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The Status of Coastal Benthic Ecosystems in the Mediterranean Sea: Evidence From Ecological Indicators

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The Mediterranean Sea is subject to multiple human pressures increasingly threatening its unique biodiversity. Spatially explicit information on the ecological status of marine ecosystems is therefore key to an effective maritime spatial planning and management, and to help the achievement of environmental targets. Here, we summarized scientific data on the ecological status of a selection of marine ecosystems based on a set of ecological indicators in more than 700 sites of the Mediterranean Sea. For *Posidonia oceanica* seagrass beds, rocky intertidal fringe, and coastal soft bottoms, more than 70% of investigated sites exhibited good to high ecological conditions. In contrast, about two-thirds of sites for subtidal rocky reefs were classified to be in moderate to bad conditions, stressing the need for prioritizing conservation initiatives on these productive and diverse environments. Very little quantitative information was available for the southern Mediterranean Sea, thus monitoring programs and assessments in this area are essential for a representative assessment of the health of marine coastal ecosystems in the whole basin. This overview represents a first step to implement a baseline that, through georeferenced data on ecological status, could help identifying information gaps, directing future research priorities, and supporting improvements to spatial models of expected cumulative impacts on marine ecosystems.

Keywords: ecological quality ratio, rocky intertidal, rocky subtidal reefs, seagrass beds, soft bottoms

INTRODUCTION

Despite its relatively small size, the Mediterranean Sea is unique because of the number of habitats, level of endemism, and overall marine biodiversity it hosts. Yet it is among the marine regions most exposed to human pressure globally (Halpern et al., 2008; Lejeusne et al., 2010). In the last three decades, environmental policies attempted to cope with the increasing threats to marine biodiversity, leading to a proliferation of conservation and management initiatives that still do not deliver conservation benefits at a basin scale (Micheli et al., 2013b; Fraschetti et al., 2018). The fragmented geopolitical scenario and transboundary disputes in the Mediterranean Sea can be considered a major impediment for a unified vision of marine strategies (Katsanevakis et al., 2015; Cavallo et al., 2019). However, even when common actions are expected to be facilitated by the shared membership to supranational bodies in much of the basin, such as the European Union (EU), differences among countries in the compliance with the common regulation reduce their effectiveness (Fraschetti et al., 2018).

Aside from legislation concerns, the fulfilment of the European environmental policies can be hampered by the intrinsic difficulty to put them into practice. The implementation of the EU Marine Strategy Framework Directive (MSFD; 2008/56/EC) represented a crucial step toward a coordinated action for assessing and monitoring the achievement of Good Environmental Status for Mediterranean marine ecosystems and, more generally, of all European marine waters. The EU Maritime Spatial Planning Directive (MSPD; 2014/89/EC), which complemented the holistic approach of the MSFD, aims at guiding decision-makers to plan and manage the spatial distribution of human uses, reducing conflicts among users, and allowing socio-economic development while ensuring ecological goals of sustainability and maintenance of healthy and functioning marine ecosystems. As yet, monitoring the status of marine ecosystem components and their key ecosystem functions in the course of MSFD is nevertheless spatially discrete and limited to selected sites, which are not sufficient to exhaustively inform MSPD. This, in turn, ideally requires spatially continuous information on the ecological condition of marine environments for an effective planning (Gissi et al., 2017).

Cumulative effects assessments (CEA), and especially mapping approaches to CEA (Halpern et al., 2008, 2019; Korpinen and Andersen, 2016), provide spatially explicit models of expected cumulative effects that could help marine spatial planning by identifying priority areas for conservation or restoration, and estimating the intensity and distribution of human pressures (Hodgson and Halpern, 2019). An application of CEA at a basin scale in the Mediterranean Sea depicted a dire situation, with 60–99% of coastal areas (within 12 nm from the coastline) facing medium to very high levels of cumulative effects (Micheli et al., 2013a). However, the uncertainty of these projections might be high (Stock and Micheli, 2016; Stock et al., 2018), particularly due to the general lack of sound characterizations of pressure-state response relationships in marine ecosystems, which are rarely based on empirical evidence, with the risk of unreliable representations of spatial distribution of effects (Gissi et al., 2017; Bevilacqua et al., 2018).

A major hindrance to speeding the process of evaluating the ecological status of marine ecosystems and improving estimates of cumulative effects is the difficulty to capitalize on existing data, which are often fragmented in the scientific literature and reports from environmental management agencies, or not easily available (Stelzenmüller et al., 2018; Hodgson et al., 2019). Data on ecological indicators that return a quantification of the ecological conditions of a specific habitat/ecosystem, for instance, may be particularly useful in this respect. The Multivariate AZTI Marine Biotic Index (M-AMBI; Borja et al., 2000; Muxika et al., 2007) or the CARtography of LITtoral Index (CARLIT; Ballesteros et al., 2007), as well as many other indicators, are extensively applied in the Mediterranean Sea. They are often recognized by governmental policies and used at national/regional level by environmental agencies for marine monitoring, thus representing an essential source of quantitative data on the ecological status of different marine communities and ecosystems.

Here, we summarized the results of the application of a set of ecological indicators in the Mediterranean Sea over the last decade. Information was gathered through a review of the scientific literature, official reports from governmental agencies, and available field data, with the aim to provide an overview of the status of main coastal ecosystems based on empirical evidence. Hence, this effort allowed highlighting gaps in information and cues on the current status of Mediterranean marine benthic ecosystems, also providing a baseline to improve the assessment of cumulative impacts.

MATERIALS AND METHODS

We focused our research on four main habitats due to their widespread distribution, ecological importance (Seitz et al., 2014), vulnerability to human threats (Gubbay et al., 2016), and availability of sound ecological indicators of common use to define their ecological status: coastal (up to 100 m depth) soft bottoms [including all MSFD broad scale habitats of category A5 (Infralittoral sand, mud, and coarse sediments; Circalittoral sand, mud, coarse, and mixed sediments)], *Posidonia oceanica* beds (category A5.53), rocky intertidal-upper subtidal fringe (category A1), and shallow (up to 15 m depth) subtidal reefs (included in the category A3) (European Marine Observation Data Network [EMODnet], 2014). These habitats altogether cover the vast majority of coastal bottoms from the intertidal to the circalittoral zone in the Mediterranean Sea (see **Supplementary Appendix S1**). M-AMBI (Muxika et al., 2007) was selected to assess the ecological status of coastal soft bottoms, the *P. oceanica* Rapid Easy Index (PREI; Gobert et al., 2009) for *P. oceanica* beds, the CARLIT index (Ballesteros et al., 2007) for the rocky intertidal fringe, and the Ecosystem Based Quality Index for rocky reefs (reef-EBQI; Thibaut et al., 2017) for subtidal reefs.

M-AMBI combines species richness, the Shannon–Wiener diversity, and the value of AMBI (Borja et al., 2000) of soft bottom invertebrate communities to obtain a "multivariate" quantification of their ecological status. PREI integrates information on shoot density, the maximum depth and the type of meadow lower limit, the epiphytes-leaf biomass ratio, and the leaf surface area. CARLIT relies on the occurrence of the most common macroalgal communities in the rocky intertidal-upper subtidal fringe and their ecological value defined according to the scientific literature and expert judgment (Mangialajo et al., 2007). Finally, reef-EBQI is an ecosystem-based index accounting for density and/or biomass of main functional groups (e.g., detritivores, predators), including benthic assemblages, fish fauna, and seabirds (Thibaut et al., 2017). For all selected indices, we quantified the Ecological Quality Ratio (EQR; a numerical value between 0 and 1 that standardizes in a single scale environmental quality measurement from various indices) as a measure of ecological condition, according to the EU Water Framework Directive (2006/60/EC). The EQR is the ratio between the value of indices in a given site and its value in reference sites (or its maximum value), allowing the classification of sites into five categories reflecting the ecological status of the ecosystem (i.e., bad, poor, moderate, good, high).

The *ISI Web of Knowledge* was queried to collect data on the application of these ecological indicators in the Mediterranean Sea. We searched all the available databases using the acronyms of indicators and "Mediterranean Sea" as keywords in the *Topic* field, limiting our search to the period from 2007 (year of first publication of two of the selected indicators) until 2019. For coastal soft bottoms, the scientific literature was searched also for papers applying the AMBI index since, in many cases, publications reported the index value along with the species richness and the Shannon-Wiener diversity, allowing calculating the value of M-AMBI *a posteriori*. In all cases, publications based on data collected before 2000 were not considered, as well as papers not including actual data on indices (e.g., commentaries, methodological papers) or not focused on coastal marine environments (e.g., internal estuaries), or reporting studies carried out outside the Mediterranean Sea.

The set of data on ecological indicators mined from the scientific literature were integrated with those from assessments carried out by governmental agencies (e.g., the Italian Regional Agencies for Environmental Protection), which used CARLIT, M-AMBI, and PREI indices for their routine monitoring programs of marine environments. Official databases of environmental agencies available online (see **Supplementary Appendixes S2, S3**) were consulted and the most recent reports were used to extract additional data on the selected ecological indicators. Also, published and unpublished data on community structure of the investigated benthic ecosystems owned by the authors were used to calculate values of indices in additional sites in order to increase the spatial extent and coverage of the dataset.

Further details on literature search, calculation of the selected indices, and ranges of values corresponding to the different ecological status are reported in **Supplementary Appendix S2**. For each data point, we collected information on (i) data source, (ii) year of data collection, (iii) geographic positioning (country, location, latitude and longitude), (iv) the EQR, and (v) other relevant details of the case (see **Supplementary Appendix S3**).

RESULTS

The EQR was retrieved or calculated for a total of 709 sites located in coastal areas from 14 different countries (**Supplementary Appendix S3**). The EQR related to 284 sites for coastal soft bottoms, 120 for *P. oceanica* beds, 216 for the intertidal fringe, and 85 for subtidal reefs. Assessments carried out in the last 10 years accounted for 60% of data entries, whereas 23% of assessments were performed during the period from 2006 until 2010, and the remaining data (17%) come from assessments dating back to 2001–2005.

The NW Mediterranean Sea was the most represented area accounting for 29% of sites across the four ecosystems, followed by the Tyrrhenian Sea (26%), and the Adriatic Sea (15%). Representativeness of data for the other sub-basins were lower with, on average, 13% for the SW Mediterranean/Alboran Sea, 12% of sites for the Aegean Sea/Levant and, 5% for the Ionian Sea (**Figure 1**). Assessments on *P. oceanica* beds and intertidal fringe were concentrated in the NW Mediterranean Sea and Tyrrhenian Sea, while a more even distribution of study sites was found for coastal soft bottoms. Sites for subtidal reefs were well distributed in the western and eastern Mediterranean Sea, but very few sites were investigated in the central portions of the basin (**Figure 1**) despite subtidal reefs are present with large extensions in these areas (**Supplementary Appendix S1**). The spatial distribution of sites for the four investigated ecosystems is reported in **Supplementary Appendix S1**.

The status of the four investigated coastal ecosystems is summarized in **Figures 1**, **2**. About 79% of coastal soft bottom sites were characterized by a good or high environmental status, whereas a moderate to poor status was recorded for the remaining cases (**Figure 1**), without substantial change among sub-regions (**Figure 2**). *P. oceanica* beds were characterized by the best condition, with 80% of sites in good to high status. The status of rocky intertidal fringe was good to high in the 69% of sites, with about 28% in moderate to poor conditions, and highly degraded in 3% (**Figure 1**). The worst condition was recorded for subtidal reefs, for which most sites (40%) were in a moderate status, 27% in poor to bad status, and only 33% of sites exhibited good to high ecological status (**Figure 1**). For both rocky habitats, poor conditions characterized particularly the Aegean/Levant region (**Figure 2**).

DISCUSSION

Coastal areas are the most productive and diverse marine environments, providing habitat, nursery, and feeding grounds for marine species (Seitz et al., 2014), and largely contributing to the provision of goods and services from seas and oceans (Barbier et al., 2011). Quantifying their ecological status is therefore essential to understand how cumulative human impact affects the integrity of marine ecosystems, and to help assessing potential consequences on exploited marine resources (Vasconcelos et al., 2014; Lipcius et al., 2019).

We provided a comprehensive synthesis of the ecological status of main coastal ecosystems in the Mediterranean Sea based

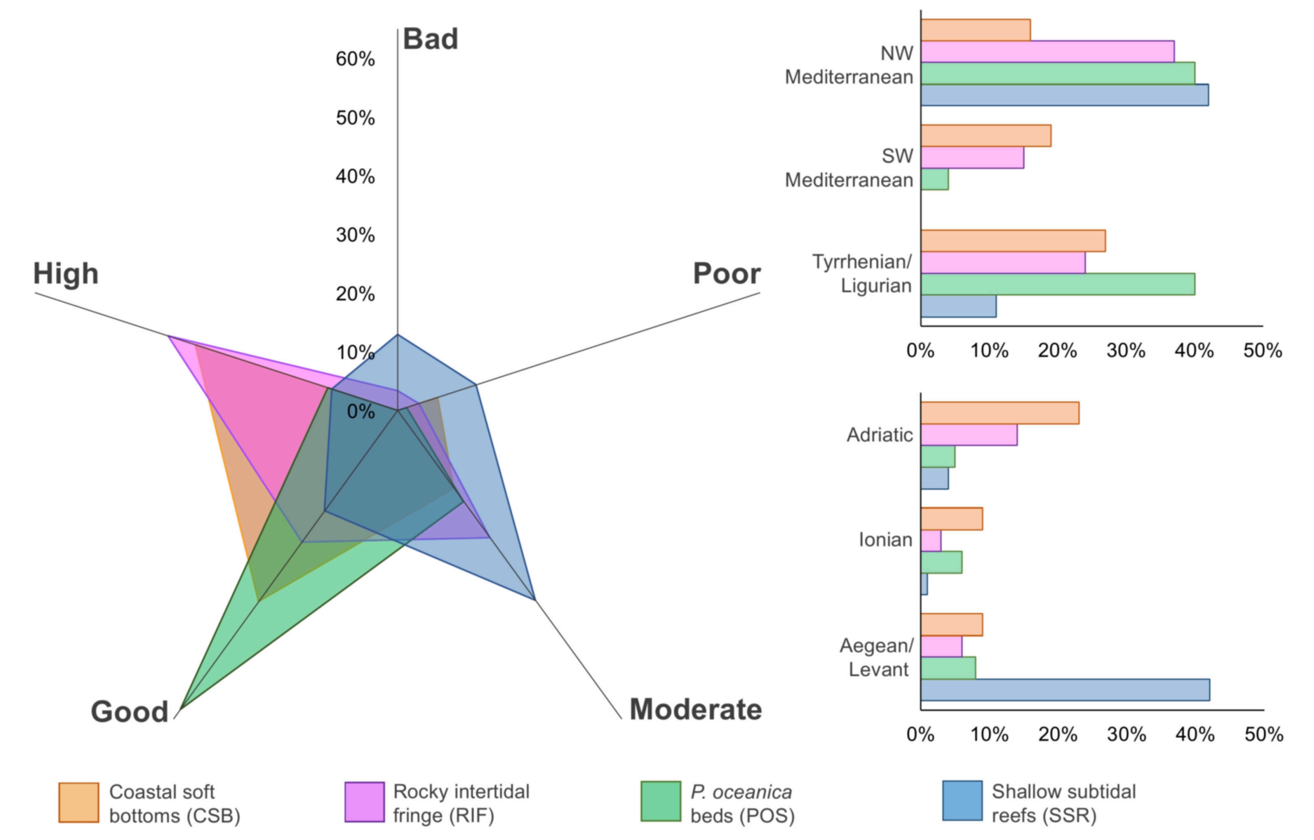

FIGURE 1 | Ecological status of the four investigated ecosystems based on data collection and the literature review (see **Supplementary Appendix S3**). For each ecosystem, the percentage of sites (CSB: *n* = 284, RIF: *n* = 216, POS: *n* = 120, SSR: *n* = 85) classified in bad, poor, moderate, good, and high ecological conditions is indicated in the radar plot (left side of the figure). Classification was based on the Ecological Quality Ratio (EQR) calculated using the M-AMBI index (CSB), CARLIT index (RIF), PREI index (POS), and reef-EBQI (SSR). For each ecosystem, the percentage of sites located in the different geographic areas of the Mediterranean Sea is also reported (right side of the figure).

on evidence from ecological indicators. Three of these indicators, namely, M-AMBI, CARLIT, and reef-EBQI, rely on data from multivariate species complexes or ecological compartments, thus integrating multiple components of ecosystems when quantifying their ecological status. The only exception is the PREI index, which focuses on a set of variables defining the status of *P. oceanica*. In this case, we assumed that the condition of the whole seagrass bed ecosystem is related to the status of its foundation species. The selected indicators are calibrated to take into account variations among geographic areas or different habitat features (e.g., as for soft bottoms), allowing coherent comparisons over large spatial scales. The only one still lacking a comprehensive calibration is the EBQI-reef. However, evidence from the western Mediterranean Sea seems to indicate a general robustness of this indicator to geographic variations (Thibaut et al., 2017). Above all, irrespective of methodological differences among indicators, the ecological status is standardized for all of them when calculating the EQR, allowing stringent comparisons among areas and habitats.

Overall, the ecological status of Mediterranean coastal environments emerging from ecological indicators appeared moderate to high with a relatively minor proportion of sites in bad to poor conditions, at least considering the investigated ecosystems. However, the reduced availability of data for large portions of the Mediterranean Sea limits a generalization to the whole basin (see **Supplementary Appendix S1**). Indeed, with the exception of Tunisia (where the available data are focused almost exclusively on coastal soft bottoms), published data on the selected ecological indicators are virtually lacking for the southern Mediterranean coast, from Egypt, Libya, Algeria, and Morocco, and are really scant in the Levant region (**Supplementary Appendix S1**), recommending a precautionary interpretation of these results.

Our findings are, nevertheless, encouraging taking into account that the examined sites were often located in areas subject to strong human influence. This is particularly true for coastal soft bottoms, which appeared to be in rather good conditions despite the fact that their EQR values generally come from impact assessments, or routine monitoring of sites under surveillance due to risk of contamination or organic enrichment. On the other hand, data on coastal soft bottoms come from sites which are generally very close to the coastline where trawling, one of the most impacting activities on soft bottoms (e.g., de Juan et al., 2007) is virtually absent or limited, compared to offshore

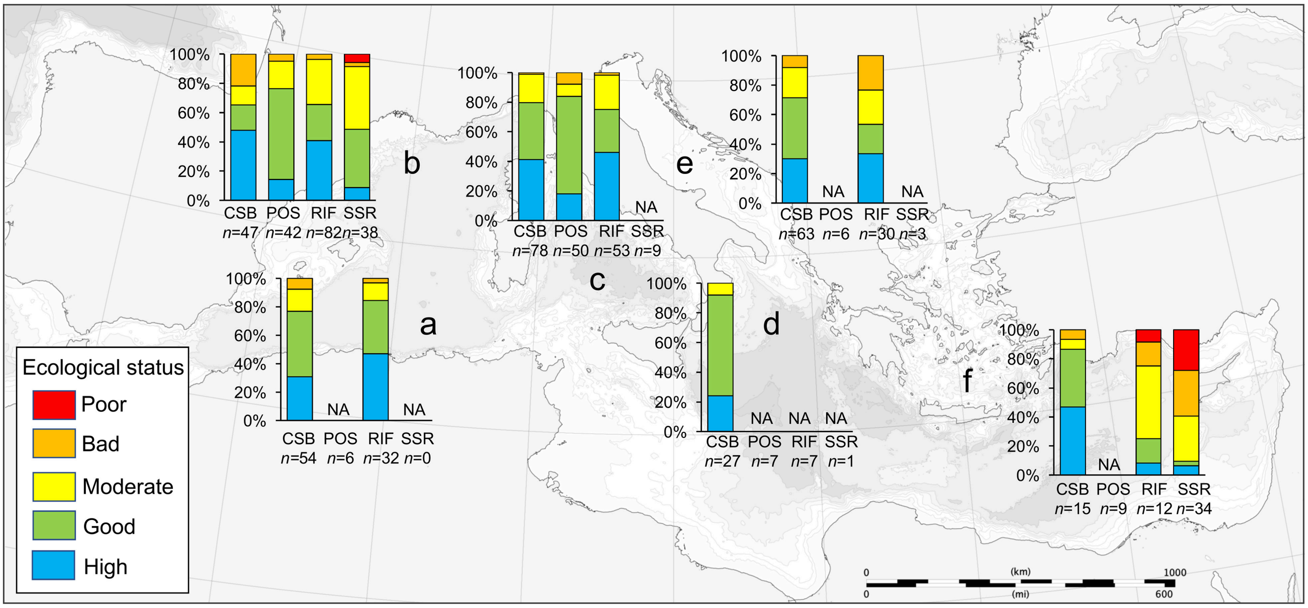

FIGURE 2 | Ecological status of the four investigated ecosystems in sites from **(a)** SW Mediterranean Sea (including the Alboran Sea), **(b)** NW Mediterranean Sea, **(c)** Tyrrhenian/Ligurian Sea, **(d)** Ionian Sea, **(e)** Adriatic Sea, and **(f)** Aegean/Levant Sea. CSB, coastal soft bottoms; POS, *P. oceanica* beds; RIF, rocky intertidal-upper subtidal fringe; SSR, subtidal reefs. NA $\leq$ 10 sites available. Ecological status, from the top to the bottom of bars: poor (red), bad (orange), moderate (yellow), good (green), high (blue).

areas. Moreover, M-AMBI is based only on macroinvertebrate communities, not accounting for other ecological compartments, such as fish fauna, thus providing an incomplete representation of the ecological status of the whole soft bottom ecosystem.

The good to high ecological status of *P. oceanica* beds seems quite counterintuitive given the wide concerns on the decline of seagrass meadows in the Mediterranean Sea (e.g., Telesca et al., 2015). The last assessment of the European Environmental Agency for the conservation status of *P. oceanica* within the sites of the European Conservation Network, recorded some rather different findings. More specifically, over the period 2013–2018, a favorable status was assigned only for sites from Cyprus, Malta, and Slovenia, while an inadequate status was recognized for sites from France, Greece, Italy, and Spain (the status of sites from Croatia is unknown). These contrasting outcomes can be partially explained by the fact that, unlike our assessment, the status of sites of the European Conservation Network is rarely defined on quantitative and local-scale data. Another reason could be that the PREI index, as well as other ecological indicators for *P. oceanica*, although incorporating information on potential regressive signals (e.g., accounting for the type and depth of the lower limit of beds), might not be able to capture their spatial regression over time. Therefore, we may argue that present-day *P. oceanica* beds still persist in relatively good conditions, while their spatial extension is gradually shrinking with respect to the past as a consequence of the increasing degradation of the marine environment related to human activities, including climate change. It is worth noting also that, while the risk of habitat fragmentation and reduction faced by seagrass meadows worldwide is undeniable (Waycott et al., 2009), evidence of change is not univocal in the Mediterranean Sea. There are still areas showing no decline, or even cases where an expansion or recovery of meadows has been detected (de los Santos et al., 2019). Moreover, even when the regression of meadows occurred, its magnitude could be often overestimated depending on scant data quality of past distribution maps used as reference (Bonacorsi et al., 2013).

Our review raised major concerns on the ecological status of rocky substrate communities. This is particularly evident for subtidal reefs, for which two-thirds of sites showed moderate to bad ecological status. The disappearance of structurally complex macroalgal stands (e.g., *Cystoseira* spp.) in favor of barren grounds or turf assemblages, increased herbivory by sea urchins or invasive fish, climate change, and decline of predator fish populations were likely among the major causes of this degradation (Sala et al., 2012; Strain et al., 2014; Mannino et al., 2017; Bevilacqua et al., 2019; Sini et al., 2019). Despite potential biogeographic limitations regarding thresholds between EQR categories, our results suggested that the degradation of shallow subtidal reefs is ongoing at a basin scale, although likely due to different causes depending on the region. The massive simplification of Mediterranean food webs through the depletion of large animal populations, from monk seals to large fish (Sala, 2004), and the extreme reduction of biomass and size of fish predators of sea urchins (Sala et al., 2012) has been associated with the decline of algal forests and associated fauna (Sala et al., 1998). The loss of algal forests also inhibits the recruitment of predatory fish (Cheminée et al., 2013) that could have a role in the structuring of the benthic community. In the Eastern Mediterranean, invasive herbivorous fish from the Red Sea have turned former infralittoral algal communities into barrens (Sala et al., 2011), partly because of the absence of large native predators such as groupers (Sini et al., 2019; Z. Kizilkaya, unpublished data), reducing the ability of native benthic communities to preserve their structure as prior to the invasion (Giakoumi et al., 2019). The fact that >50% of investigated sites for subtidal reefs are within Marine Protected Areas and/or the European Conservation Network (**Supplementary Appendix S3**) seems to indicate that current conservation strategies might not be sufficient to preserve the integrity of these important ecosystems, deserving prioritization in future conservation and restoration initiatives, in monitoring programs within the MSFD, and careful consideration when developing marine spatial plans.

Future research should be devoted to enhance our knowledge on the status of marine ecosystems in the Mediterranean Sea especially through an increased transnational cooperation between EU and non-EU countries, to extend data coverage to poorly studied regions. Data deficiency over large areas is, however, only one aspect limiting information at a basin scale. Differences in habitat classification systems, monitoring methods and threshold levels adopted by different countries hinder the assessment and reporting of ecosystem degradation (Gerovasileiou et al., 2019). In well-studied areas, such as the western Mediterranean, the plethora of indicators used (Teixeira et al., 2016) makes comparisons difficult, impairing the potential to obtain a reliable and extensive picture of the situation of the main benthic ecosystems. There is an urgent need to achieve a general consensus on which data and which indicators have to be used to classify the status of marine ecosystem health (Miloslavich et al., 2018), and further attempts to integrate and gather existing information (e.g., Borja et al., 2019; Hodgson et al., 2019). Current practices are too fragmented depending on decision-makers, researchers, and practitioners' preferences or interests. It is crucial to implement a consistent record of ecological conditions of marine ecosystems, allowing stringent comparisons of their status through time and space, in order to set priorities for management and to attain environmental targets. As climate change is becoming a major stressor on ecosystems, it is also important to consider its impacts in ecological studies including monitoring and management (Rilov et al., 2019a), something that has been poorly considered by most EU countries in their efforts to implement the MSFD and MSPD (Rilov et al., 2019b).

The achievement and maintenance of good ecological conditions requires large-scale management of human activities and their ensuing pressures to marine ecosystems (Borja et al., 2019; Mazaris et al., 2019). CEA approaches, through mapping estimated cumulative impacts, could represent a powerful tool in this view, especially if embedded in a risk management process (Stelzenmüller et al., 2018). Although some refinements have been attempted (Menegon et al., 2018), the substantial lack of quantitative relationships between cumulative levels of pressure and the ensuing effects on ecosystems remains a major limitation of the approach. The potential of ecological indicators to serve as a benchmark for CEA and improve our understanding of spatial distribution of cumulative effects has been largely neglected in past and current attempts to large-scale assessments of the status of marine ecosystems. Integrating consistent and spatially explicit information on EQR with georeferenced data on cumulative pressure from human activities could help modeling pressure-response relationships in marine ecosystems, thus increasing the reliability of CEA predictions and allowing to fully exploit the potential of the approach to inform marine spatial management.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Material**, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

SB and SF conceived the idea and performed the literature review. SK, SF, FM, ES, SB, VG, MS, GR, GS, and AT collected additional field data. SB analyzed data with the support of SF, SK, VG, and MS and led the writing of the manuscript with considerable improvements provided by all authors.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmars.2020.00475/full#supplementary-material

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