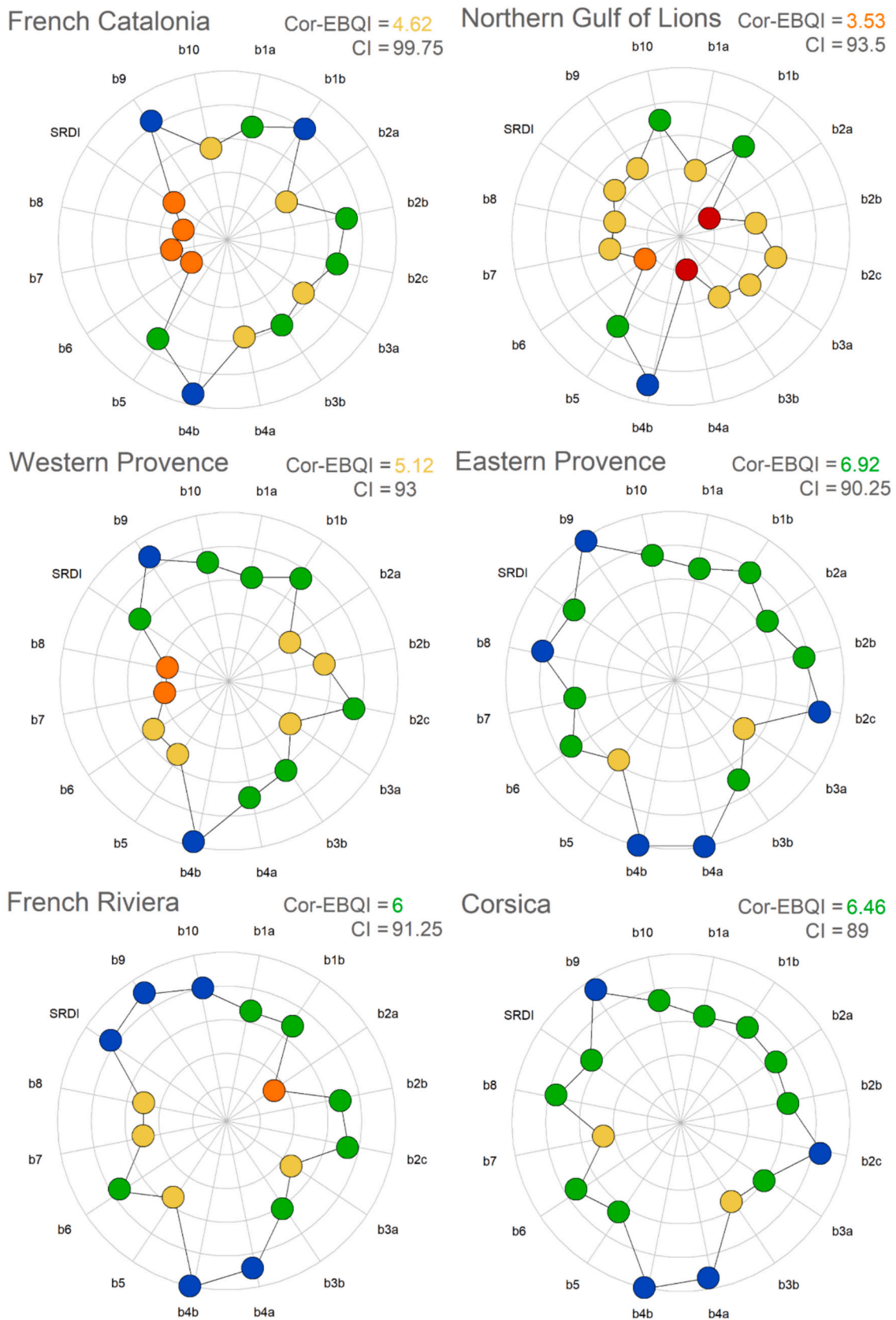


Fig. 7. Radar charts depicting the mean ecological status per functional box for each region. Mean Cor-EBQI scores and CI (in %) are presented. See Table 3 for colour correspondence and Table 4 for box correspondence.

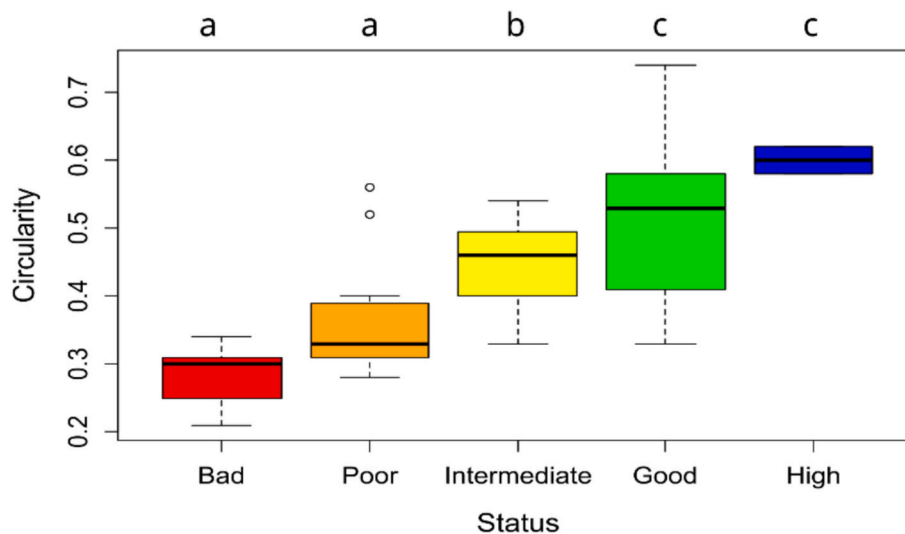


Fig. 8. Boxplot displaying the Circularity sorted per Cor-EBQI status. The box represents the interquartile range (IQR), the line inside indicates the median, the whiskers extend to 1.5 times the IQR, and dots represent outliers beyond this range. Letters correspond to the different groups showing statistical differences (permanova and pairwise test).

human-impacted Gulf of Fos to the comparatively more pristine Port-Cros Archipelago) and natural features (e.g., from the Rhône River influence to the oligotrophic zone of Corsica). The training of MPA managers in EBQIs implementation, including the Cor-EBQI, have provided empiric feedback highlighting the issues and perspectives for improvement (Astruch et al., 2022). One of their requests has been to consider these local specificities. However, it would be of no interest to adapt the Cor-EBQI and define an actual protocol for each sub-region, the results provided by the Cor-EBQI being explained by different factors, including these local specificities (Fig. 6). As an alternative, we propose considering these specificities by using reference sites or reference conditions (from a dataset or from the present work), with the same approach as adopted by other ecological quality indices (e.g., Gobert et al., 2009; Deter et al., 2012a; Labrune et al., 2021). This alternative allows consideration of the local specificities of the sub-regions without modifying the Cor-EBQI protocol and calculation.

4.4. Towards an operational implementation of the Cor-EBQI

The French Mediterranean coast, located in the northwestern part of the Mediterranean, offers a very interesting panel of environmental (Blouet et al., 2024) and management contexts well-suited to define and test the Cor-EBQI. The whole Mediterranean basin is displayed in several ecoregions characterised by different conditions in terms of thermal patterns, nutrient level, management and pressure level (Spalding et al., 2007). Particularly in eastern and southern sectors, characteristic native assemblages observed in coralligenous can differ from what we observed in our work: e.g., some Fucales have disappeared from the coralligenous reefs in the Gulf of Lions due to the increase in turbidity (e.g., *Gongolaria montagnei* var. *compressa*, deep taxa among *Sargassum*) (Thibaut et al., 2005, 2015); *Cystoseira michelae* is only observed in southern Mediterranean (Sellam et al., 2017); the sponge *Axinella cannabina*, virtually absent in the northwestern Mediterranean, is common in the Adriatic, Ionian and Aegean seas; the coral *Astroides calycularis* is abundant in the southern Tyrrhenian Sea and north African coast; the gorgonian *Eunicella verrucosa* is far more abundant along the Algerian coast and in the Alboran Sea where the species *E. labiata*, *E. gazella* and *Paramuricea macrospina* can be observed (Pérez, 2024). Defining a specific protocol for each biogeographical sector of the Mediterranean Sea should not be necessary, although minor adjustments in the species lists might be opportune. The taxa list for boxes 1 (bio-builders), 2 (MPOs) and 3 (filter- and suspension feeders) (Table 1) defined for Cor-EBQI may need

to be adapted according to ecoregions by adding characteristic taxa and possibly by removing naturally absent taxa. Such minor adjustments would make Cor-EBQI suitable for implementation in all Mediterranean ecoregions.

On the basis of our results, considering that the Cor-EBQI score is not only driven by the level of pressure and the related level of management, we propose hereafter a scheme detailing the steps towards interpreting the Cor-EBQI score (Fig. 12): i) 75 % of CI as the limit to consider the assessment as robust enough; ii) local specificities, habitat geomorphology, anthropogenic pressures and management might be the factors explaining the score; iii) the Cor-EBQI protocol allows an a posteriori detailed assessment of the results per functional compartment; iv) the assessment of anthropogenic pressures must be carried out to establish the link between the ecological status (both at compartment and ecosystem levels); v) findings can lead to the assessment of complementary descriptors related to pressures (e.g., fish assemblages monitoring related to the impact of fisheries, see Guidetti et al., 2014; animal marine forest monitoring following marine heat waves, see Garrabou et al., 2022), and therefore vi) enabling suitable management measures to be proposed; vii) we recommend a complete survey every three years. These steps are also applicable to other ecosystems assessed with EBQIs.

The Cor-EBQI defined in this work is based on a spatial analysis. In order to monitor coralligenous reefs in phase with EU MSFD and HD purposes, a temporal long-term monitoring network is needed applying an ecosystem-based assessment together with the assessment of anthropogenic pressures. Even if our work has evidenced a strong gradient of environmental conditions (temperature, oligotrophy), we suggest that Cor-EBQI be tested in other Mediterranean ecoregions.

In contrast with indices based upon a single species or a few species, and with species-by-species management, the Cor-EBQI, like other EBQIs, enables an ecosystem-based approach for the management of the marine environment. In France, several MPAs (e.g., the Port-Cros National Park, the Nature Marine Reserve of Cerbère-Banyuls and the Nature Marine Park of the Gulf of Lions) have clearly begun to reorient their management strategy towards the ecosystem-based approach, which includes an evolution-based approach (Sarrazin and Lecomte, 2016; Boudouresque et al., 2020a, 2020c; Peirache et al., 2023).

5. Conclusion

We have proposed an original ecosystem-based quality index

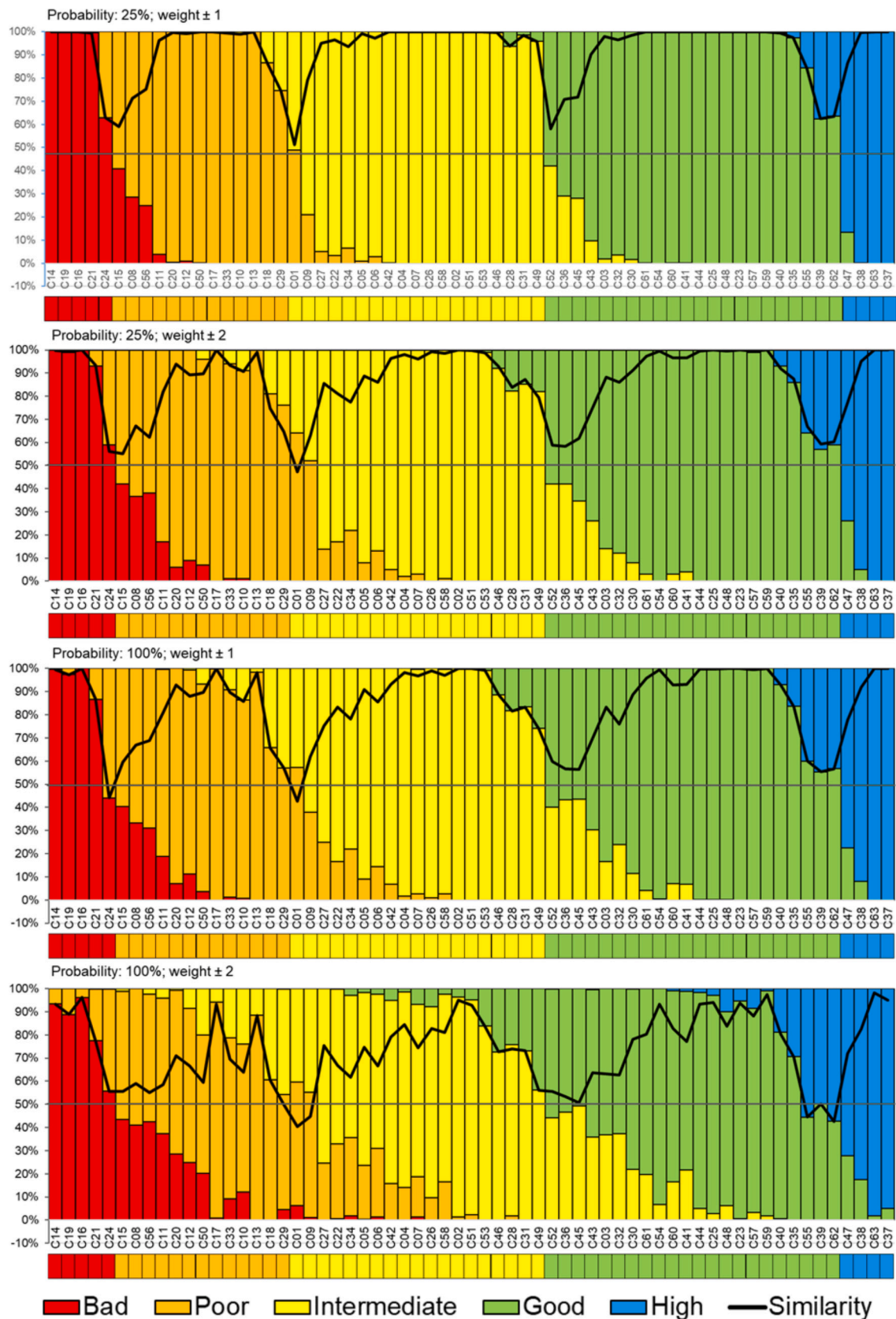


Fig. 9. Robustness analysis of the Cor-EBQI score by perturbing the weight (± 1 and ± 2) of the boxes with a probability of 25 % or 100 %.

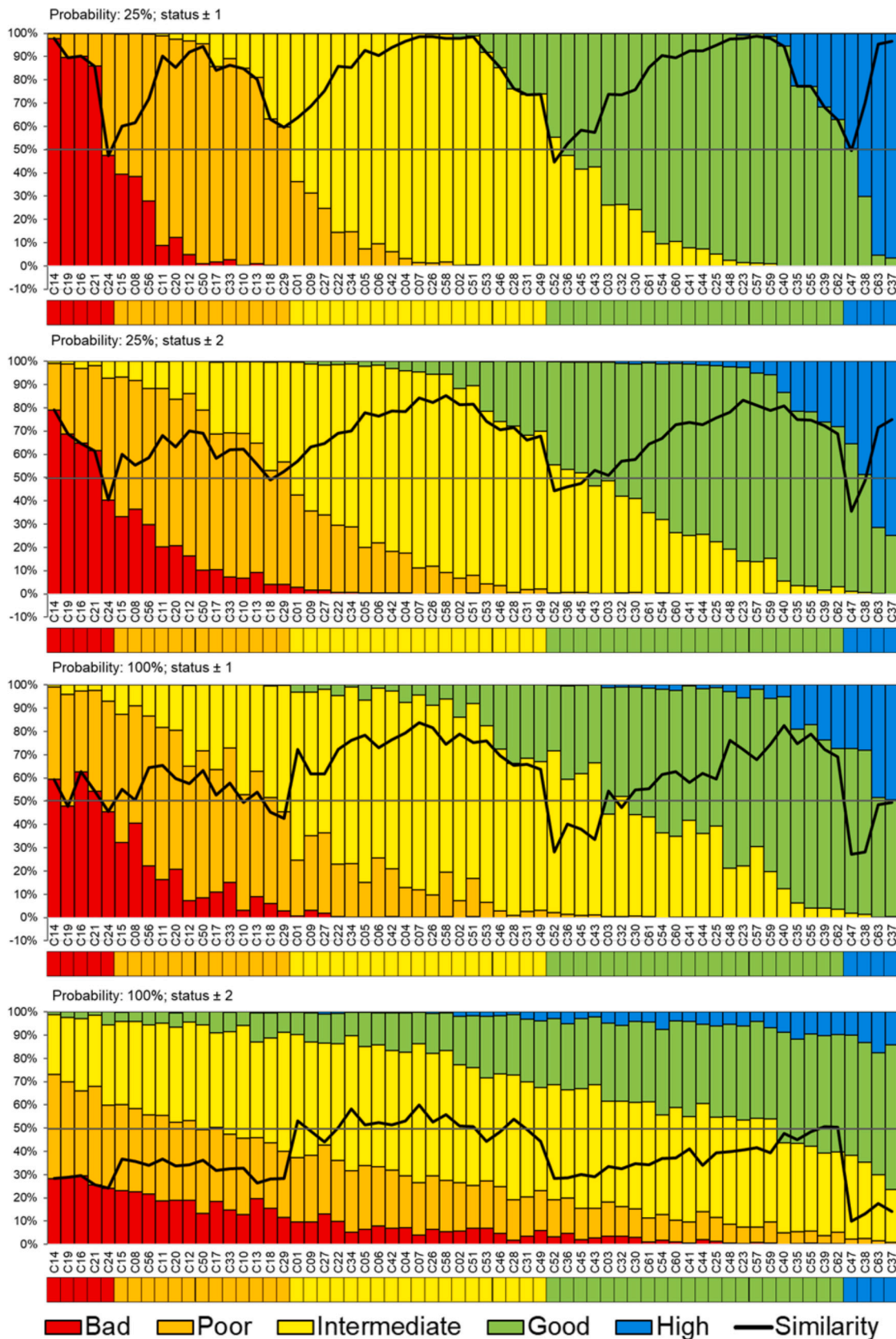


Fig. 10. Robustness analysis of the Cor-EBQI score by perturbing the status (± 1 and ± 2) of the boxes with a probability of 25 % or 100 %.

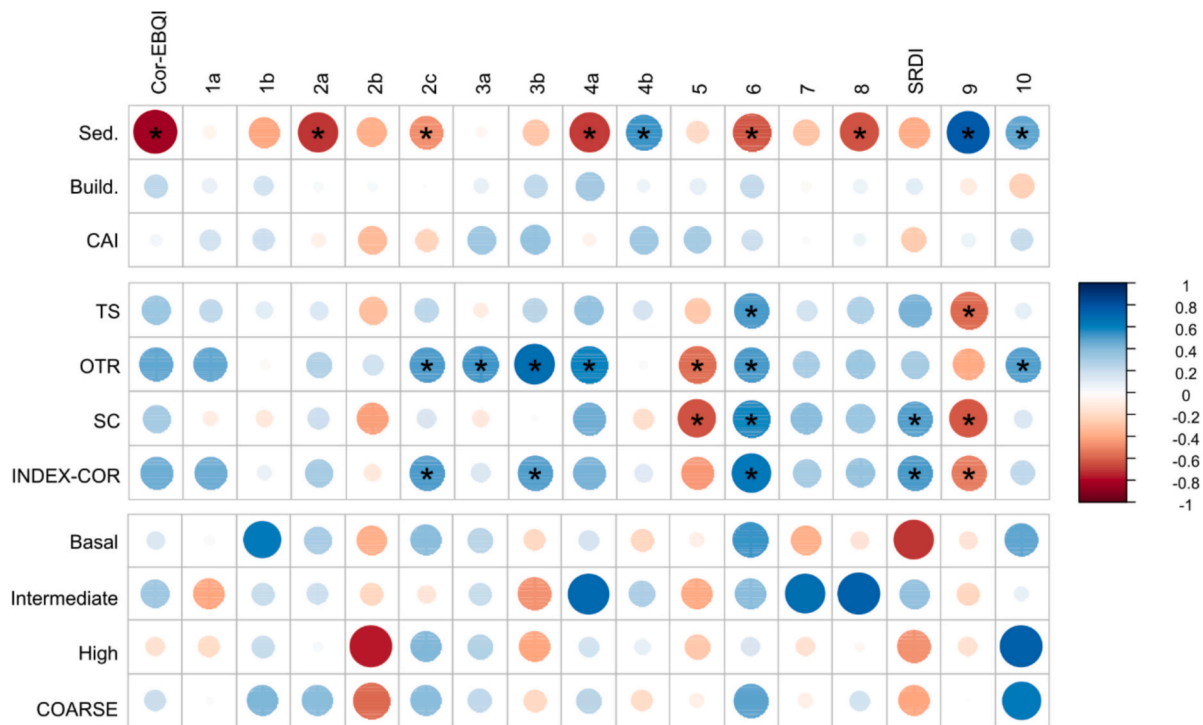


Fig. 11. Correlation matrix between Cor-EBQI score and related functional compartment descriptors, sediment cover (Sed.), builder cover (Build.), CAI, TS (Taxonomic Sensitivity), OTR (Observable Taxonomic Richness), SC (Structural Complexity), INDEX-COR, basal, intermediate and high layers and COARSE. Stars correspond to significant Spearman correlations ($p \leq 0.05$).

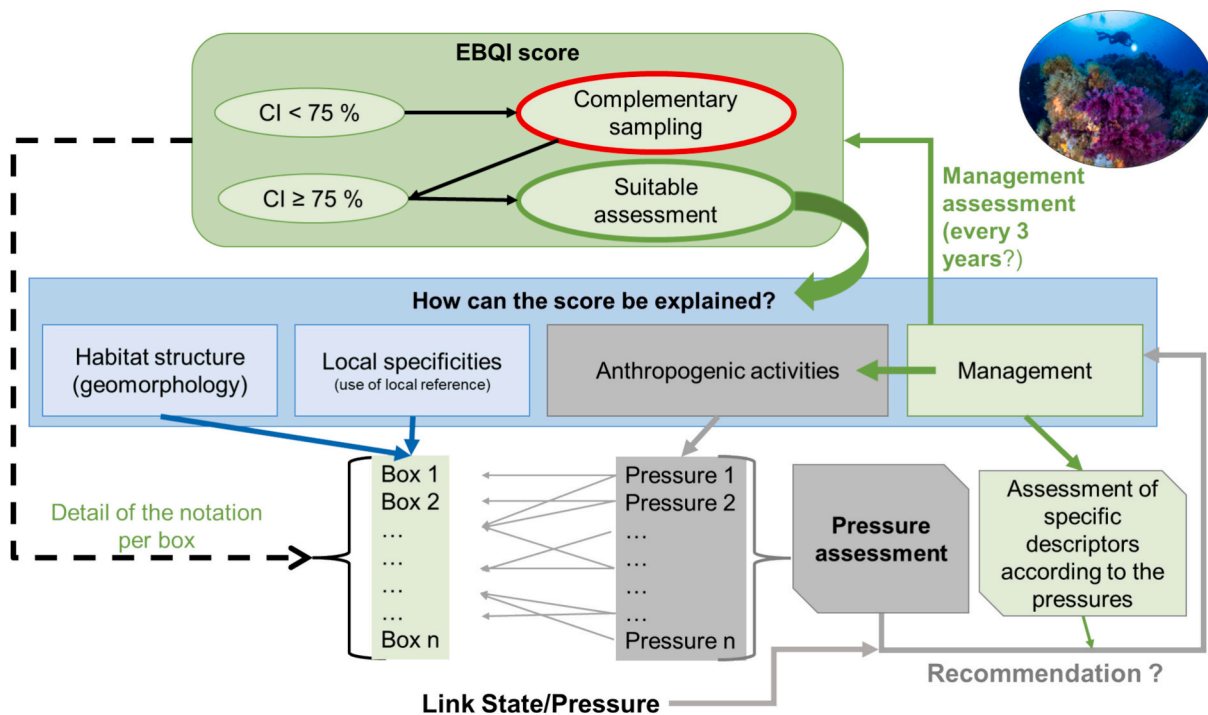


Fig. 12. Decision model for interpreting EBQI score (CI: Confidence Index), applicable for Cor-EBQI and all other EBQIs.

designed for coralligenous reefs (Cor-EBQI) and tested along the French Mediterranean coast (northwestern Mediterranean). On the basis of a conceptual model, descriptors were defined to assess the main functional compartments (e.g., bio-builders, filter-feeders, MPOs, bio-eroders, fish, etc.). A weighting was defined for each functional compartment according to its importance in the ecosystem functioning

to allow the calculation of the index. The results have shown major differences between sites linked to the management level, the level of anthropogenic pressure and also to habitat features and local specificities. The detail provided by the variety of descriptors enables analyses to be done per individual functional compartment and links to be established with environmental and anthropogenic factors. The Cor-

EBQI can be implemented in one or two dives per site with four operators (depending on the depth). The protocol is easy to put into practice after some training. We highlight the need for a long term-monitoring network at a large scale, in the northwestern Mediterranean Sea as well as in other Mediterranean regions, the Cor-EBQI providing a suitable method in phase with the purposes of the MSFD and HD European Directives.

CRedit authorship contribution statement

Patrick Astruch: Writing – original draft, Supervision, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Charles-François Boudouresque:** Writing – review & editing, Conceptualization. **Mélanie Cabral:** Writing – review & editing, Project administration, Methodology, Formal analysis, Data curation. **Thomas Schohn:** Methodology, Investigation, Formal analysis. **Enric Ballesteros:** Writing – review & editing. **Denise Bellan-Santini:** Writing – review & editing. **Bruno Belloni:** Investigation. **Carlo Nike Bianchi:** Writing – review & editing. **Olivia Cassetti:** Writing – review & editing, Investigation. **Pierre Chevaldonné:** Writing – review & editing. **Maïa Fourt:** Writing – review & editing. **Paolo Guidetti:** Writing – review & editing. **Virginie Hartmann:** Writing – review & editing, Investigation. **Élodie Jacob:** Writing – review & editing, Investigation. **Laurence Le Diréach:** Writing – review & editing, Project administration. **Noémie Michez:** Writing – review & editing, Investigation. **Monica Montefalcone:** Writing – review & editing. **Cala Morri:** Writing – review & editing. **David Nérini:** Writing – review & editing. **Thierry Pérez:** Writing – review & editing. **Alain Pibot:** Writing – review & editing, Project administration. **Jean-Christophe Poggiale:** Writing – review & editing. **Claude Reveret:** Writing – review & editing, Investigation. **Félix Valance:** Writing – review & editing, Investigation. **Sandrine Ruitton:** Writing – review & editing, Methodology, Investigation, Conceptualization. **Stéphane Sartoretto:** Writing – review & editing, Investigation, Data curation. **Sylvain Blouet:** Writing – review & editing. **Laurent Ricquiers:** Investigation. **Thierry Thibaut:** Writing – review & editing. **Jean Vacelet:** Writing – review & editing. **Marc Verlaque:** Writing – review & editing.

Declaration of competing interest

The authors have declared that there are no competing interests.

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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.2025.118375>.

Data availability

Data will be made available on request.

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