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Multiple indices on different habitats and descriptors provide consistent assessments of environmental quality in a marine protected area

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In the last decades, climate change and human pressures have increasingly and dramatically impacted the ocean worldwide, calling for urgent actions to safeguard coastal marine ecosystems. The European Commission, in particular, has set ambitious targets for member states with two major directives, the Water Framework Directive (WFD) and the Marine Strategy Framework Directive (MSFD), both designed to protect the marine environment in EU waters. Diverse biotic indices have accordingly been developed to assess water and habitat quality. The WFD adopts four Biological Quality Elements (BQEs), whereas the MSFD recommends a set of eleven qualitative descriptors. The borderline between water quality and habitat quality is hard to trace and so far most assessments have involved the use of a few indices and were mainly related to a single BQE or qualitative descriptor. In this study, thanks to the availability of a large dataset encompassing a wide array of descriptors, we compared the performance of 11 biotic indices relative to three habitats/biotic components (reefs, seagrass, and fish) of the Marine Protected Area (MPA) of Capo Carbonara (SE Sardinia, Italy). The aim was to assess whether the indices were consistent in defining the environmental status in the MPA investigated. We used the graphical approach RESQUE (REsilience and QUality of Ecosystem), which enabled us to obtain a single and comprehensive measure of the status of the environment by integrating several metrics. This approach was applied here to different habitats for the first time. All indices were consistent with each other in confirming the good status of Capo Carbonara MPA. The use of RESQUE provided insights to interpret the differences between water quality, defined according to the WFD, and habitat quality, defined according to the MSFD. Differences between the two EU directives, in terms of either requirements or goals, have long been discussed but the present study highlights for the first time that they are congruent in their assessment of the environmental status of marine ecosystems.

KEYWORDS

water quality, habitat quality, marine biotic indices, water framework directive, Marine Strategy Framework Directive , Mediterranean Sea

1 Introduction

Over the last decades, the need for assessment of the state of the natural environment has become a primary concern. Marine habitats, under increasing human pressure, are declining at an accelerating rate (Claudet and Fraschetti, 2010). Change is now affecting so many compartments and levels of the ecosystems that, while easily perceived, the phenomenon is challenging to quantify (Sala et al., 2000). To address this need, diverse biotic indices have been developed based on different target organisms or habitats deemed particularly sensitive to alterations of the surrounding environment (Birk et al., 2012). In addition, there is a growing trend to develop novel indices that consider the resources required to make an ecosystem function (Rigo et al., 2020, 2021), the ecological complexity (Paoli et al., 2016) or the environmental DNA (Pawlowski et al., 2018). Indices typically provide measures of the structure, function or some particular characteristics of marine communities that show a predictable response to anthropogenic disturbances. Regardless of the wide range of indices available, there is to date no rule for the proper selection of an index or a combination of indices that should be used in the assessment of the environmental quality (Borja et al., 2015).

Across the European seas, the use of biotic indices to define the ecological quality of the marine environment has been strongly supported by two consecutive EU directives: the Water Framework Directive (WFD, Directive 2000/60/EC) and the Marine Strategy Framework Directive (MSFD, Directive 2008/56/EC). The WFD suggests the use of four Biological Quality Elements (BQEs) (i.e., phytoplankton, aquatic flora, benthic invertebrates, and fish) through which a measure of water quality can be obtained and ranked, on the basis of their abundance, diversity, biomass, distribution and/or cover. The MSFD describes the quality of the habitat on the basis of 11 qualitative descriptors (Annex 1) (Borja et al., 2013). The overlapping of the two European directives has generated some confusion in the distinction between 'water quality' and 'habitat quality': the two compartments might not be equivalent, as water naturally has a more rapid turnover with respect to the whole habitat. In practice, however, the borderline between water quality and habitat quality is hard to trace and indices initially created for the WFD in 2000 were then adopted for the MSFD in 2008 and are still widely used today. All the indices considered in the present paper may be taken as responsive to the requirements of both directives. In both the MSFD and WFD, the good status of the environment may correspond to the so-called reference condition from which the change is measured, in the absence of pre-disturbance historic data or data referring to analogous pristine areas (Smit et al., 2021).

Marine Protected Areas (MPAs), where the goal of marine conservation dovetails with the regulated use of marine resources (i.e., fishing) (Grorud-Colvert et al., 2021), have gained further relevance in this context as they are often taken as a reference point, and improved environmental conditions are expected to be found there (Bianchi et al., 2022; Fraschetti et al., 2022). Most of the priority habitats and valuable species with conservation priority considered in the EU directives and typically included in MPAs, are concentrated in coastal areas (Vassallo et al., 2020), where they are also exposed to multiple pressures (Azzola et al., 2023). The alteration of the natural environment due to anthropogenic and natural disturbances may be more evident if the flora and fauna are investigated together (Smit et al., 2021). The quality of the marine environment is often assessed on the basis of a single index and/or the status of a single indicator, which can be an oversimplification. The combination of several metrics has been proved to be more accurate than the use of single metrics in habitat assessment (Pinto et al., 2009; Ruitton et al., 2014; Rastorgueff et al., 2015; Sartoretto et al., 2017; Thibaut et al., 2017; Enrichetti et al., 2019; Astruch et al., 2022). The challenge is to understand the complexity of coastal systems by considering all their components without trying to oversimplify them (Paoli et al., 2016).

The present study aims to compare 11 biotic indices with reference to three habitats/biotic components (*i.e.*, reefs, seagrass, and fish) of the Marine Protected Area (MPA) of Capo Carbonara (SE Sardinia, Italy). Although data have been collected in the frame of distinct projects with different specific objectives focused on single descriptors each time, the resulting large dataset offers a unique opportunity to compare the performance of a variety of indices. We used the graphical approach RESQUE (REsilience and QUality of Ecosystem), which provides a single and comprehensive measure of the status of the environment by integrating several metrics (Oprandi et al., 2021), here applied to different habitats for the first time.

2 Material and methods

2.1 Study area

The Capo Carbonara MPA has been in existence since 1998, and it is recognized as a Specially Protected Area of Mediterranean

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Importance (SPAMI) due to its ecologically significant habitats and the presence of rare, threatened, and/or endemic species. It is located around the south-eastern tip of Sardinia Island (Italy) (39° 5.626’N; 9° 31.462’E), where it covers a surface area of 14,360 ha and comprises about 31 km of coastline, including two minor islets: Cavoli and Serpentara (Figure 1). A complete description and map of the benthic habitats of the area can be found in Andromède (2017): seagrass meadows, formed by *Posidonia oceanica*, are located between about 5 m and 35 m, in three large patches; shallow reefs, where macroalgal communities thrive, are located all around the main coast and the islets; deeper reefs, including coralligenous reefs down to about 45 m depth, are mostly found in relation with the islets and rocky shoals.

2.2 Data collection and sampling activities

All data were collected independently during two consecutive summers, in 2020 and 2021, within the Capo Carbonara MPA. As the specific target habitats (fish, seagrass and reefs) were not necessarily present in the same territorial units within the investigated MPA, sampling sites did not always overlap for the different targets assessed in this study. Fish assemblages were studied in 2021, seagrass and reefs in 2020 (shallow reefs and deep reefs surveyed separately at distinct sites). Data were collected following a sampling design stratified per habitat, with survey sites randomly placed within each habitat type. We collated *a posteriori* all the data available to calculate 11 indices (Table 1). Each index provided information on the status of a specific ecosystem or biotic component (reef, seagrass or fish), and matched at least one of the three, out of four, Biological Quality Elements (BQEs) for coastal and transitional waters advocated by the WFD (i.e., aquatic flora; benthic invertebrates; fish) and one of the five, out of eleven, qualitative descriptors set out by the MSFD (i.e., biodiversity; non-indigenous species; exploited fish; food web; seafloor integrity).

2.2.1 Indices describing the ‘fish’ component

Data on fish assemblages were collected at 5 sites all characterized by rocky reefs (Figure 1), as the inherent complexity of these habitats is known to support fish diversity (Lingo and Szedlmayer, 2006). Fish assemblages were assessed by scuba diving in a depth range of 5–18 m through underwater visual census along non-overlapping random transects of 25 m × 5 m (Harmelin-Vivien et al., 1985). A total of 16 transects were surveyed per site. Sampling was repeated at two random times through the study year, for a total of 160 visual census transects. Abundance and size (total length) of all fishes encountered along each transect were recorded by trained diving scientists. Fish biomass was estimated from size data by means of length–weight relationships (Froese and Pauly, 2018), then the total biomass of fish per transect (expressed in g m^{-2}) was used to calculate the indices (Morey et al., 2003; Guidetti et al., 2014).

- *Fish H’*. Diversity of the fish community was estimated using the Shannon–Wiener diversity index, performed on the data matrix of fish biomass by means of the free software PaSt (Hammer et al., 2001).
- *Exploited Fish*. The total biomass of exploited fish per site was calculated considering only the 23 species targeted by commercial and recreational fisheries listed by Di Franco et al. (2009).
- *High Level Predators*. The abundance of top carnivores has been suggested as an indicator of the integrity of the marine

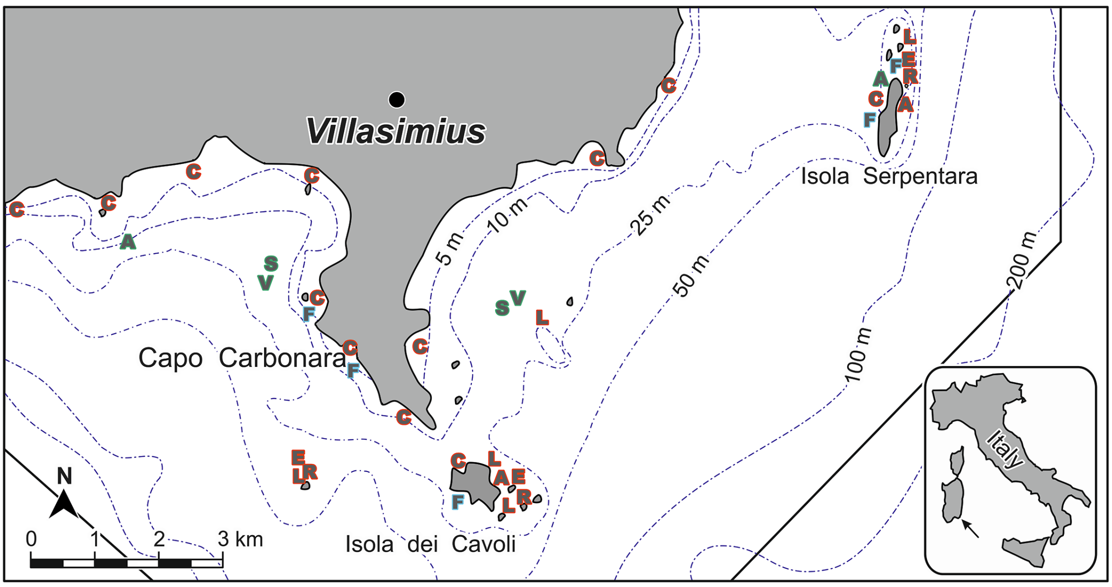

FIGURE 1
Survey sites within the study area. Colors refer to the different habitat/biotic components (blue: fish; red: reef; green: seagrass) for which indices provide information. Capital letters indicate the measured index: A (ALEX); C (CARLIT); E (ESCA); F (all three fish indices); L (LIMA); R (COARSE); S (SI); V (CI).

TABLE 1 List of the indices adopted in the present study and their corresponding Biological Quality Elements (BQEs) and qualitative descriptors according to the European directives.

Index	Habitat/ Biotic component	Biological Quality Elements (WFD)	Qualitative descriptors (MSFD)	Recovery time
Fish H'	Fish	Fish fauna	1 Biodiversity	fast
CARLIT	Reef	Aquatic flora	1 Biodiversity	fast
ESCA	Reef	Aquatic flora and benthic invertebrates	1 Biodiversity	medium
$ALEX_S$	Seagrass	Aquatic flora	2 NIS	medium (or not evaluable)
$ALEX_R$	Reef	Aquatic flora	2 NIS	medium (or not evaluable)
SI	Seagrass	Aquatic flora	2 NIS	medium
Exploited Fish	Fish	Fish fauna	3 Exploited fish	fast
Fish (High Level Predators)	Fish	Fish fauna	4 Food web	fast
LIMA	Reef	Aquatic flora and benthic invertebrates	6 Seafloor integrity	slow
COARSE	Reef	Aquatic flora and benthic invertebrates	6 Seafloor integrity	slow
CI	Seagrass	Aquatic flora	6 Seafloor integrity	slow

food web structure (Bianchi and Morri, 1985; Heithaus et al., 2008). Fishes belonging to the category of High Level Predators (HLP) were selected on the basis of the Trophic Level, using the information on diet from previous Mediterranean studies (Stergiou and Karpouzi, 2002; Froese and Pauly, 2011; Sala et al., 2012). Based on the literature and according to our expert judgement, we set the threshold of 3.65 as the minimum trophic level value for a species to be included in the category, and then the total biomass of HLP per site was estimated.

2.2.2 Indices describing the 'reef' habitat

Surveys were carried out from the surface down to about 40 m depth, at different sites within the MPA depending on the index considered.

- *CARLIT*. Shallow benthic communities of rocky substrate dominated by macroalgae were visually investigated through the CARLIT (Cartography of Littoral and upper-sublittoral rocky-shore communities) method (Ballesteros et al., 2007). Observations were done from the boat, considering only macroalgal communities between 20 cm above and 50 cm below the surface. The sampling unit was 50 linear meters, at 12 sites randomly dispersed along the 31 km of the MPA coastline, including the two islets of Serpentara and Cavoli.
- *ESCA*. Circalittoral benthic communities, including macroalgal assemblages and sessile invertebrates typical of coralligenous reefs, were assessed using the ESCA (Ecological Status of Coralligenous Assemblages) index (Cecchi et al., 2014; Piazzi et al., 2017a). Vertical rocky walls at three sites within the MPA were investigated at about 35 m depth by means of photographic sampling. At each site, a total of 30 photographic samples of 0.2 m^2 were collected across three areas 10 m apart from each other.
- *$ALEX_R$*. Non-indigenous macroalgal species (no information on the invertebrate fauna was available, while non-indigenous fish species were not recorded) detected within the sessile assemblages of hard bottom habitats have been quantified through the application of ALEX (ALien Biotic IndEX) (Çinar and Bakir, 2014; Piazzi et al., 2015), here renamed $ALEX_R$ to indicate that it was applied to reefs. Two sites were selected, then the sampling was carried out on shallow and deep rocky bottoms, respectively at 5 and 30 m depth, in three replicates of 400 cm^2 (within which area all macroalgae were collected by scraping). A total substrate area of 2400 cm^2 was sampled per site.
- *LIMA*. The environmental quality of rocky reefs and the seascape complexity were assessed through the implementation of the LIMA index (Gobert et al., 2014), with some adjustments. Data were collected along depth transects from a depth of about 40 m to the surface at five sites. Compared to the original formulation of LIMA, we considered as negative the scores attributed to the typology 'dead matte' and 'sandy-muddy' in the topographical description, as their occurrence is deemed to reduce the submerged seascape value; similarly, the biological indicator 'invasive species' was subtracted, instead of added, in the biological description formula, as aliens are universally perceived as harmful for the native communities (Morri et al., 2019). With these adjustments, the final index increases as the quality of the site increases.
- *COARSE*. The three-dimensional structure of coralligenous reefs, together with their biotic cover and conspicuous species richness, were assessed using the COARSE

(COralligenous Assessment by Reef Scape Estimation) index (Gatti et al., 2015). Three sites within the MPA were investigated at about 35 m depth through the RVA (Rapid Visual Assessment) method proposed by Gatti et al. (2012), replicated three times at each site.

2.2.3 Indices describing the 'seagrass' habitat

Four sites within *Posidonia oceanica* meadows were investigated by scuba diving. Field activities included visual surveys of the seafloor at random isolated stations and collection of samples depending on the index considered.

- *$ALEX_S$*. Non-indigenous species (NIS) of macroalgae (no data were available for the fauna) detected within the *P. oceanica* seagrass meadows were quantified using ALEX (Piazzi et al., 2015, 2021a), here renamed $ALEX_S$ to indicate that it was applied to seagrass meadows. Two sites were selected to sample shallow and deep areas of bare 'matte' (tangle of seagrass rhizomes and roots with trapped sediment, without living shoots) at the edge of the meadows, in three replicates of 400 cm^2 (area within which all macroalgae were manually sampled) for a total of 2400 cm^2 of bottom area sampled per site.
- *CI*. Loss of *P. oceanica* meadow areas, mostly due to human induced disturbances, was assessed by means of the Conservation Index (CI) (Moreno et al., 2001; Montefalcone, 2009). Percent cover data of the seabed by dead matte and living *P. oceanica* were visually estimated at the lower limit, at the upper limit and in the central sector of two *P. oceanica* meadows for a total of 18 visual surveys per site.
- *SI*. The extent of colonization by less structuring species than *P. oceanica*, such as the other Mediterranean seagrass *Cymodocea nodosa* and the green algae of the genus *Caulerpa*, was assessed through the Substitution Index (SI) (Montefalcone, 2009). Data on percent cover of the bottom by substitute species were visually estimated at the lower limit, at the upper limit and in the central sector of two *P. oceanica* meadows for a total of 18 visual surveys per site.

2.3 Implementation of RESQUE approach

In order to test whether the different indices were consistent in defining the environmental status of the MPA and to highlight either concordant or discordant responses, data were normalized to obtain comparable values within the range between 0 and 1. To this end, the Ecological Quality Ratio (EQR) was estimated for each index by dividing the measured values for a reference value and then its mean value was graphically depicted on a radar chart. In the absence of known references for the territorial unit under investigation, reference values were calculated as the average of the three highest values of the considered metric after having discarded the maximum, following the protocol established by Gobert et al. (2009). However, expert advice has been elicited to set references whenever necessary (e.g., in case of conditions with little variability and low environmental quality); all experts are included among the authors of the present paper. The complement to unit (1-EQR) of SI was calculated to make the index increase with the quality of the habitat and to allow comparison with the other indices.

Following the RESQUE approach, the total area of the polygon resulting from the radar chart was considered as a measure of the overall environmental quality. The consistency among indices was expressed by the circularity of the polygon perimeter and has been interpreted as a measure of resilience (Oprandi et al., 2021). Area (in pixels) and circularity of polygons were computed using the software Adobe Photoshop® CC.

3 Results

3.1 Indices values

Biodiversity

The quality and occurrence of habitats, and the distribution and abundance of species were described by three out of eleven measured indices: Fish H', CARLIT (shallow water macroalgae) and ESCA (macroalgae and sessile invertebrates). Fish H' ranged between 1.59 and 1.72 across the five sites investigated with an average of 1.64 ± 0.05. CARLIT ranged between 0.738 (good status) and 0.989 (high status) showing an average value of 0.829 ± 0.07, which revealed an overall high status of shallow water macroalgal communities. ESCA showed very little variation between sites, displaying an average value of 0.847 ± 0.05 that revealed again a high status of coralligenous benthic assemblages.

Non-indigenous Species

The evidence that the presence of NIS was at levels that did not adversely alter the ecosystems was provided by three of the indices measured: $ALEX_R$, $ALEX_S$ and SI. $ALEX_R$ exhibited values ranging from moderate (0.632) to high (1), while $ALEX_S$ ranged from good (0.716) to high (0.983). Overall, $ALEX_R$ showed a high status (0.901 ±0.13), while $ALEX_S$ only had a good status (0.851± 0.07). SI showed a moderate status (0.30) at only one of the sites investigated, while no substitute species was detected in the other *P. oceanica* meadows. The average SI value was 0.05±0.12, corresponding to a high status.

Exploited fish

The biomass of the target species ranged from 32.7 g m^{-2} to 68.7 g m^{-2}, with an average value of 53.8 ± 15.3 g m^{-2}.

Food web

The biomass of High Level Predators was taken into account in the assessment of the food web status. Biomass of HLP ranged from a minimum of 11.42 g m^{-2} to a maximum of 33.9 g m^{-2}, with an average of 24.4 ± 9.5 g m^{-2}.

Seafloor integrity

Information about the structure and functions of the benthic ecosystems was obtained through the indices LIMA, COARSE and CI. LIMA varied widely between the five sites surveyed, from poor (0.38) to good (0.78) status, overall showing a moderate status (0.59), possibly due to the complexity of the MPA seascapes. COARSE showed little variation between the three sites, exhibiting an overall high status (2.48± 0.29) of coralligenous reefs. CI ranged from 0.50 (moderate status) to 0.83 (good status) showing an average value of 0.63 ± 0.14, which ultimately revealed a moderate conservation status of the meadows.

3.2 Comparison through the RESQUE approach

Overall, the eleven indices analyzed through the RESQUE approach showed consistent responses, as confirmed by the quite rounded shape of the irregular hendecagon and the resulting high value of circularity (0.848) (Figure 2). Polygon area (132060 pixels) corresponded to 73% of the area of an ideal regular hendecagon (180258 pixels) where all EQR values are equal to 1 (circularity: 0.877) (Figure 2). In particular, the indices describing *Biodiversity* and *NIS* showed the highest values of EQR (on average 0.91 ± 0.06 and 0.91± 0.04, respectively) and were followed by the *Seafloor integrity* indices with a mean EQR of 0.83 ± 0.09, the *Exploited fish* index with an EQR value of 0.78 ± 0.11, and lastly by the *Food webs* index with an EQR of 0.72 ± 0.16 (Figure 3).

When indices were grouped according to the BQEs indicated by the WFD, their EQR values showed virtually no differences. *Benthic invertebrates*' indices (i.e., ESCA, LIMA and COARSE) showed the higher mean EQR value corresponding to 0.88 ± 0.09, followed by the *Aquatic flora* indices (i.e., CARLIT, $ALEX_R$, $ALEX_S$, 1-SI, CI) with a mean EQR of 0.86 ± 0.07 and the *Fish* fauna indices (H', Exploited fish and HLP) with an EQR equal to 0.82 ± 0.12 (Figure 3).

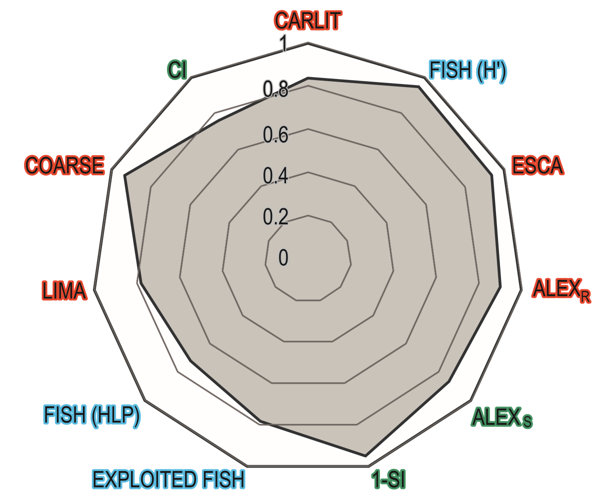

FIGURE 2
Polygon resulting from the EQR scores of all the indices (grey shape). An ideal hendecagon (white polygon) is shown below as a reference. Colors refer to the different habitat/biotic components (blue: fish; red: reef; green: seagrass) for which indices provide information.

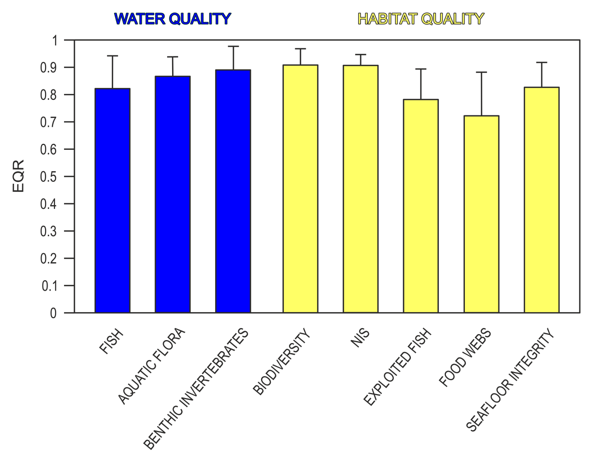

FIGURE 3
Mean EQR scores according to the indices of Water quality (blue) and Habitat quality (yellow).

4 Discussion

To reliably assess the state of the marine environment, considering as many habitats and biotic components as possible, is desirable, as single indicators/indices may provide only partial answers (Rombouts et al., 2013; Smit et al., 2021). The dataset collated for the present study has enabled us to consider three out of the four BQEs mentioned in the WFD and five out of the 11 qualitative descriptors listed in the MSFD. Being based on a significant proportion of the biological indicators suggested by the abovementioned EU directives, the analysis we carried out can be considered a useful alternative when more specific assessments with purposely planned sampling designs cannot be applied.

Indices are indeed suitable and easy to use tools for management purposes (Gatti et al., 2012), but when possible analytical approaches such as BACI and beyond BACI (Underwood, 1994; Smith, 2002; Christie et al., 2019) should be preferred to get a solid assessment of environmental status or of the impacts occurred in a certain area. These approaches, however, require data collected specifically according to dedicated protocols, which was not the case for the present study.

We utilized data collected for different purposes, with specific and distinct sampling designs, which certainly represents one of the limitations of our study. Of course, some important habitats/biotic components (e.g., soft bottom) were not taken into account, but the main aim of our work was not to explore all the marine habitats included within the MPA, nor to verify the efficacy of the protection regime, but rather to see whether a number of components of the marine environment that are customarily considered by environmental agencies and administrations were in agreement in terms of state of the environment. Even with a dedicated study, sampling all the habitats/biotic components of the MPA would have required a huge effort in terms of funds, time, and people, and therefore be virtually impossible to implement. The monitoring activities that are carried out more or less regularly in the MPA enabled us to dispose of a large dataset covering most of the environmental features of the study area.

The problem is not only the availability of data but also how to assess the whole to achieve an unequivocal measure of the ecosystem status, avoiding loss of information. The risk, when considering many different or conflicting responses together, is to fail to interpret them and thus simplify the final result (Gatti et al., 2012; Gatti et al., 2015; Thibaut et al., 2017; Mancini et al., 2020). The RESQUE approach had already revealed its potential in comparing different metrics related to the same ecosystem (seagrass meadows), whether it changed over time or space (Oprandi et al., 2021, 2022). Here, it also proved to be effective in the comparison of indices relating to different habitats and biological components, clearly showing that all the indices were highly congruent. In contrast, previous Mediterranean studies comparing different indices in soft bottom habitats provided results that were not conclusive or were even contradictory (Occhipinti Ambrogi et al., 2009; Reizopoulou et al., 2014; Sánchez-Moyano et al., 2017; Magni et al., 2023). Peleg et al. (2023) found only “some consistent patterns” when using nine health indicators to assess the status of rocky reefs in New Zealand.

The available reference classifications of indices are often inadequate when the geographical context is different from the one in which they were originally created (Pinto et al., 2009). The method we used does not actually require the use of reference classifications, but is based on the calculation of EQRs, and thus on the identification of a reference value for each index, which represents the best obtainable value for that index in the investigated area (Oprandi et al., 2021). Having a large available dataset is a key asset in order to identify reference values consistent with local scale patterns (Smit et al., 2021). In the case of Capo Carbonara MPA, it was possible to successfully apply the RESQUE approach thanks to the availability of a considerable amount of data which, being collected in independent studies, were designed to maximize information in the study area.

For simplicity, in the present work, we have referred to the method of Gobert et al. (2009) for the identification of the reference values, which is widely used by the Italian environmental agencies in their monitoring plans. This approach, however, implies that particularly low EQR values can only be observed when there is great variability in the data. Thus, values close to 1 could also be observed in the case of conditions with little variability but low environmental quality. This was never the case for Capo Carbonara MPA: all indices, taken individually, presented ecological status between good and high, and the data used to calculate them showed high variability.

The choice of reference is a hotly-debated issue that has no univocal answers (Muxika et al., 2007; Borja et al., 2012). Standardizing (i.e., bring all values in the range 0-1) remains the correct thing to do (Legendre and Legendre, 2012). However, a better definition of the references and related EQR calculation would certainly be desirable; to this end, expert judgement is a key tool to include. Future studies may explore further this issue to find more effective ways of providing a reference for the EQR.

We assumed that an ideal hendecagon, which is obtained when all indices values reach their maximum (i.e., are equal to 1), was the benchmark describing the best conditions for the Capo Carbonara MPA, corresponding to a high environmental status. Area and circularity values of the polygon obtained from RESQUE analysis corresponded to 73% and 97%, respectively, of those of the ideal hendecagon: thus, all the indices considered not only provided strong suggestive evidence that support the good status of Capo Carbonara MPA, but also – and even more importantly – that they are fully consistent.

NIS and Biodiversity are, by far, the descriptors that contributed the most to the overall good status of the MPA. Paradoxically, NIS also represents the only descriptor that should not be directly affected by the protection. There is evidence, however, that habitat maintenance contributes, to some extent, to limiting NIS establishment (Bernardeau-Esteller et al., 2020; Houngnandan et al., 2022). The general healthy status of the benthic communities within the MPA possibly manages to keep allochthonous species at a rather low level (Piazzi et al., 2021a). This is particularly true with regard to *Posidonia oceanica* meadows, as NIS substitutes are known to settle mostly on dead matte areas rather than within dense canopies of living shoots (Oprandi et al., 2014; Montefalcone et al., 2015; Piazzi et al., 2016). In Capo Carbonara MPA, the values of the Conservation Index, which measures meadow degradation (by comparing the cover of dead matte with that of living *P. oceanica*), indicated a reduced state of conservation in some areas inside the meadow, which likely facilitated the establishment of NIS. In fact, the mean value of $ALEX_S$ was slightly lower than $ALEX_R$. The reduced abundance of macroalgal NIS could be the result of successive colonization stages that led to the achievement of a balance between native and NIS assemblages (Boudouresque and Verlaque, 2012). It is likely that the general healthy status of the benthic communities manages to limit the expansion of NIS in the study area (Piazzi et al., 2021a).

According to CARLIT, more than 50% of the rocky coastline of the Capo Carbonara AMP is characterized by species with a medium to medium-high level of sensitivity (Ballesteros et al., 2007; Atzori et al., 2020), thus indicating good water quality. Similarly, the ESCA index, which is known to be sensitive to human disturbances (Piazzi et al., 2021b), displayed high values. These outcomes underline how proper management can positively affect both shallow macroalgal communities and circalittoral coralligenous assemblages.

The benefits of protection on fish biomass and abundance are well known (Guidetti et al., 2014), and can be perceived over a time span of 5 to 20 years (Edgar et al., 2009; Babcock et al., 2010), while the reserve effect on fish diversity is still debated, as it may depend on the time since the enforcement of the protection and other factors not yet fully elucidated. A recent study showed that a stabilizing effect on fish biodiversity is apparent within 4 years since the establishment of an MPA (Pettersen et al., 2022): Capo Carbonara MPA was established about 20 years ago.

COARSE was created in the frame of the MSFD, for the specific purpose of providing information on seafloor integrity (Gatti et al., 2015). The index consists of three distinct parts concerning bioconstruction, biodiversity, and the three-dimensional structure of the coralligenous habitat. These are able to detect alterations in the environmental quality that are not only related to human pressure. In particular, the diversity of the intermediate layer and the conditions of the upper layer seem to be sentinels of climate change (Piazzi et al., 2017b). Recent comparative studies reported significant changes in the deep reef communities of Capo Carbonara MPA over the last 20 years (Azzola et al., 2022), including a local mass mortality event of gorgonians following summer heatwaves (Piazzi et al., 2021b). Boundaries of MPAs do not constitute a physical barrier against sea warming. However, the high COARSE value we found, may indicate high resilience of the coralligenous reefs of Capo Carbonara MPA.

CI and LIMA indices, adopted to assess seafloor integrity, reported comparatively lower values. However, both indices consider benthic associations that have a wider distribution and bathymetric range than coralligenous reefs and are, therefore, potentially exposed to greater risk of impact and a greater natural variability. CI in particular may have been affected by leisure boating, as signs of anchoring were reported during routine monitoring activities on *P. oceanica* meadows (Montefalcone and Oprandi, 2020). With regard to LIMA, it should be emphasized that the formulation of this index takes the topography of the seabed into account when assessing habitat complexity. This can be to the detriment of the biological part at those sites where, notwithstanding equal presence of species, bottom rugosity is lower.

Indices of exploited fish and food webs (Exploited fish and HLP) showed similar trends as they focus mostly on the same species: approximately 75% of high-level predators are actually commercially exploited. The average biomasses of exploited fish and HLP we estimated in Capo Carbonara MPA are comparable to those found in other regional-scale studies where the MPA management was deemed sufficient to obtain measurable effects on fish (Di Franco et al., 2009; Guidetti et al., 2014; Guidetti et al., 2019; Rojo et al., 2021).

Besides the comparison of different indices, the use of RESQUE provided some valuable insights into the way of interpreting the differences between water quality, defined according to the WFD, and habitat quality, defined according to the MSFD. This type of analysis strengthened our results, because apparently both Good Ecological Status and Good Environmental Status were achieved in the Capo Carbonara MPA. The differences, in terms of requirements and goals, between the two European directives have long been discussed (Borja et al., 2010), but the present study evidences for the first time that they are congruent in their assessments of the status of marine ecosystems.

The necessity of using a combination of several indicators to define the quality of the marine environment has been emphasized more than once. To date, there is no risk of failing to achieve this objective given the number of existing indices. The question is no longer just how (structural approach vs. functional approach) to assess what (water quality or habitat quality), but more importantly, with which metrics/indices and how many (Borja et al., 2015).

Although our study has been carried out at a local scale, the approach used here offers a starting point for further work in the near future, as biological indicators are being implemented at broader scales (Fraschetti et al., 2022). We consider that our approach may represent an example to be followed in other areas where monitoring data are available, in comparative studies involving both protected and unprotected environments.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

AO: conceptualization, investigation, data analysis, and writing original draft – review & editing. FA: writing – review & editing. AA: investigation and data analysis. CNB: conceptualization, data analysis, and writing – review & editing. NC: investigation and data analysis. LC: data analysis. ED: investigation and writing – review & editing. FF: investigation and data analysis. MG: investigation. PG: investigation and writing – review & editing. CM: data analysis and writing – review & editing. LP: investigation, data analysis, and writing – review & editing. FP: data analysis and writing – review & editing. MM: investigation, supervision, and project administration. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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References

Andromède, (2017). *Inventaire et cartographie des biocénoses marines de l'Aire Marine Protégée Capo Carbonara – Sardaigne (Italie)* (France: Contrat Andromède Océanologie / Agence de l'Eau RMC / Area Marina Protetta Capo Carbonara).

Astruch, P., Orts, A., Schohn, T., Belloni, B., Ballesteros, E., Bianchi, C. N., et al. (2022). "Towards an ecosystem-based index to assess the ecological status of Mediterranean coastal detrital bottoms," in *Proceedings of the 4th Mediterranean symposium on the conservation of coralligenous & other calcareous bio-concretions*. Eds. C. Bouafif and A. Ouerghi (Tunis, TN: SPA/RAC Publications), 137–138.

Atzori, F., Cadoni, N., Carosso, L., Frau, F., and Garcìa Gutiérrez, M. L. (2020). *Monitoraggio dello stato ecologico delle acque costiere dell'area marina protetta "Capo carbonara" secondo la metodologia CARLIT* (Villasimius (IT: Area Marina Protetta Capo Carbonara).

Azzola, A., Atzori, F., Bianchi, C. N., Cadoni, N., Frau, F., Mora, F., et al. (2022). Variability between observers does not hamper detecting change over time in a temperate reef. *Mar. Environ. Res.* 177, 105617. doi: 10.1016/j.marenvres.2022.105617

Azzola, A., Picchio, V., Asnaghi, V., Bianchi, C. N., Morri, C., Oprandi, A., et al. (2023). Troubles never come alone: outcome of multiple pressures on a temperate rocky reef. *Water* 15 (4), 825. doi: 10.3390/w15040825

Babcock, R. C., Shears, N. T., Alcala, A. C., Barrett, N. S., Edgar, G. J., Lafferty, K. D., et al. (2010). Decadal trends in marine reserves reveal differential rates of change in direct and indirect effects. *Proc. Natl. Acad. Sci. U.S.A.* 107, 18256–18261. doi: 10.1073/pnas.0908012107

Ballesteros, E., Torras, X., Pinedo, S., Garcìa, M., Mangialajo, L., and De Torres, M. (2007). A new methodology based on littoral community cartography for the implementation of the European water framework directive. *Mar. pollut. Bull.* 55, 172–180. doi: 10.1016/j.marpolbul.2006.08.038

Bernardeau-Esteller, J., Marín-Guirao, L., Sandoval-Gil, J. M., García-Muñoz, R., Ramos-Segura, A., and Ruiz, J. M. (2020). Evidence for the long-term resistance of *Posidonia oceanica* meadows to *Caulerpa cylindracea* invasion. *Aquat. Bot.* 160, 103167. doi: 10.1016/j.aquabot.2019.103167

Bianchi, C. N., Azzola, A., Cocito, S., Morri, C., Oprandi, A., Peirano, A., et al. (2022). Biodiversity monitoring in Mediterranean marine protected areas: Scientific and methodological challenges. *Diversity* 14 (1), 43. doi: 10.3390/d14010043

Bianchi, C. N., and Morri, C. (1985). Polychaetes as descriptors of the trophic structure of benthic marine ecosystems. *Oebalia* 11, 203214.

Birk, S., Bonne, W., Borja, A., Brucet, S., Courrat, A., Poikane, S., et al. (2012). Three hundred ways to assess europe's surface waters: an almost complete overview of biological methods to implement the water framework directive. *Ecol. Indic.* 18, 31–41. doi: 10.1016/j.ecolind.2011.10.009

Borja, Á., Dauer, D. M., and Grémare, A. (2012). The importance of setting targets and reference conditions in assessing marine ecosystem quality. *Ecol. Indic.* 12 (1), 1–7. doi: 10.1016/j.ecolind.2011.06.018

Borja, Á., Elliott, M., Andersen, J. H., Cardoso, A. C., Carstensen, J., Ferreira, J. G., et al. (2013). Good environmental status of marine ecosystems: what is it and how do we know when we have attained it? *Mar. pollut. Bull.* 76 (1-2), 16–27. doi: 10.1016/j.marpolbul.2013.08.042

Borja, Á., Elliott, M., Carstensen, J., Heiskanen, A. S., and van de Bund, W. (2010). Marine management–towards an integrated implementation of the European marine strategy framework and the water framework directives. *Mar. pollut. Bull.* 60 (12), 2175–2186. doi: 10.1016/j.marpolbul.2010.09.026

Borja, Á., Marín, S. L., Muxika, I., Pino, L., and Rodríguez, J. G. (2015). Is there a possibility of ranking benthic quality assessment indices to select the most responsive to different human pressures? *Mar. pollut. Bull.* 97 (1-2), 85–94. doi: 10.1016/j.marpolbul.2015.06.030

Boudouresque, C. F., and Verlaque, M. (2012). An overview of species introduction and invasion processes in marine and coastal lagoon habitats. *Cah. Biol. Mar.* 53, 309–317.

Cecchi, E., Gennaro, P., Piazzi, L., Ricevuto, E., and Serena, F. (2014). Development of a new biotic index for ecological status assessment of Italian coastal waters based on coralligenous macroalgal assemblages. *Eur. J. Phycol.* 49, 298–312. doi: 10.1080/09670262.2014.918657

Christie, A. P., Amano, T., Martin, P. A., Shackelford, G. E., Simmons, B. I., and Sutherland, W. J. (2019). Simple study designs in ecology produce inaccurate estimates of biodiversity responses. *J. Appl. Ecol.* 56 (12), 2742–2754. doi: 10.1111/1365-2664.13499

Çinar, M. E., and Bakir, K. (2014). ALien biotic IndEX (ALEX) – a new index for assessing impacts of alien species on benthic communities. *Mar. pollut. Bull.* 87, 171–179. doi: 10.1016/j.marpolbul.2014.07.061

Claudet, J., and Fraschetti, S. (2010). Human-driven impacts on marine habitats: a regional meta-analysis in the Mediterranean Sea. *Biol. Conserv.* 143 (9), 2195–2206. doi: 10.1016/j.biocon.2010.06.004

Di Franco, A., Bussotti, S., Navone, A., Panzalis, P., and Guidetti, P. (2009). Evaluating effects of total and partial restrictions to fishing on Mediterranean rocky-reef fish assemblages. *Mar. Ecol. Prog. Ser.* 387, 275–285. doi: 10.3354/meps08051

Edgar, G. J., Barrett, N. S., and Stuart-Smith, R. D. (2009). Exploited reefs protected from fishing transform over decades into conservation features otherwise absent from seascapes. *Ecol. Appl.* 19, 1967–1974. doi: 10.1890/09-0610.1

Enrichetti, F., Bo, M., Morri, C., Montefalcone, M., Toma, M., Bavestrello, G., et al. (2019). Assessing the environmental status of temperate mesophotic reefs: a new, integrated methodological approach. *Ecol. Indic.* 102, 218–229. doi: 10.1016/j.ecolind.2019.02.028

Fraschetti, S., Fabbrizzi, E., Tamburello, L., Uyarra, M. C., Micheli, F., Sala, E., et al. (2022). An integrated assessment of the good environmental status of Mediterranean marine protected areas. *J. Environ. Manage.* 305, 114370. doi: 10.1016/j.jenvman.2021.114370

Froese, R., and Pauly, D. (2011). *FishBase* Vol. 2011 (World wide web electronic publication).

Froese, R., and Pauly, D. (2018) *FishBase, version (06/2018)*. Available at: www.fishbase.org.

Gatti, G., Bianchi, C. N., Morri, C., Montefalcone, M., and Sartoretto, S. (2015). Coralligenous reefs state along anthropized coasts: Application and validation of the COARSE index, based on a rapid visual assessment (RVA) approach. *Ecol. Indic.* 52, 567–576. doi: 10.1016/j.ecolind.2014.12.026

Gatti, G., Montefalcone, M., Rovere, A., Parravicini, V., Morri, C., Albertelli, G., et al. (2012). Sea-Floor integrity down the harbor waterfront: the coralligenous shoals off vado ligure (NW Mediterranean). *Adv. Oceanol. Limnol.* 3 (1), 51–67. doi: 10.1080/19475721.2012.671190

Gobert, S., Chéry, A., Volpon, A., Pelaprat, C., and Lejeune, P. (2014). "The seascape as an indicator of environmental interest and quality of the Mediterranean benthos: the in situ development of a description index: the LIMA," in *Underwater seascapes* (Cham: Springer), 277–291. doi: 10.1007/978-3-319-03440-9_18

Gobert, S., Sartoretto, S., Rico-Raimondino, V., Andral, B., Chery, A., Lejeune, P., et al. (2009). Assessment of the ecological status of Mediterranean French coastal waters as required by the water framework directive using the *Posidonia oceanica* rapid easy index: PREI. *Mar. pollut. Bull.* 58 (11), 1727–1733. doi: 10.1016/j.marpolbul.2009.06.012

Grorud-Colvert, K., Sullivan-Stack, J., Roberts, C., Constant, V., Horta e Costa, B., Pike, E. P., et al. (2021). The MPA guide: A framework to achieve global goals for the ocean. *Science* 373 (6560), eabf0861. doi: 10.1126/science.abf0861

Guidetti, P., Addis, P., Atzori, F., Bussotti, S., Calò, A., Cau, A., et al. (2019). Assessing the potential of marine natura 2000 sites to produce ecosystem-wide effects in rocky reefs: A case study from Sardinia island (Italy). *Aquat. Conserv. Mar. Freshw. Ecosyst.* 29 (4), 537–545. doi: 10.1002/aqc.3026

Guidetti, P., Baiata, P., Ballesteros, E., Di Franco, A., Hereu, B., Macpherson, E., et al. (2014). Large-Scale assessment of Mediterranean marine protected areas effects on fish assemblages. *PloS One* 9 (4), e91841. doi: 10.1371/journal.pone.0091841

Hammer, Ø., Harper, D. A. T., and Ryan, P. D. (2001). PaSt: Paleontological statistics software package for education and data analysis. *Palaeontol. Electron* 4, 4.

Harmelin-Vivien, M. L., Harmelin, J. G., Chauvet, C., Duval, C., Galzin, R., Lejeune, P., et al. (1985). Evaluation visuelle des peuplements et populations de poissons méthodes et problèmes. *Rev. d'Ecologie Terre Vie* 40 (4), 467–539. doi: 10.3406/revec.1985.5297

Heithaus, M. R., Frid, A., Wirsing, A. J., and Worm, B. (2008). Predicting ecological consequences of marine top predator declines. *Trends Ecol. Evol.* 23 (4), 202–210. doi: 10.1016/j.tree.2008.01.003

Houngnandan, F., Kefi, S., Bockel, T., and Deter, J. (2022). The joint influence of environmental and anthropogenic factors on the invasion of two alien caulerpae in northwestern Mediterranean. *Biol. Invasions* 24 (2), 449–462. doi: 10.1007/s10530-021-02654-w

Legendre, P., and Legendre, L. (2012). *Numerical ecology* (Netherlands: Elsevier Amsterdam).

Lingo, M. E., and Szedlmayer, S. T. (2006). The influence of habitat complexity on reef fish communities in the northeastern gulf of Mexico. *Environ. Biol. Fishes* 76, 71–80. doi: 10.1016/j.marpolbul.2009.06.012

Magni, P., Vesal, S. E., Giampaoletti, J., Como, S., and Gravina, M. F. (2023). Joint use of biological traits, diversity and biotic indices to assess the ecological quality status of a Mediterranean transitional system. *Ecol. Indic.* 147, 109939. doi: 10.1016/j.ecolind.2023.109939

Mancini, I., Rigo, I., Oprandi, A., Montefalcone, M., Morri, C., Peirano,, et al. (2020). What biotic indices tell us about ecosystem change: Lessons from the seagrass *Posidonia oceanica*. *Vie Milieu/Life Environ.* 70 (3-4), 55–56.

Montefalcone, M. (2009). Ecosystem health assessment using the Mediterranean seagrass *Posidonia oceanica*: a review. *Ecol. Indic.* 9 (4), 595–604. doi: 10.1016/j.ecolind.2008.09.013

Montefalcone, M., and Oprandi, A. (2020). *Definizione della qualità ecologica dell'habitat marino prioritario praterie di Posidonia oceanica nell'Area Marina protetta Capo Carbonara (Villasimius)* (Genoa (IT: University of Genoa).

Montefalcone, M., Vassallo, P., Gatti, G., Parravicini, V., Paoli, C., Morri, C., et al. (2015). The exergy of a phase shift: ecosystem functioning loss in seagrass meadows of the Mediterranean Sea. *Estuar. Coast. Shelf Sci.* 156, 186–194. doi: 10.1016/j.ecss.2014.12.001

Moreno, D., Aguilera, P. A., and Castro, H. (2001). Assessment of the conservation status of seagrass (*Posidonia oceanica*) meadows: implications for monitoring strategy and the decision-making process. *Biol. Conserv.* 102 (3), 325–332. doi: 10.1016/S0006-3207(01)00080-5

Morey, G., Moranta, J., Massuti, E., Grau, A., Linde, M., Riera, F., et al. (2003). Weight-length relationships of littoral to lower slope fishes from the Western Mediterranean. *Fish Res.* 62, 89–96. doi: 10.1016/S0165-7836(02)00250-3

Morri, C., Montefalcone, M., Gatti, G., Vassallo, P., Paoli, C., and Bianchi, C. N. (2019). An alien invader is the cause of homogenization in the recipient ecosystem: a simulation-like approach. *Diversity* 11, 146. doi: 10.3390/d11090146

Muxika, I., Borja, Á., and Bald, J. (2007). Using historical data, expert judgement and multivariate analysis in assessing reference conditions and benthic ecological status, according to the European water framework directive. *Mar. Poll. Bull.* 55, 16–29. doi: 10.1016/j.marpolbul.2006.05.025

Occhipinti Ambrogi, A., Forni, G., and Silvestri, C. (2009). The Mediterranean intercalibration exercise on soft-bottom benthic invertebrates with special emphasis on the Italian situation. *Mar. Ecol.* 30 (4), 495–504. doi: 10.1111/j.1439-0485.2009.00317.x

Oprandi, A., Bianchi, C. N., Karayali, O., Morri, C., Rigo, I., and Montefalcone, M. (2021). RESQUE: A novel comprehensive approach to compare the performance of different indices in evaluating seagrass health. *Ecol. Indic.* 131, 108118. doi: 10.1016/j.ecolind.2021.108118

Oprandi, A., Mancini, I., Bianchi, C. N., Morri, C., Azzola, A., and Montefalcone, M. (2022). "Indices from the past: relevance in the status assessment of posidonia oceanica meadows," in *Proceedings of the 7th Mediterranean symposium on marine vegetation*. Eds. C. Bouafif and A. Ouerghi (Tunis, TN: SPA/RAC Publications), 71–77.

Oprandi, A., Montefalcone, M., Vacchi, M., Coppo, S., Diviacco, G., Morri, C., et al. (2014). "Combining modelling and historical data to define the status of posidonia oceanica meadows," in *Proceedings of the 5th Mediterranean symposium on marine vegetation*. Eds. H. Langar, C. Bouafif and A. Ouerghi (Tunis, TN: RAC/SPA Publications), 119–124.

Paoli, C., Morten, A., Bianchi, C. N., Morri, C., Fabiano, M., and Vassallo, P. (2016). Capturing ecological complexity: OCI, a novel combination of ecological indices as applied to benthic marine habitats. *Ecol. Indic.* 66, 86–102. doi: 10.1016/j.ecolind.2016.01.029

Pawlowski, J., Kelly-Quinn, M., Altermatt, F., Apothéloz-Perret-Gentil, L., Beja, P., Boggero, A., et al. (2018). The future of biotic indices in the ecogenomic era: Integrating (e) DNA metabarcoding in biological assessment of aquatic ecosystems. *Sci. Total Environ.* 637, 1295–1310. doi: 10.1016/j.scitotenv.2018.05.002

Peleg, O., Blain, C., and Shears, N. (2023). Multi-indicator 'state space'approach to assessing changes in shallow urban reef ecosystem health. *Mar. Environ. Res.* 186, 105895. doi: 10.1016/j.marenvres.2023.105895

Pettersen, A. K., Marzinelli, E. M., Steinberg, P. D., and Coleman, M. A. (2022). Impact of marine protected areas on temporal stability of fish species diversity. *Conserv. Biol.* 36 (2), e13815. doi: 10.1111/cobi.13815

Piazzi, L., Atzori, F., Cadoni, N., Cinti, M. F., Frau, F., and Ceccherelli, G. (2021a). Monitoring non-indigenous macroalgae in a Mediterranean MPA: Lessons from a short-temporal variability of pristine habitats invasion. *Ocean Coast. Manage.* 207, 105608. doi: 10.1016/j.ocecoaman.2021.105608

Piazzi, L., Atzori, F., Cadoni, N., Cinti, M. F., Frau, F., Pansini, A., et al. (2021b). Animal forest mortality: Following the consequences of a gorgonian coral loss on a Mediterranean coralligenous assemblage. *Diversity* 13 (3), 133. doi: 10.3390/d13030133

Piazzi, L., Balata, D., Bulleri, F., Gennaro, P., and Ceccherelli, G. (2016). The invasion of *Caulerpa cylindracea* in the Mediterranean: the known, the unknown and the knowable. *Mar. Biol.* 163, 161. doi: 10.1007/s00227-016-2937-4

Piazzi, L., Bianchi, C. N., Cecchi, E., Gatti, G., Guala, I., Morri, C., et al. (2017b). What's in an index? comparing the ecological information provided by two indices to assess the status of coralligenous reefs in the NW Mediterranean Sea. *Aquat. Conserv.: Mar. Freshw. Ecosyst.* 27 (6), 1091–1100. doi: 10.1002/aqc.2773

Piazzi, L., Gennaro, P., and Ceccherelli, G. (2015). Suitability of the alien biotic index (ALEX) for assessing invasion of macroalgae across different Mediterranean habitats. *Mar. Pollut. Bull.* 97, 234–240. doi: 10.1016/j.marpolbul.2015.06.011

Piazzi, L., Gennaro, P., Cecchi, E., Serena, F., Bianchi, C. N., Morri,, et al. (2017a). Integration of ESCA index through the use of sessile invertebrates. *Sci. Mar.* 81, 1–8. doi: 10.3989/scimar.04565.01B

Pinto, R., Patrício, J., Baeta, A., Fath, B. D., Neto, J. M., and Marques, J. C. (2009). Review and evaluation of estuarine biotic indices to assess benthic condition. *Ecol. Indic.* 9 (1), 1–25. doi: 10.1016/j.ecolind.2008.01.005

Rastorgueff, P. A., Bellan-Santini, D., Bianchi, C. N., Bussotti, S., Chevaldonné, P., Guidetti, P., et al. (2015). An ecosystem-based approach to evaluate the ecological quality of Mediterranean undersea caves. *Ecol. Indic.* 54, 137–152. doi: 10.1016/j.ecolind.2015.02.014

Reizopoulou, S., Simboura, N., Sigala, K., Barbone, E., Aleffi, F., Kaisakis, G., et al. (2014). Assessing the ecological status of Mediterranean coastal lagoons using macroinvertebrates. comparison of the most commonly used methods. *Medit. Mar. Sci.* 15 (3), 602–612. doi: 10.12681/mms.606

Rigo, I., Dapueto, G., Paoli, C., Massa, F., Oprandi, A., Venturini, S., et al. (2020). Changes in the ecological status and natural capital of *Posidonia oceanica* meadows due to human pressure and extreme events. *Vie Milieu/Life Environ.* 70, 137–148.

Rigo, I., Paoli, C., Dapueto, G., Pergent-Martini, C., Pergent, G., Oprandi, A., et al. (2021). The natural capital value of the seagrass *Posidonia oceanica* in the north-Western Mediterranean. *Diversity* 13, 499. doi: 10.3390/d13100499

Rojo, I., Anadón, J. D., and García-Charton, J. A. (2021). Exceptionally high but still growing predatory reef fish biomass after 23 years of protection in a marine protected area. *PloS One* 16 (2), e0246335. doi: 10.1371/journal.pone.0246335

Rombouts, I., Beaugrand, G., Artigas, L. F., Dauvin, J. C., Gevaert, F., Goberville, E., et al. (2013). Evaluating marine ecosystem health: case studies of indicators using direct observations and modelling methods. *Ecol. Ind.* 24, 353–365. doi: 10.1016/j.ecolind.2012.07.001

Ruitton, S., Personnic, S., Ballesteros, E., Bellan-Santini, D., Boudouresque, C. F., Chevaldonné, P., et al. (2014). "An ecosystem-based approach to assess the status of the Mediterranean coralligenous habitat," in *Proceedings of the 2nd Mediterranean symposium on the conservation of coralligenous and other calcareous bio-concretions*. Eds. C. Bouafif, H. Langar and A. Ouerghi (Tunis, TN: SPA/RAC Publications), 153–158.

Sala, E., Ballesteros, E., Dendrinos, P., Di Franco, A., Ferretti, F., Foley, D., et al. (2012). The structure of Mediterranean rocky reef ecosystems across environmental and human gradients, and conservation implications. *PloS One* 7 (2), e32742. doi: 10.1371/journal.pone.0032742

Sala, O. E., Stuart Chapin, F., Armesto, J. J., Berlow, E., Bloomfield, J., Dirzo, R., et al. (2000). Global biodiversity scenarios for the year 2100. *Science* 287 (5459), 1770–1774. doi: 10.1126/science.287.5459.1770

Sánchez-Moyano, J. E., García-Asencio, I., Donázar-Aramendía, I., Miró, J. M., Megina, C., and García-Gómez, J. C. (2017). BENFES, a new biotic index for assessing ecological status of soft-bottom communities. towards a lower taxonomic complexity, greater reliability and less effort. *Mar. Environ. Res.* 132, 41–50. doi: 10.1016/j.marenvres.2017.10.014

Sartoretto, S., Schohn, T., Bianchi, C. N., Morri, C., Garrabou, J., Ballesteros, E., et al. (2017). An integrated method to evaluate and monitor the conservation state of coralligenous habitats: the INDEX-COR approach. *Mar. pollut. Bull.* 120, 222–231. doi: 10.1016/j.marpolbul.2017.05.020

Smit, K. P., Bernard, A. T., Lombard, A. T., and Sink, K. J. (2021). Assessing marine ecosystem condition: A review to support indicator choice and framework development. *Ecol. Indic.* 121, 107148. doi: 10.1016/j.ecolind.2020.107148

Smith, E. P. (2002). "BACI design," in *Encyclopedia of environmetrics*. Eds. A. H. El-Shaarawi and W. W. Piegorsch (Chichester: John Wiley and Sons Ltd), 141–148.

Stergiou, K.I., and Karpouzi, V.S. (2002). Feeding habits and trophic levels of Mediterranean fish. *Rev. Fish Biol. Fisheries* 11, 217-254. doi: 10.1023/A:1020556722822

Thibaut, T., Blanfuné, A., Boudouresque, C. F., Personnic, S., Ruitton, S., Ballesteros, E., et al. (2017). An ecosystem-based approach to assess the status of Mediterranean algae-dominated shallow rocky reefs. *Mar. Pollut. Bull.* 117, 311–329. doi: 10.1016/j.marpolbul.2017.01.029

Underwood, A. J. (1994). On beyond BACI: sampling designs that might reliably detect environmental disturbances. *Ecol. Appl.* 4 (1), 3–15. doi: 10.2307/1942110

Vassallo, P., Paoli, C., Aliani, S., Cocito, S., Morri, C., and Bianchi, C. N. (2020). Benthic diversity patterns and predictors: a study case with inferences for conservation. *Mar. Pollut. Bull.* 150, 110748. doi: 10.1016/j.marpolbul.2019.110748