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Charles Sheppard

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Preface

This volume and part of the next is slightly different from most others. It contains reviews, as usual, and all the authors were specially invited because they wrote reviews several years ago on issues or in areas that I considered particularly important. The authors were asked to specifically address changes in their subject area that have happened over the time since their last review; in particular, they were asked to comment on why their subject is either specially important or representative of a broader subject area, why there has been very little progress in that area or subject matter, what the failings are in this subject—biological, scientific, or political and policy-wise—and what the prognosis is now, given this lack of progress.

The first review is on a sea that encapsulates many problems humankind faces today—the Mediterranean. This sea does not embrace a huge range of habitats in the manner that an ocean does, but is more homogenous and has been affected by all the usual kinds of human impacts for at least the last several thousand years: overfishing, areas of dense population, and is affected by industrial, sewage, and agricultural pollution. But it is small and discrete enough for a human to comprehend and understand it. There are many types of government in the countries around its shores, from democratic to dictatorial, which itself adds both variety and complications.

The second review is on a habitat that is truly global in the deep sea. Almost every new piece of research shows that its diversity is greater than was previously thought, and although new technology allows it to be visited more, either directly or by remote sampling, problems in accessing this habitat are still severe. This habitat, long protected by its inaccessibility, is becoming increasingly vulnerable as deep sea fisheries improve their technology and industrial mining detects more deposits of valuable materials, notably rare-earth minerals needed for modern circuitry. One component of this are the vast sponge grounds; even recently, I found myself arguing against a part of the oil industry that was using deep sponge reefs as an area for dumping dredge spoil, sponges being viewed as being of little value since they are not primary producers (or, perhaps, not so photogenic to some people).

The third review covers the kinds of research that are being done today. This has become very much more biased in recent decades towards high-tech, cutting-edge, innovative, and leading (call it what you will) methods to the extent that one essential, underpinning element needed for our use and exploitation of the ocean—monitoring—is being neglected. Yet, monitoring, even if it uses older methods that are generally not viewed as being ‘cutting-edge’, is what shows us what the trends are. Trends are far more important than single snapshots for many purposes, and not only trends themselves but the rate of change may be key to the continued functioning of an ecosystem, and many of our marine ecosystems are simply no longer functioning properly. In today’s oceans with increasing changes from climate warming and acidification, this is increasingly important; at the same time, funding for measuring this has reduced. As an aside, this neglect in basic monitoring has been mirrored in two recent editorials in *Advances,* one on the neglect of basic taxonomy and the other advocating more holistic approaches.

In the fourth review which will appear in the next issue, a group of species has been selected which fits several criteria—charismatic, economically important, ecologically important, and overexploited to the point of their collapse—namely, sharks and their conservation. The story of these animals in the eastern Pacific Ocean matches that in most of the rest or the World’s ocean, and lessons can be gained from this.

Finally, in the fifth review ‘The future ocean we want’, we have an integrated account embracing several theories, namely, backcasting, forecasting, and the difficulties of modelling and managing the oceans. It is now quite widely accepted that we cannot manage the oceans—this is mostly hubris—we can scarcely manage a handful of species within it, but what we can manage is our activities upon it. But even with this, it is very difficult if not impossible to manage the activities of a large number of hungry people wishing to exploit it ever more. As Boero ends, ‘It is not difficult to predict that the current mismatch between the stated priorities (i.e. the health of biodiversity and ecosystems) and the actual pursued actions will hinder the attainment of any “strategy” aimed at improving planetary conditions. Meanwhile, all agree to go back to the Moon and to colonize Mars, as if the option of a Planet B were reasonable’.

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CHAPTER ONE

Mediterranean rocky reefs in the Anthropocene: Present status and future concerns

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Contents

Abstract

Global change is striking harder and faster in the Mediterranean Sea than elsewhere, where high levels of human pressure and proneness to climate change interact in modifying the structure and disrupting regulative mechanisms of marine ecosystems. Rocky reefs are particularly exposed to such environmental changes with ongoing trends of degradation being impressive. Due to the variety of habitat types and associated marine biodiversity, rocky reefs are critical for the functioning of marine ecosystems, and their decline could profoundly affect the provision of essential goods and services which human populations in coastal areas rely upon. Here, we provide an up-to-date overview of the status of rocky reefs, trends in human-driven changes undermining their integrity, and current and upcoming management and conservation strategies, attempting a projection on what could be the future of this essential component of Mediterranean marine ecosystems.

1. Introduction

The unprecedented anthropogenic modifications of the global environment are leading the planet towards uncharted conditions, with the risk of crossing safe operating boundaries beyond which undesirable, and probably abrupt, ecological shifts could pose serious concerns about the future of our society (Steffen et al., 2015). The pace of increasing human impact is particularly alarming for seas and oceans (Halpern et al., 2019), especially in coastal areas, where human activities and populations concentrate and the current emphasis for blue economy might, indeed, ultimately harm marine ecosystems (Bennett et al., 2019).

Reef habitats are highly sensitive to global change and have undergone a drastic deterioration worldwide, which still continues without signs of slowing down (Hughes et al., 2010; Krumhansl et al., 2016). They are among the most productive and diverse marine environments, largely contributing to the functioning of much wider ecosystems that comprise vast volumes of marine space (Boero et al., 2019) and are, therefore, crucial for the provision of goods and services by the ocean.

In the Mediterranean Sea, hard bottoms are of paramount ecological importance for coastal ecosystems. More than half of the shores are rocky (Furlani et al., 2014) and biogenic hard substrates may extend for hundreds of thousands hectares in shelf areas (Martin et al., 2014). The variety of coastal rocky habitats is extremely high, spanning from the mediolittoral to the infralittoral and circalittoral zone, and comprising macroalgal and animal forests, rock beds and cliffs, submarine caves, and several types of bioconstructions (Fig. 1) that, along with seagrass beds, host most of the vast and endemism-rich Mediterranean marine biodiversity (Ballesteros, 2006; Coll et al., 2010; Ingrosso et al., 2018). Their complexity and the associated species, phylogenetic, and functional diversity place rocky reefs among the habitats that are often represented within Marine Protected Areas (MPAs) (Agnesi et al., 2020). However, shoreline and nearshore reefs are experiencing a widespread degradation over the entire basin (Bevilacqua et al., 2020; Sala et al., 2012), so that the ecological condition of 1/3–2/3 of them might be classified as moderate to poor (Bevilacqua et al., 2020).

Understanding causes and mechanisms underlying this trend and the ensuing detrimental effects on the integrity of marine ecosystems is critical to develop future strategies that could counteract the ongoing degradation, and to build socioeconomic resilience (Branch et al., 2008; Rilov et al., 2019a). In this chapter, we attempted to synthesize current information on diversity, structure and functioning of Mediterranean rocky reef ecosystems, the main human threats, and the potential implications for their integrity and persistence. We also provided an up-to-date overview of present and forthcoming conservation measures, current research needs and potential future avenues, trying to envisage what could be the fate of Mediterranean rocky reefs in the coming years.

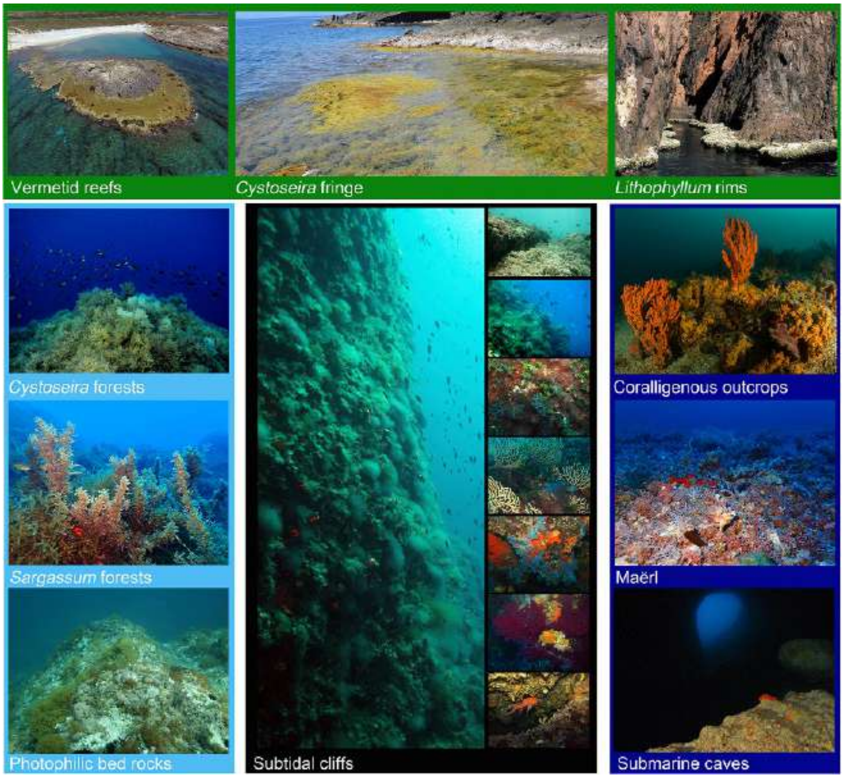

Fig. 1 Examples of Mediterranean rocky habitats. Mediolittoral/upper infralittoral (green contour): vermetid reefs[1] (Levantine, Israel); *Cystoseira* fringe[2] (NW Mediterranean, Italy); *Lithophyllum* rims[3] (NW Mediterranean, France). Infralittoral (light blue contour): *Cystoseira* forests[4] (NW Mediterranean, France); *Sargassum* forests[5] (NW Mediterranean, Spain); photophilic bed rocks[6] (Adriatic Sea, Italy). Circalittoral/sciaphilic (dark blue contour): coralligenous outcrops[7] (Aegean Sea, Greece); Maërl[8] (NW Mediterranean, Spain); submarine caves[9] (Ionian Sea, Italy). Sublittoral cliffs[10] (black contour, Adriatic Sea, Croatia): the sequence of panels showed the gradient in benthic assemblages from 2–3 m until 60 m depth on the rocky wall. *Photo credits: G. Rilov[1], L. Benedetti-Cecchi[2], E. Ballesteros[3,4,5,8], G. Guarnieri[6,9], Th. Dailianis[7], G. Guarnieri and S. Bevilacqua[10].*

2. Mediterranean rocky reef communities: Structure and dynamics

2.1 Patterns and processes in benthic assemblages

2.1.1 Mediolittoral and infralittoral zone

The Mediterranean Sea should be classified somewhere between a subtropical (mostly the southeast basin) and a temperate sea (mostly the western basin). The seasonal variability in temperature, light availability and dissolved nutrient concentrations are similar to temperate environments but the average values are closer to subtropical seas. These features hinder the development of kelps and hermatypic corals (Zabala and Ballesteros, 1989), which, although present in the Mediterranean (i.e., *Laminaria rodriguezii*, *Cladocora caespitosa*), have a limited occurrence. Instead, rocky reefs where light intensity allows supporting photosynthetic growth are characterized by a large diversity of erect, turf, and encrusting algae (Rodríguez-Prieto et al., 2013).

In a sea where tidal ranges are extremely small (except for the Alboran Sea and the northern Adriatic), the wide intertidal assemblages characterizing most oceanic rocky shores are almost absent with several mediolittoral assemblages alternating at different levels of the shore, usually arranged in very narrow belts. The upper mediolittoral is dominated by barnacles and littorinids, whereas the lower levels show belts of different species of erect and encrusting algae (Chappuis et al., 2014). In strongly exposed sites of the northern Mediterranean, the massive coralline alga *Lithophyllum byssoides* can produce hard calcareous concretions called 'trottoirs' (Fig. 1) which form rims over the sea level. The lower part of the mediolittoral fringe is occupied erect and turf red algae, but mussels (*Mytilus galloprovincialis*) and green algae (*Cladophora* spp., *Ulva* spp.) thrive in nutrient-rich environments (Rodríguez-Prieto et al., 2013). In the warmest regions, gregarious vermetid gastropods form dense aggregations cemented by the encrusting coralline alga *Neogoniolithon brassica-florida*, favouring the development of conspicuous platforms on subhorizontal surfaces, hosting diverse macrobenthic assemblages (Fig. 1) (Rilov et al., 2020a).

The horizontal to almost vertical rocky bottoms in the infralittoral zone are dominated by macroalgae, although extensive meadows of seagrass *Posidonia oceanica* can also be found on shallow horizontal hard substrates (Rodríguez-Prieto et al., 2013). At the upper infralittoral level, belts of Fucales (*Ericaria*, *Gongolaria*, *Cystoseira*, *Sargassum*) develop both in exposed and sheltered areas (Fig. 1). The eastern Mediterranean also hosts concretions of the coralline algae *Tenarea tortuosa* and *Titanoderma trochanter* in the shallows. In areas below 2 m depth, photophilic assemblages composed mostly by Sphacelariales, Dictyotales, Gigartinales or Bryopsidales are extremely common, although the best preserved sites are usually occupied by stands of Fucales (Rodríguez-Prieto et al., 2013). In the Alboran Sea and the Strait of Messina, *Saccorhiza polyschides* (Tylopteridales) makes impressive underwater beds (Giaccone, 1972).

An interesting feature of Mediterranean macroalgal stands is their high biodiversity associated with a high miniaturization (Coppejans, 1980); more than 100 different algal species can coexist in a small surface not larger than a sheet of paper (600 cm^2). This means that the so-called Mediterranean marine forests dominated by Fucales are miniaturized representatives of the huge oceanic temperate forests of Laminariales, with canopies not exceeding 20–40 cm but with a similar structural complexity. The complex three-dimensional structure of such canopies allows very speciose animal assemblages to develop in the understory or as epiphytes, whose diversity and distribution is strongly influenced by spatio-temporal variations of macroalgal stands (Fraschetti et al., 2006; Piazzi et al., 2018).

Most Mediterranean shallow macroalgal assemblages show a marked seasonality. In the mediolittoral zone, midwinter is the period of maximum growth, with the maximum development showing up from early spring to midsummer (Ballesteros, 1991). In autumn and early winter, Mediterranean vegetation is usually in a resting phase, although invasive species such as *Lophocladia lallemandii*, *Womersleyella setacea* or *Caulerpa cylindracea* can attain high growth rates and biomass in autumn. Measured average yearly production reaches 900 $g\,C\,m^{-2}\,year^{-1}$ in the upper part of the infralittoral fringe from exposed environments with dense populations of Fucales, whereas figures around 100–300 $g\,C\,m^{-2}\,year^{-1}$ are common in infralittoral communities with canopy-forming algae (Ballesteros, 1989).

Aside from anthropogenic drivers (see Section 3), the spatial distribution of macroalgae and associated invertebrate assemblages reflects a combination of different bottom-up and top-down processes (Hereu et al., 2008). The distribution of different species of Fucales along the depth gradient mainly depends on each species' photosynthetic efficiency (Sant and Ballesteros, 2021), whereas the interplay among changes in vegetation, life cycles, feeding habits and competitive abilities shape species composition and abundances of invertebrate assemblages (e.g., Terlizzi et al., 2003). Biomineralogy plays an important role in community assembly, influencing settlement and recruitment processes of different species associated with rocky reefs, from algae to fishes, depending on rocky lithology (Guidetti et al., 2004). Other factors, such as regimes of exposure to air and nutrient availability are pivotal for mediolittoral and upper infralittoral assemblages respectively. Catastrophic events such as huge storms or thermal anomalies also regularly shape shallow assemblages (e.g., Navarro et al., 2011; Verdura et al., 2021). Among top-down processes, overgrazing by sea urchins such as *Paracentrotus lividus* and *Arbacia lixula* (but also by herbivorous fishes, see Section 2.2), can strongly reduce algal biomass, availability and export of algal detritus, and simplify the associated community structure (Sala et al., 1998, 2012; Yeruham et al., 2020).

2.1.2 Circalittoral zone

Although extremely limited geographically, most impressive algal beds in the circalittoral zone are those with kelp *Laminaria ochroleuca* from the Alboran Sea and the Strait of Messina (Giaccone, 1972). Much more widespread are other canopy-forming algal assemblages dominated by Fucales, Dictyotales, Sphacelariales, Ceramiales or Gigartinales (Rodríguez-Prieto et al., 2013). Worth mentioning are the assemblages dominated by the endemic kelp *Laminaria rodriguezii* in western Mediterranean and the Adriatic Sea, which can be found down to almost 100 m depth (Žuljević et al., 2016). Erect members of the order Bryopsidales and Peyssonneliales are usually dominant in the upper circalittoral zone but a huge number of red algae are also common and characteristic of these environments (UNEP-RAC/SPA, 2003).

The most widespread Mediterranean deep-water macroalgal assemblages are coralligenous outcrops, biogenic reefs built by calcareous algae of the genus *Lithophyllum*, *Mesophyllum*, *Neogoniolithon*, *Lithothamnion* and *Peyssonnelia* (Ballesteros, 2006). Above the basal layer made by calcareous algae, a rich flora and fauna develop, ranking the coralligenous bioconstructions among the most biodiverse assemblages in the Mediterranean Sea, with a rough estimate of species richness being far above 1500 species (Ballesteros, 2006). These bioconstructions, which are made by living benthic organisms that overgrow the calcareous remnants of previous generations, change the primary geological substrate creating a secondary biogenic hard substrate, representing a preferred habitat for the settlement, spawning, recruitment, feeding and shelter of a wide variety of marine species. The habitat provision through bioconstruction can be mediated by either vegetal (e.g., coralline algae, coralligenous *sensu stricto*) (Ingrosso et al., 2018) and/or animal organisms such as corals, sponges, bryozoans, molluscs and polychaetes among others (Cardone et al., 2020; Corriero et al., 2019). The general pattern of coralligenous allows to recognize four main levels of organization due to (i) cryptic/boring, (ii) encrusting, (iii) massive, and (iv) arborescent organisms (Fig. 2A).

In coralligenous bioconstruction (Fig. 2Bv), the three-dimensional complexity created by both boring and erect organisms influences the biodiversity of vagile benthic fauna with gastropods, polychaetes, crustaceans, echinoderms, and fishes representing the most common vagile organisms inhabiting bioconcretions (Ballesteros, 2006; Valisano et al., 2016). When the primary geological substrate is granitic, volcanic or not calcareous, the contribution of bioeroders is reduced; epilithic coralline algae and calcified

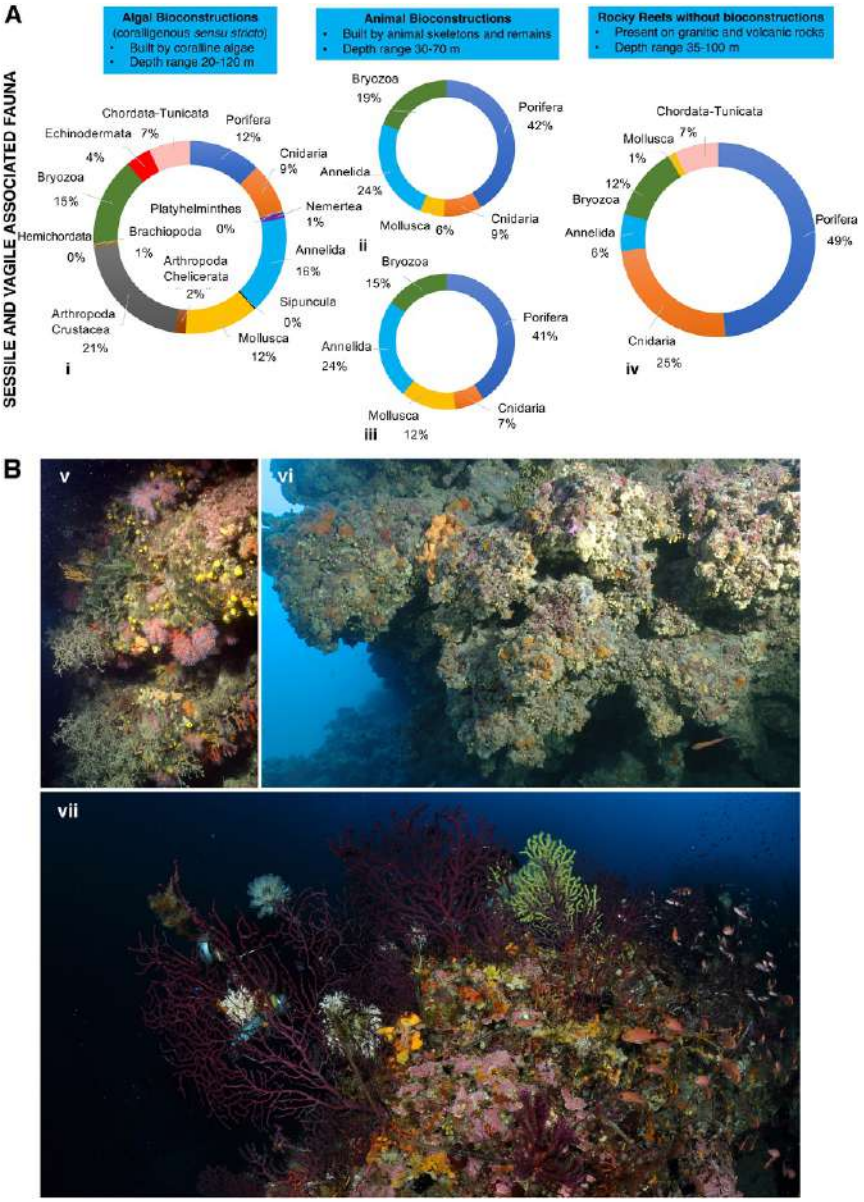

Fig. 2 (A) Percentage abundance of sessile and vagile taxa associated with bioconstructions dominated by macroalgae (i), invertebrates (ii, iii) and rocky reefs without bioconstruction (iv). Data extracted from: (i) Ballesteros (2006); (ii) Cardone et al. (2020); (iii) Corriero et al. (2019); (iv) Canessa et al. (2020). (B) Coralligenous *sensu stricto* (v); animal bioconstruction dominated by *Neopycnodonte cochlear* (vi), granitic rocky reef (vii). *Photo credits: C. Cerrano (v), G. Corriero (vi), B. Borrelli (vii).*

animals show lower capability to build thick concretions on granite compared to limestone (Canessa et al., 2020). In this case, the bioconstruction can be very limited (Fig. 2Bvii) and the general structure of the community is less complex, confirming the pivotal role of biomineralogy in structuring benthic assemblages (Bavestrello et al., 2000). Recently, a new type of bioconstruction has been described along the Italian coast of Apulia (Cardone et al., 2020). Main builders of this bioconstruction are scleractinians and the bivalve *Neopycnodonte cochlear*, which make mass aggregations on the sea bottom on both soft and hard substrates, supporting the development of a rich benthic associated fauna (Fig. 2Bvi).

Light availability drives the dynamics of circalittoral assemblages, mediating the depth distribution of the algal components (Sant and Ballesteros, 2021). Seasonality is also important in determining temporal variations of macroalgae in the circalittoral zone, with the period of maximum growth ranging between late spring and early summer (Ballesteros, 1991) and average yearly production ranging from 30 to 150 $\mathrm{g\,C\,m^{-2}\,year^{-1}}$ in upper circalittoral coralligenous environments (Ballesteros, 1989; UNEP-RAC/SPA, 2003). Competition for food and space is the main process affecting species distribution and abundance, the species being forced to develop a highly specialized diet and niche to coexist in the same habitat (Morganti et al., 2017). However, cooperation among species is common, with some species facilitating the settlement of others (Gribben et al., 2019). In the absence of human impacts, the development of slow-growing and long-living species, especially sponges and anthozoans, is favoured (Montero-Serra et al., 2018) and mediate long-term stability conditions (Cerrano et al., 2010, 2019). Stability and longevity enhance intra and inter-specific interactions facilitating coevolutionary pathways, which, in turn, further contribute to the persistence of the ecosystem itself (Pola et al., 2020).

2.2 The role of fish

Out of the approximately 650 fish species inhabiting the Mediterranean Sea, rocky reefs host about 200 species belonging to 40 families, covering a wide range of trophic levels (Bussotti et al., 2015; Guidetti et al., 2014; Sala et al., 2012). Species richness has been suggested to be driven by biogeographic patterns with the highest values recorded between 10° and 20°E longitude (Guidetti et al., 2014), and be positively correlated with depth (Harmelin-Vivien et al., 2005). The highly diversified fish assemblages of

Mediterranean rocky reefs support a large variety of ecological traits and functions (Albouy et al., 2015).

Rocky reef fish act as trophic vectors connecting different Mediterranean habitats. This is the case of small-sized and gregarious fish like the widespread damselfish *Chromis chromis* and the cardinal fish *Apogon imberbis*, whose nycthemeral migrations between the water column and the bottom and in/out of marine caves, transfer organic matter—mostly via faecal pellets—into depleted rocky reef habitats (Bussotti et al., 2018; Pinnegar and Polunin, 2006).

High-level predator fishes exert top-down controls triggering trophic cascades directly and indirectly affecting a large number of species, finally shaping the structure and functioning of the entire coastal rocky ecosystems (Prato et al., 2013). These large-sized and long living animals, such as sharks and groupers, nowadays are generally depleted in the Mediterranean Sea due to overfishing. The reduction in populations of high-level predators has determined the disruption of the ecological functions that these species perform especially in shallow rocky habitats. Here, the decreased functional redundancy at high trophic levels has left medium-sized fish like seabreams alone to control ecosystem structure by regulating the grazing pressure exerted by sea urchins on erect macroalgae, increasing the chance of drastic shifts in coastal ecosystems (see Section 3.3).

Contrary to what has been thought until a decade ago, even the very few macro-herbivorous fish species present in the Mediterranean Sea heavily contribute to regulating the functioning of shallow rocky ecosystems (Vergés et al., 2009). Both the native salema *Sarpa salpa*, widely distributed in the western Mediterranean, and the invasive rabbitfishes *Siganus luridus* and *S. rivulatus*, that entered via the Suez Canal between 1927 and 1956 and more recently replacing the native salema in the eastern Mediterranean, may represent a threat to macroalgal canopies and indirectly to the high diversity they support (Gianni et al., 2017; Rilov et al., 2018; Vergés et al., 2014).

In this regard, a more general reshuffling of the Mediterranean reef fish assemblages has occurred in the last few decades. This was mainly attributed to changes in the relative abundances of native species as a result of geographical range contractions and deepening of cool-water fishes, rapid range extensions of alien warm-water and tropical fishes, and changing interspecific interactions (Azzurro et al., 2019; Milazzo et al., 2013). Model projections suggest a dramatic reduction of Mediterranean endemic fish by the end of this century (Ben Rais Lasram et al., 2010).

2.3 The contribution of rocky reefs to coastal ecosystem functioning and services

Mediterranean rocky reefs, from the shore to shelf areas, are highly dynamic, in both time and space, and productive systems. They receive abiotic and biotic inputs from both the open sea and the mainland, through water mass movements that locally may have seasonal fluctuations and that are able to connect adjacent ecosystems. Ecological connectivity can be very high at a regional scale (Bevilacqua and Terlizzi, 2020; Rattray et al., 2016) being the outcome of community assembly processes, which are mainly driven by the local species pools (Briton et al., 2018). However, spatial patterns of compositional and functional diversity in Mediterranean rocky reefs can overlap or diverge due to the complex interplay among functional redundancy of species, environmental filtering and biogeography (Bevilacqua and Terlizzi, 2020). Due to their high habitat heterogeneity and diversity, which offer a variety of niches available from the upper mediolittoral to the deeper circalittoral habitats, the biological components of the Mediterranean rocky reefs express a lot of different ecological functions (de la Torriente et al., 2020).

The large variety of rocky reef species and the associated functional traits are responsible for a range of benefits to humans in terms of ecosystem services, which are at the base of the human wellbeing of most Mediterranean coastal countries. For example, despite the mediolittoral being limited to a few tens of centimetres, assemblages in this zone play a fundamental role in the overall functioning of coastal ecosystems. Trottoirs formed by vermetid platforms, distributed across the warmest coastlines of the basin, provide several ecosystem services associated with production functions (e.g., the provision of food and baits), to regulation functions by influencing water column quality (e.g., filtering) and enhancing anthropogenic disturbance prevention, to support functions, through the provision of food and organisms to adjacent systems, and to cultural functions, by offering space for recreation/leisure, exploration and relaxation (Milanese et al., 2011). In the lower mediolittoral fringe, and where trophic conditions are more enriched, mussel beds are mainly built by *Mytilus galloprovincialis* and represent a crucial element of the rocky shore biodiversity. Their local loss or reduction in density generates changes in the associated assemblages (Maggi et al., 2009) with a net loss of services such as water quality regulation, habitat and refugia, and enhancement of habitat heterogeneity.

At the other depth extreme, in the circalittoral zone, coralligenous habitats are so structured and biodiverse that are able to provide a number of ecosystem services (UNEP-RAC/SPA, 2003), from provisioning (e.g., food, red coral and species for aquariums), regulating (e.g., carbon sequestration and water filtration), cultural (e.g., recreational diving and intellectual/spiritual inspiration) to supporting (e.g., species nursery and refugia) services (de Ville d'Avray et al., 2019).

In the middle of these two depth extremes, in the infralittoral zone, vegetated rocky substrates certainly provide the most important contribution to the functioning of coastal ecosystems. They are primary sources and sinks of blue carbon, participate in nutrient cycling, provide essential support for marine coastal biota by providing food, nursery and shelter (Mineur et al., 2015; Zunino et al., 2020), and foster the diversity of important ecological compartments, such as microbiota and meiofauna (Bianchelli and Danovaro, 2020).

Recent attempts to quantify energy flows in Mediterranean algal forests and coralligenous outcrops revealed a prominent input of these habitats to the energetic budget of coastal ecosystems (Buonocore et al., 2020; De la Fuente et al., 2019a). Nonetheless, an accurate and synthetic evaluation of ecosystem services provided by rocky reefs across the Mediterranean Sea is still not addressed, although it would be of paramount importance for decision-makers and environmental practitioners in order to set appropriate conservation and management measures.

3. Human threats to Mediterranean reefs: Status and trends

Rocky reef assemblages have shown critical changes due to anthropogenic activities in most of the Mediterranean Sea (Claudet and Fraschetti, 2010; Rilov et al., 2018). The prevalent and widely reported modification concerns the structure of macroalgal stands, shifting from canopies to less complex communities dominated by turf or encrusting algae (e.g., Rilov et al., 2018; Thibaut et al., 2015). The ensuing reduction in primary production and habitat complexity largely turned into profound changes of the animal component of rocky reef assemblages (Peleg et al., 2020). Several benthic invertebrates and fish species of Mediterranean rocky reefs have also been threatened by a long history of intense exploitation. In some cases, such as for collection of commercial sponges and red coral, highly damaging fishing tools have been adopted in the last centuries (Cattaneo-Vietti et al., 2016), deeply altering the structure of benthic assemblages of many rocky reefs. However, one major driver of change cannot be unequivocally identified and most studies infer several interacting anthropogenic stressors in determining the ongoing alterations of reefs (Bevilacqua et al., 2018; Rilov et al., 2018), including pollution (Iveša et al., 2016), urbanization (Mangialajo et al., 2008), destructive fishing (Rodríguez-Prieto et al., 2013), increase in sedimentation rates (Airoldi, 2003), overfishing (Sala et al., 1998; Sini et al., 2019), biological invasions and disease outbreaks (Rilov et al., 2018; Sala et al., 2011; Vezzulli et al., 2013).

In the last 20 years, the increase in intensity and frequency of thermal anomalies and extreme marine weather events is causing destructive disturbance episodes and mass mortalities, leading to very marked alterations of density and size of the epibenthic structuring species (Garrabou et al., 2019; Sarà et al., 2014; Teixidó et al., 2013), or mining their reproductive potential, and therefore, their persistence (Bevilacqua et al., 2019). Acidification may also deeply influence benthic assemblages, affecting the structural component represented by coralline algae and hard shelled invertebrates (Martin and Gattuso, 2009; Rastelli et al., 2020), thus altering the balance between bioconstruction and bioerosion processes of rocky reefs (Cerrano et al., 2001). Climate change, therefore, will exacerbate human impacts (Gissi et al., 2021; Verdura et al., 2021), with additive effects on the degradation of reef assemblages (e.g., Peleg et al., 2020; Rilov et al., 2018), further eroding their resilience potential.

3.1 Pollution

A closed basin like the Mediterranean Sea, which receives multiple inputs from the mainland, from maritime transportation and aquaculture, and has little turnover, is particularly exposed to pollution. Urban and industrial wastewater, agricultural activities, livestock farms and solid waste treatment are the main land-based sources of pollution, through rivers, direct discharge in coastal areas, or run-off waters (Danovaro, 2003). On shallow rocky reefs, the emblematic outcome of organic and inorganic pollution from waste discharges is the proliferation of tolerant, opportunistic species, over sensitive, habitat-structuring species (e.g., Terlizzi et al., 2005), which in turn results in biodiversity loss of the understorey and associated fish assemblages (Azzurro et al., 2010). Under over-enrichment of nutrients in coastal waters, eutrophication often leads to an excessive production of algal biomass, whose decomposition causes transitory response to alterations of physical factors (e.g., deoxygenation) and destabilizes the natural fluctuations of benthic assemblages which could promote shifts towards simplified rocky reef communities (Ivešа et al., 2016; Pinedo et al., 2015; Worm and Lotze, 2006). *Cystoseira s.l.* species and other habitat formers, like vermetids, for instance, can be particularly affected by surface pollutants such as hydrocarbons, surfactant detergents, and pesticides (Badreddine et al., 2019; de Caralt et al., 2020), suggesting that pollution could have contributed to their decline in the basin.

In recent years, although contamination levels in coastal areas have decreased, concerns on emerging pollutants have been raised, especially on plastic litter (UNEP/MAP, 2017). Marine litter has been found in the Mediterranean Sea in similar quantities to those observed in the five oceanic garbage patches (Fossi et al., 2020), and the presence of microplastic (i.e., fragment size 1 μm–5 mm) has been widely documented throughout the basin (Martellini et al., 2018). The average concentration of microplastic in the water column in the Mediterranean Sea is 2.3 kg km^{-2}, ranging between 6.5 and 1.5 kg km^{-2} (Soto-Navarro et al., 2020). Since many invertebrates on rocky reefs are suspension-filter feeders, the increasing amount of microplastics is particularly alarming due to their potential bioaccumulation and biomagnification through the trophic web.

Several studies have suggested that microplastics can carry toxic chemicals, as well as microscopic organisms, that animals inadvertently swallow (e.g., van Der Hal et al., 2019). The transport of microplastics in the environment is accompanied by the immigration of contaminants (e.g., polychlorinated biphenyls, brominated flame retardants, polycyclic aromatic hydrocarbons, bisphenol A) via sorption/desorption, known as the 'Trojan-Horse effect' (Zhang and Xu, 2020). This phenomenon significantly changes the potential health risks of microplastics by enhancing the bioavailability of contaminants for living organisms (Li et al., 2016). Also, many organisms, such as benthic diatoms and microalgae, adhere to the fragments and can be involuntarily swallowed causing also dietary alterations or the introduction of potentially pathogenic or toxic species (Cole et al., 2011). Microplastics are only one aspect of the problem, since plastic fragments smaller than microplastics, the so-called nanoplastics (i.e., fragment size 1–1000 nm), are likely to represent a more subtle hazard for marine organisms, since they can have a higher ability to adsorb and carry toxic compounds if compared to microplastics (Piccardo et al., 2020; Rios Mendoza et al., 2018).

Other emerging environmental pollutants for the marine environment are pharmaceutical residues, which have been detected in different marine organisms, from algae to bivalves, crustaceans and fish (Almeida et al., 2020; Fabbri and Franzellitti, 2016). These substances may interfere with subcellular and cellular processes of marine organisms, threatening the survival of the marine microbiota, with consequences that can potentially propagate to the highest levels of the trophic web, posing a health risk also for humans (Fabbri and Franzellitti, 2016).

The long-term effects that old and new pollutants could have on the marine environment are not yet fully understood, especially in light of potential synergies with other drivers of global change, increasing the uncertainty on future scenarios. Global warming and the ocean acidification can have direct consequences on the balance of ecosystems, acting on the basis of microbial components (Coelho et al., 2013), and causing a greater dispersion and availability of pollutants, intensifying their effects on the marine biota. Considering the current state, and that measures such as the local protection of species and areas are not fully effective to mitigate (Soto-Navarro et al., 2021) or reverse the trends of pollution, the implementation of containment/prevention measures for all kinds of pollutants, mainly through regulatory instruments and by vast plans of decontamination, are urgently required.

3.2 Direct physical habitat disruption and artificialisation

In past decades, the European date mussel (*Lithophaga lithophaga*) fishery has been the main anthropogenic source of direct physical damage on shallow rocky reefs (e.g., Bevilacqua et al., 2006; Fanelli et al., 1994). This destructive fishing practice, which requires breaking rocky surfaces and removing the whole benthic assemblage to collect the endolithic bivalves, has led to the destruction of large extensions of rocky reefs in the whole basin, from Morocco to Israel (Colletti et al., 2020). Though banned since the end of 1980s in most Mediterranean countries, the date mussel fishery still continues illegally in several regions (Colletti et al., 2020; Katsanevakis et al., 2011) and the current extent of damaged areas remains largely unknown. Other activities associated with human presence, such as trampling, anchoring, and diving can cause direct damage to shallow benthic communities inhabiting rocky reefs (Guarnieri et al., 2012; Milazzo et al., 2004), although these impacts are often limited and locally concentrated in crowded sites.

For hard substrates at greater depths, and especially for coralligenous outcrops and maërl, bottom trawling is primarily responsible for habitat degradation and loss. Trawling may have either a direct physical impact caused by otter boards and nets that destroy the three-dimensional structure of arborescent invertebrate colonies or an indirect impact due to sediment resuspension and deposition on benthic habitats (D'Onghia et al., 2017; Savini et al., 2014). Altered sedimentary regime due to bottom trawling for crustaceans (e.g., Aristeidae shrimps, Norway lobster) is one of the main threats for fragile cold-water corals (Lastras et al., 2016). In the Mediterranean Sea, fishing efforts by trawling are intensifying especially at shallow depths (Ferrà et al., 2018), suggesting a future increase in the extent and magnitude of deterioration and loss of rocky habitats in the circalittoral zone.

Coastal habitats in the Mediterranean Sea are experiencing profound modifications also due to the continuous expansion of coastal anthropization since the 1950s (Airoldi and Beck, 2007; Bugnot et al., 2020). From 1990 until 2000, the surface of coastal artificial structures within 1 km from the shoreline increased on average by ~3%, whereas coastal armouring extended over ~8% of coasts (EEA, 2006). Recent estimates projected an increase in urbanized areas below 20 m of elevation ranging between 67% and 104% in many Mediterranean countries (Wolff et al., 2020). Coastal development may involve the introduction of artificial substrates but also massive land reclamation, which causes the irreversible destruction/loss of original habitats. Recent data concerning the Monaco Principality (see http://www.medam.org), for instance, show that >90% of the coastline and >90% of shallow marine habitats (between 0 and 10 m depth, including rocky reefs) have been destroyed/artificialized, with extensive land reclamation allowing the small country to gain more and more 'emerged surfaces' to build upon. These massive interventions of coastal engineering may appear irrelevant at the Mediterranean scale, but they deeply and irreversibly impact local marine biodiversity with the potential risk of scaling-up effects at regional or even larger scale with future expansion of these practices.

Besides the direct effects, indirect effects on rocky reef communities due to the introduction of artificial substrates, coastal urbanization, coastline modifications and ensuing alterations of sedimentary regimes are even more harmful (Airoldi et al., 2015; Bulleri, 2005). The presence of breakwaters, sea walls, jetties, and other man-made structures in coastal environments, as well as offshore oil and gas platforms could affect species populations and communities from native hard substrates by modifying natural patterns of ecological connectivity, either enhancing or dampening dispersal and trophic connections (Bishop et al., 2017). Assemblages on artificial structures are generally less diverse and complex than those on natural hard substrates, which make them more prone to be colonized by non-indigenous species (NIS) and to act as stepping stones disproportionately favouring the spread of alien species over native rocky reef species (Airoldi et al., 2015). Moreover, coastal engineering often relates to sediment resuspension and dislodgement as a direct consequence of interventions (e.g., dredging) or indirectly by modifying hydrodynamic coastal regimes, causing pulse or chronic increases in water turbidity and sedimentation. Burial, abrasion, and limitation of photosynthetic activity due to increased sediment suspension and deposition may drastically curb settlement, recruitment and survival abilities of sessile organisms, causing dramatic changes in rocky reef communities, which typically exhibit a shift from complex and highly diverse algal canopies towards homogenized assemblages dominated by a few sediment-tolerant turf-forming algae and suspension feeders (Airoldi, 2003; Ballesteros, 2006; Claudet and Fraschetti, 2010).

Eco-engineering could be of help in mitigating potential impact of man-made marine structures and, in some cases, restoration actions could effectively sustain the recovery of damaged habitats. Reversing this trend should necessarily imply a radical rethinking of the use of marine space, especially in urban and periurban coastal areas (Airoldi et al., 2021), along with a consistent reduction of direct physical impacts.

3.3 Overfishing

Mediterranean rocky reefs along with their food webs are well known to be diverse, complex and, to some extent, fragile. Modern and traditional ecological knowledge can be paired with the long tradition of natural history studies in the Mediterranean to better understand temporal trajectories of changes attributable to human activities. Mediterranean rocky reefs, from this perspective, have been exploited by humans for millennia (Sala, 2004), with many species of vertebrates (e.g., fishes) and invertebrates (e.g., sea urchins, molluscs, crustaceans) that have been fished/harvested since ancient times for food and decorative uses.

Fishing, both professional and recreational, is widely considered one of the major causes of community-wide alterations of Mediterranean rocky reefs (Font and Lloret, 2014; Sini et al., 2019). Fishing methods can be multi-specific (e.g., fixed nets) or target one or few species (e.g., spearfishing), but the overall result is often the alteration of trophic relationships through the depletion of ecologically important species, and mostly high-level predators.

An emblematic example of the impact of fishing on large fish predators concerns the dusky grouper *Epinephelus marginatus*, a commercially important species and one of the largest predators on Mediterranean rocky reefs. Targeted by commercial and recreational fishing, its abundance and size dramatically decreased in recent decades. Large groupers were fished since prehistory and then in Greek and Roman times in very shallow stands, while nowadays abundant and large groupers can be observed just in fully protected zones of well enforced MPAs or deeper than 25–30 m in areas open to fishing (Giakoumi et al., 2017; Guidetti and Micheli, 2011). However, the paradigm of fishing impact producing community-wide consequences in the Mediterranean rocky reefs relates to sparid fishes, which thrive in these habitats and are targeted by professional and recreational fishers (Guidetti and Sala, 2007). Some sparids of high commercial value belonging to the genus *Diplodus* (especially the seabreams *Diplodus sargus* and *D. vulgaris*) actively feed on sea urchins. These seabreams have the potential of shaping the structure of entire communities associated with subtidal rocky reefs (Guidetti, 2006; Sala et al., 1998) as they might control the abundance of sea urchins and, indirectly, of erect macroalgae. Overfishing these seabreams may trigger a trophic cascade: in some areas, when seabream abundance and size are reduced, sea urchin populations are released from predation and then dramatically increase, erect macroalgal forests disappear due to overgrazing and are replaced by the so-called barren grounds (Fig. 3). This transition implies a dramatic loss of biodiversity (of fish, invertebrate and algal species) and consequently of important ecosystem functions and services (e.g., reduced carbon sequestration, decreased vegetal biomass and detritus available for consumers, reduced three-dimensional habitat available for juvenile/adult fishes and invertebrates; Cheminée et al., 2013; Guidetti, 2006; Prato et al., 2013; Sala et al., 1998). Such species- to community-wide consequences of overfishing in subtidal rocky reefs can be effectively reversed with the creation of well enforced MPAs, especially if large enough to include species' home range (Di Franco et al., 2018; Guidetti et al., 2014).

Overfishing is not limited to infralittoral rocky reefs, but there is clear evidence of the impact of unregulated harvesting on mediolittoral limpets. In particular, the giant Mediterranean limpet *Patella ferruginea*, an endemic species harvested by man since prehistory (Fa, 2008), is the most endangered marine macroinvertebrate in the Mediterranean Sea. Presently, its distribution is restricted to only a few sites along the western Mediterranean rocky shores where, although officially protected (Annex IV of the Habitats Directive and Annex II of the Berne and Barcelona Conventions), limpet populations are declining at an alarming rate due to poaching in MPAs (Coppa et al., 2016). Circalittoral rocky communities in some areas of the Mediterranean have been since long impacted by the red coral *Corallium rubrum* harvesting, performed using the destructive trawling gear called St. Andrew Cross, nowadays banned and replaced by the employment of

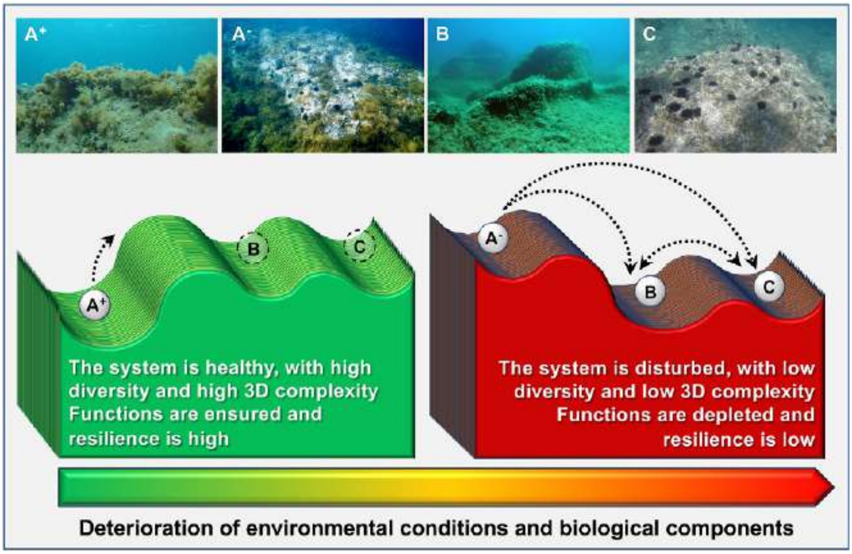

Fig. 3 Conceptual representation of regime shifts from Mediterranean algal forests towards barren grounds and turf-dominated assemblages. In good environmental conditions (green landscape), the system is dominated by habitat-forming macroalgae (e.g., *Cystoseira s.l.*) (A^+). Resilience is high, and pulse disturbances, if occurring, are unable to trigger a critical transition, with perturbations of the state (dotted black lines) being rapidly absorbed. As human-driven deterioration of environmental conditions increase and cause chronic disturbance (red landscape), the system approximates to a tipping point. Diversity decreases, the trophic network starts to disrupt and the recovery potential slows down, increasing system fragility (A^-). In such a situation, pulse disturbance events (e.g., organic enrichment, herbivore outbreaks) could drive the system to shift towards algal turfs (B) or barren grounds (C). Depending on changing conditions, the system could exhibit a 'flickering' behaviour between alternative stable states B and C. However, the return to the original state (A^+) is difficult to happen if not over a long period, unless a substantial improvement of environmental conditions occurs and active restoration interventions are carried out to help the system to recover.

specialized divers and ROVs (Cattaneo-Vietti et al., 2016). Clear and widespread impacts from lost debris/gears ascribable to both professional and recreational deep-water fishing activities on rocky substrates are reported to affect deep-water habitats and sessile organisms (Bo et al., 2014).

Finally, a quite often neglected point is the virtual elimination of large species (i.e., monk seal, loggerhead turtle, sharks). These ecologically extinct megafauna were crucially important in terms of trophic interactions, and their removal certainly had strong ecological consequences on rocky reef ecosystems in the Mediterranean Sea (Sala, 2004; Zogaris and De Maddalena, 2014).

3.4 Bioinvasions

Non-indigenous species (NIS) are introduced by human activities, accidentally or intentionally and through multiple vectors (Mack et al., 2000). In the last decades, the number of NIS in the Mediterranean Sea has continuously increased and the most recent studies have documented the presence of >1000 marine NIS, more than half of which are established and widespread, with almost 120 species being definitively invasive (Zenetos and Galanidi, 2020). Most NIS entered the Mediterranean Sea through the Suez Canal (namely Lessepsian species; Rilov and Galil, 2009; Katsanevakis et al., 2014; Galil et al., 2015). Other important pathways of marine NIS introduction in the Mediterranean include maritime transport (ballast waters, or hull fouling), aquaculture, and the aquarium trade (Zenetos et al., 2012).

Not all NIS, however, exert negative ecological effects as those caused by invasive species. In fact, only a fraction of NIS, thanks to combinations of favourable abiotic and biotic factors in the recipient ecosystem, become invasive alien species (IAS), and may severely affect its functioning (Butchart et al., 2010). IAS are, indeed, among the most pernicious outcomes of global change (Geraldi et al., 2020), so that their spread has been suggested as being a case of 'biopollution' (Occhipinti-Ambrogi, 2021).

In the Mediterranean Sea, examples include outbreaks of the the fish *Pterois miles* (Dimitriadis et al., 2020) and *Siganus rivulatus* (Renanel et al., 2018). In some cases, also native species may be considered invasive, when, due to contingent conditions, they proliferate well above the carrying capacity of their system. Examples of the latter include outbreaks of the dinoflagellate *Noctiluca scintillans* (Hallegraeff et al., 2021), the medusa *Rhizostoma pulmo* (Basso et al., 2019) and the fish *Pomatomus saltatrix* (Villegas-Hernández et al., 2015).

Some invaders have large direct structural or consumptive impacts on the local communities, and sometimes both. One of the best examples is the invasion of the two Indopacific herbivorous rabbitfish in the previous century, that, by overgrazing, have depleted lush macroalgal stands in the eastern Mediterranean (Sala et al., 2011; Vergés et al., 2014). This overgrazing most probably also contributed (in combination with sea warming) to the collapse of sea urchin populations on the southeastern Levant reefs through competition for food that reduced population viability (Yeruham et al., 2015). The recent rapid invasion of the lionfish (*P. miles*) (Dimitriadis et al., 2020), a voracious predator that has already caused extensive ecological impacts in the Caribbean Sea (Albins, 2015), is also expected to cause extensive ecological impacts on reefs in the region.

IAS can also exert indirect, and often elusive, effects on biological and behavioural traits of native species. A good example of an invader with such a potential is the green alga *Caulerpa cylindracea*, native to southwestern Australia, reported for the first time in the Mediterranean Sea along the coasts of Tunisia in 1990 and then rapidly spreading in the whole basin (e.g., Piazzi et al., 2016; Rizzo et al., 2017). The basin-scale outbreak of this alga is likely due to its capacity to thrive in either hard or soft substrates at depths ranging from 0 to >70 m (Klein and Verlaque, 2008) and to easily invade ecosystems already degraded by other anthropogenic stressors (Ceccherelli et al., 2014; Piazzi et al., 2016).

At the same time, *C. cylindracea* is among the most paradigmatic examples of chemical pollution mediated by molecules produced by the living biota. Caulerpenyne, caulerpine and caulerpicin, are the most abundant and investigated secondary metabolites of *C. cylindracea*, and all possess biological properties such as allelochemical, neurotoxic and cytotoxic activities (Raniello et al., 2007), which, by interfering native species, may contribute to the invasion potential of the alga. Despite the toxicity of these metabolites, *C. cylindracea* has become an important food item in the diet of the common Mediterranean seabream *Diplodus sargus*, whereas recent evidence indicates the presence of the alga in stomach contents of both other native Mediterranean fishes (i.e., the sparids *Spondyliosoma cantharus*, *Sarpa salpa*, *Diplodus vulgaris*, and the scarid, *Sparisoma cretense*) and the siganid Lessepsian migrant, *Siganus luridus* (Felline et al., 2017).

Such a 'new' diet has been related to the appearance of cellular and physiological alterations in fish, which include enhanced oxidative stress, the onset of genotoxic damage and the possible appearance of neurotoxic damage and anomalous behaviour that can lead to higher mortality rates (Felline et al., 2012). Fish consuming *C. cylindracea* show important changes in the gonadosomatic index (GSI) and a significant induction of the vitellogenin gene expression, altogether indicating the alteration of gross gonad morphology and possible adverse implications on the fish reproductive performance (Gorbi et al., 2014). Also, the ingestion of *C. cylindracea* causes a sort of behavioural relaxation in fish, which could hamper, especially in juveniles, their ability to escape predators.

The tropicalisation of the Mediterranean by the interaction of rapid warming and the invasion of thermophilic species, and especially macroalgae (Israel and Einav, 2017), is already leading to the complete restructuring of the reef communities in the southeast Levantine basin (Rilov et al., 2019a), which evidently also transforms reef ecosystem functions (Peleg et al., 2020).

Concern is also raising because either NIS and IAS could also favour the introduction and spread of new pathogens, potentially harmful to native species and, through cascading effects, on the entire ecosystem.

In contrast to the terrestrial realm, in marine ecosystems, where most of NIS have larval (and sometimes adult) dispersion stages that are practically impossible to counteract, and/or possess peculiar biological traits (like the ability to produce new propagules even from fragments; Bulleri et al., 2018a; Gribben et al., 2018), eradication is impossible, unless at a very early stage of introduction. Nevertheless, for some invasive species, control of their populations can be achieved through dedicated management measures, including commercial exploitation, which could mitigate the negative effects of IAS on native communities and ecosystems (Giakoumi et al., 2019; Rotter et al., 2020).

3.5 Climate change

Anthropogenic climate change is a major driver of global biodiversity change (Poloczanska et al., 2013), and projections of many ecosystems seem grim under business-as-usual or milder emission scenarios (Gattuso et al., 2015). Multiple climate-related pressures are emerging in ocean systems including warming, acidification, deoxygenation, increased storminess, sea level rise and changes in circulation. Consequently, many marine ecosystems are rapidly restructuring (or even collapsing, Burrows et al., 2019; Garrabou et al., 2021) under the effects of climate change, which often interact with non-climatic stressors (Gissi et al., 2021).

The Mediterranean Sea is considered a hotspot for climate change (Cramer et al., 2018). Satellite sea surface observations indicate that the Mediterranean has warmed by 1.48 °C on average for the entire basin over the 1982–2018 period (Pisano et al., 2020), with a rate 3–6 times faster than the warming rate of oceans globally (Cramer et al., 2018). The increase of mean temperature has been related to the increase of the frequency and intensity of extreme temperature conditions, i.e., marine heat waves (MHW; Darmaraki et al., 2019). However, the warming trend is uneven across Mediterranean marine ecoregions, showing higher warming in eastern ecoregions than in the Western ones (Salat et al., 2019; Skliris et al., 2012).

The increase in temperature particularly affects water masses from surface down to 80 m depth causing major impacts to the reef assemblages through two main processes: the shift in abundance and distribution of indigenous species and NIS and the occurrence of unprecedented mass mortality events (MMEs). Current warming is driving the decline in abundance of cold-water affinity species (Azzurro et al., 2019) in favour of warm-water affinity species. These changes are affecting different taxa, including keystone herbivores like sea urchins (Yeruham et al., 2015), and are rapidly reshaping the composition of reefs across the entire basin. Two main movement patterns can be recognized: (i) native warm-affinity species are moving northward, while the range of geographic distribution of cold-affinity species is progressively shrinking, and (ii) warm-adapted NIS that entered through the Suez Canal are moving westwards and northwards replacing and competing with native species. MMEs have been associated with intense MHWs, which have affected a wide range of rocky reefs from the infralittoral and circalittoral zones by causing severe impacts (with mortality rates up to 80%–90%) on at least 100 macrobenthic species (macroinvertebrates, macroalgal and seagrasses), encompassing 9 phyla (Garrabou et al., 2019). The most severe ones occurred in 1999 and 2003 when more than 30 macrobenthic species along thousands of kilometres of coastlines were affected (Garrabou et al., 2009). Besides these events, several other large scale MMEs as well minor episodes which are usually more restricted in geographic extent and/or number of affected species have been reported (Garrabou et al., 2019). Most evidence comes from the coldest areas of the Mediterranean (e.g., the northern Adriatic Sea), especially in shallow coralligenous reefs where gorgonians and sponges suffered extensive impacts (Garrabou et al., 2019).

Evidence of impacts related to other climate-related alterations, such as acidification, sea-level rise and deoxygenation, are currently lacking in the scientific literature. Ocean acidification is occurring in the Mediterranean Sea (Kapsenberg et al., 2017), but it does not seem to be at levels that may cause changes to rocky reefs and associated communities yet. However, *in situ* surveys and experiments along natural CO_2 gradients as well as laboratory experiments have shown that acidification may strongly affect reef communities by 2100 (Linares et al., 2015; Milazzo et al., 2014). Furthermore, sea level rise is expected to affect mediolittoral reefs through the reduction of the associated biodiversity and the alteration of metabolic rates of marine organisms (Rilov et al., 2021).

Climate change is already severely transforming Mediterranean reefs across all ecoregions. There is mounting evidence of multiple collapse of cold-affinity, habitat-forming and keystone reef species, which will be exacerbated by future reduction in pH of sea water and sea-level rise (Azzurro et al., 2019; Sala et al., 2011; Sarà et al., 2014). The interaction of these processes will likely promote the shift of Mediterranean reef communities from temperate-Atlantic affinity towards Indopacific affinity through both regional extinctions of native species and the establishment of NIS (see also Section 3.4), first in the Levantine basin and in the future, further westward and northward, with profound changes in the functioning of reef ecosystems.

3.6 Cumulative human pressures

The Mediterranean Sea ecosystems are under high and escalating pressure from multiple uses and stressors (Coll et al., 2012; Lejeusne et al., 2010; Micheli et al., 2013), which have led to major shifts in marine ecosystems and widespread conflict among marine users (Abdulla et al., 2008; Airoldi and Beck, 2007; Claudet and Fraschetti, 2010; Ferretti et al., 2008). Because of such intense pressure, the Mediterranean is characterized as a sea 'under siege' (Coll et al., 2012).

The combination of multiple pressures from fishing, pollution, warming, acidification, direct habitat alteration and biological invasion makes the Mediterranean Sea one of the most impacted marine ecoregion globally (Halpern et al., 2008; Micheli et al., 2013). A recent global analysis showed that cumulative impacts to marine ecosystems are increasing in 60% of the ocean, including the Mediterranean Sea (Halpern et al., 2019). In the Mediterranean, the Levantine Sea, the Sicily Channel, parts of the Ionian, Alboran Sea and the western Mediterranean, particularly along the coastline of Morocco and Algeria, have undergone significant increase in cumulative impacts over a period of only a decade (2003–2013), and no region has seen a decline in cumulative impact over this time period (Fig. 4A).

Mediterranean rocky habitats are subject to multiple pressures (Fig. 4B,C). Summarizing the evidence reported in the previous paragraphs, they are affected by overfishing, which reduces biomass and diversity, alters food web structure and interactions—in some cases triggering trophic cascades and shifts to low-diversity 'barren' states (Micheli et al., 2005; Sala et al., 1998)—or directly impacts populations and alters habitat through removal of habitat forming species (e.g., red coral) and destructive practices, such as the seafloor and benthic assemblage removal associated with illegal date mussel harvesting (Guidetti, 2011). Increased sediment and nutrient loadings lead to benthic community shifts and eutrophication of the water column (Airoldi, 2003). Biological invasions, including by macroalgae and herbivorous rabbit fishes (*Siganus* spp.) have also resulted in invasive monocultures (e.g., of *Caulerpa* spp.) or desertification (Cebrian and Rodríguez-Prieto, 2012; Sala et al., 2011). Major, escalating threats to Mediterranean rocky reefs are temperature warming and MHWs, which

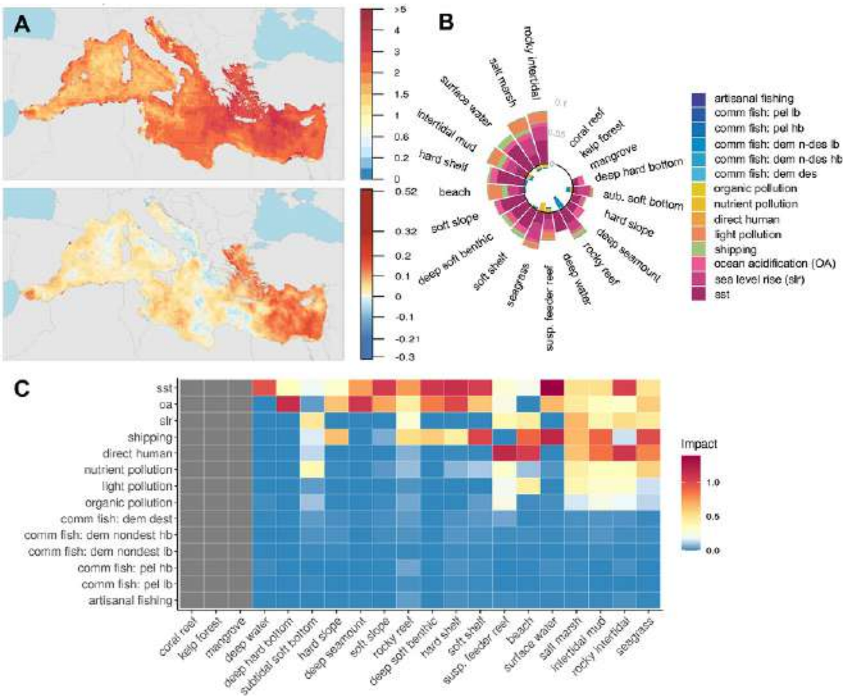

Fig. 4 (A) Cumulative human impacts (up to 2013, top panel), and annual change in cumulative human impacts (bottom panel) estimated using a linear regression model from 2003 to 2013 for each raster cell (white cells did not have a statistically significant trend, i.e., $P > 0.05$), scale values reflect min and max raster values (-0.3 and 0.52) and 99.999th quantile values (-0.21 and 0.32). (B) Annual change in all 14 impacts comprising the cumulative impacts for each Mediterranean marine ecosystem, with outer bars above zero indicating increasing impacts and inner bars below zero indicate decreasing impacts. (C) Cumulative impacts on ecosystems for the most recent year for which data are available (2013, bottom panel). Data from Halpern et al. (2019). Note that here 'rocky reef' refers to infralittoral and circalittoral reefs, 'rocky intertidal' to mediolittoral rocky reefs, and 'susp. feeder reef' to mediolittoral bioconstructions (e.g., vermetid reefs). comm fish, commercial fishing; pel, pelagic; dem, demersal; des, destructive; n-des, non-destructive; lb, low bycatch; hb, high bycatch.

are causing species range shifts, reef tropicalization, and mass mortalities (Garrabou et al., 2009).

Climate drivers are the main contributors to increased cumulative impact to rocky reefs, but overfishing and pollution are also key drivers of increased impact (Fig. 4B,C). Compared with other habitats, rocky reefs are impacted by the largest suite of different stressors, even though the magnitude of impact for some is lower than for several other ecosystem types (Fig. 4C).

Expanding and strengthening rocky reef protection through the establishment and improved management of marine protected areas, and promoting climate resilience by reducing cumulative impact are key priorities for reversing these escalating trends of reef degradation.

4. Conservation achievements and next targets

4.1 Current conservation measures

Rocky reef ecosystems are in peril at basin scale, with increasing evidence of ongoing regime shifts across habitats (Benedetti-Cecchi et al., 2019; Claudet and Fraschetti, 2010). Measuring progress to the European 2020 Biodiversity Strategy, Gubbay et al. (2016) documented that a critical proportion of rocky reef ecosystems are either vulnerable or endangered. They included macroalgal-dominated communities and circalittoral rocks, mussel and oyster beds and biogenic concretions such as those of the red algae *Lithophyllum byssoides*, platforms formed by the algae *Neogoniolithon brassica-florida* and the gastropod *Dendropoma* spp. in the European Red List of Habitats. However, the report highlighted that insufficient quantitative data often prevent determining the status of most marine ecosystems, suggesting that the list might be even longer than currently assumed to be.

There is a strong need for prioritizing conservation initiatives for these productive, diverse and vulnerable environments. Addressing the status of Mediterranean infralittoral rocky reefs, Bevilacqua et al. (2020) reported that two-thirds of sites included in their study were classified to be in moderate to poor conditions. While it should be recognized that >50% of investigated sites for infralittoral reefs were within MPAs and/or the European Conservation Network (i.e., Natura 2000 sites), care should be given in not overestimating the potential benefits of those conservation strategies to preserve the integrity of rocky reef ecosystems (Fig. 5).

Applying the recently developed Regulation-Based Classification System for MPAs (Horta e Costa et al., 2016), Claudet et al. (2020) showed that while the 1062 MPAs in the Mediterranean Sea cover 6% of the Mediterranean Basin, 95% of the total protected area lacks regulations to reduce human impacts on biodiversity. Unevenly distributed across political boundaries and eco-regions, effective levels of protection for biodiversity conservation represent only 0.23% of the Mediterranean Basin (Zupan et al., 2018). In the French Mediterranean, while infralittoral rock and other hard substrata are the habitats most covered by full or high protection, only 2.6% of these habitats receive such levels of protection (Claudet et al., 2021).

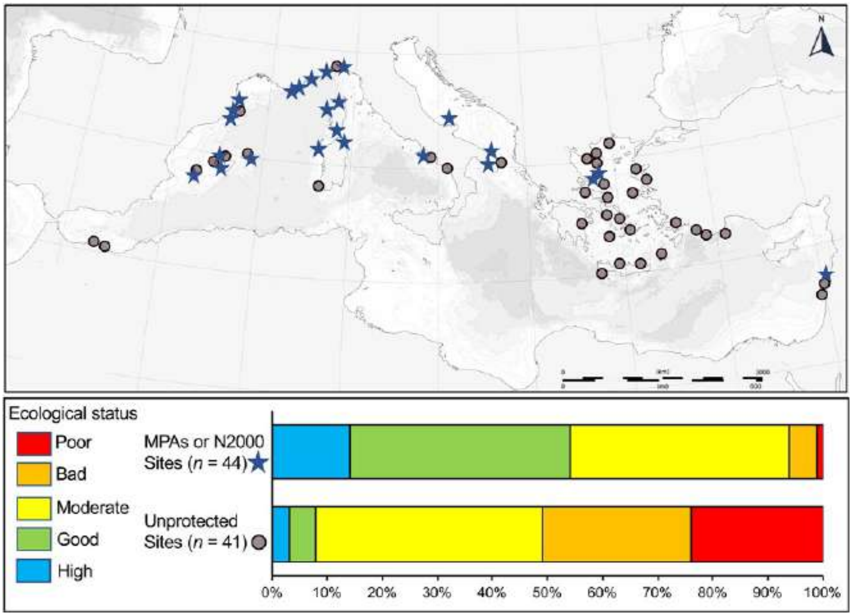

Fig. 5 Ecological status of infralittoral rocky reefs in several sites across the Mediterranean Sea ($n=85$). Ecological status is based on the Ecosystem Based Quality Index for rocky reefs (reef-EBQI; Thibaut et al., 2017). The percentage of sites falling in different categories of reef-EBQI are reported separately for protected/regulated (MPAs and/or regulated Natura 2000 sites) and unprotected sites (including unregulated Natura 2000 sites). Data from Bevilacqua et al. (2020).

It is clearly evident that current efforts are insufficient at managing human uses of nature at sea and protection levels should be increased to deliver tangible benefits for biodiversity conservation in general and for these habitats in particular. There are few exceptions. A systematic review along the Italian coasts about the occurrence and conservation status of *Cystoseira s.l.* concluded that while only a negligible proportion of their populations was protected (3%) before 2000, the proportion of 'protected' populations has increased in recent years to 77.8%, with nearly two-thirds of the populations included in MPAs (Tamburello et al., in press). MPAs might guarantee protection to *Cystoseira s.l.*, with recent evidences showing higher coverage inside MPAs compared to unprotected areas (Di Franco et al., 2021), by limiting coastal urbanization and overfishing, including illegal and destructive practices (Colletti et al., 2020), and avoiding overgrazing allowing the recovery of high-level predators, controlling herbivores populations, or directly limiting the discard of dismissed fishing gears.

Despite the European Union having progressed in implementing an massive legal framework for marine resources protection and management, there are still important gaps (Fraschetti et al., 2018) and intertidal and subtidal rocky reef ecosystems suffer from the lack of specific conservation interventions. Currently, there are no specific conservation actions for macroalgal habitats and the action plans on Protecting Coralligenous and other calcareous BioConcretions in the Mediterranean developed by Mediterranean institutions are not legally binding. The consequence is that, for most of the Mediterranean Sea, the status of the category Reef (1170) of the Habitat Directive is insufficient in terms of both 'structure and functioning' and 'future prospects'.

4.2 Future conservation needs

The failure of past conservation measures to achieve large-scale outcomes for Mediterranean reefs stresses the urgent need for holistic, integrated, effective and more ambitious conservation strategies to improve their status (Fig. 6). Shifting from the existing paper-park-dominated networks of MPAs (Claudet et al., 2020) to well-connected networks with extended no-take

Fig. 6 Improvements of management policies and conservation strategies are needed to decelerate or even reverse the declining trend on the ecological status of Mediterranean rocky reef ecosystems.

areas and well-managed multi-use MPAs that can effectively contribute to the recovery of reef ecosystems is crucial (Bevilacqua et al., 2006; Sala et al., 2012; Thibaut et al., 2017). The ambitious new European Biodiversity Strategy for 2030 and its targets for 30% protection—10% strict protection—offer an unprecedented opportunity to achieve large scale conservation of rocky reefs, substantially upgrading the current low level of the Mediterranean being effectively protected. Towards these targets, it is critical to apply a systematic conservation planning process (Katsanevakis et al., 2020), through which the full compositional and functional variability and diversity of rocky reef ecosystems is adequately represented (Bevilacqua and Terlizzi, 2020).

More than that, reduction of stressors also outside MPAs is critical. Better fisheries management and a strong overall reduction of fishing effort also in non-protected areas are needed to improve the status of rocky reef ecosystems at a large scale. A reduced fishing pressure has been related to substantially increased fish abundance and biomass in non-protected areas, including that of predators (Sini et al., 2019), which in many cases can be essential for the recovery of reef ecosystems via cascading effects (Hereu, 2006; Sala et al., 1998). Better integration of conservation strategies and the ecosystem approach of fisheries management in the EU Common Fisheries Policy and the regional fisheries management by the General Fisheries Commission for the Mediterranean will be beneficial for both reef conservation and the related Mediterranean fisheries, which are currently largely unsustainable (Colloca et al., 2017).

The need to include biological invasions and climate change considerations in conservation strategies has been highlighted as a necessity but also a grand challenge (Katsanevakis et al., 2020; Micheli et al., 2012). Despite the effectiveness of protection measures within MPAs, invasive species and climate change can substantially compromise any efforts to conserve or restore reef ecosystems (Dimitriadis et al., 2021; Rilov et al., 2018), often enhancing the impacts of overfishing, pollution and other stressors (Gissi et al., 2021). Although there are important progresses in incorporating climate change in conservation strategies (Johnson and Kenchington, 2019; Katsanevakis et al., 2020), developing frameworks to incorporate biological invasions in conservation planning (Mačić et al., 2018), and prioritizing management measures for invasive species (Giakoumi et al., 2019), current guidelines and practices for expanding the network of MPAs in the Mediterranean totally ignore the issues. Future conservation strategies (Fig. 6) need to be adaptive to account for change, identify and consider climate refugia for reef conservation and restoration, set different targets for climate change hotspots focusing on securing reef ecosystem functioning, account for both negative and positive impacts of alien species and adopt appropriate mitigation measures, and promote the identification of climate-driven eco-evolutionary changes and climate-resistant algal populations to be used for reef restoration (Katsanevakis et al., 2020; Rilov et al., 2019b, 2020b).

4.3 Frontiers in the restoration of rocky habitats

The exacerbated speeds of global and local changes from multiple stressors are decreasing the resilience of rocky habitats globally (Airoldi et al., 2009), hampering their ability to recover naturally following passive management efforts (O'Leary et al., 2017). With the pace of current loss and degradation there is a need for more active intervention-based approaches that can integrate social, economic and environmental objectives (Abelson et al., 2016). Marine habitat restoration is an emerging field to actively reverse the degradation and loss of natural ecosystems (Abelson et al., 2020) recognized by the UN Decade on Ecosystem Restoration (2021 – 2030). Here, we use restoration in its broadest possible meaning (Airoldi et al., 2021), encompassing multiple approaches to both actively repair the damaged marine life as well as to 'green' the currently grey hard infrastructure. Examples include active interventions to restore canopy forming seaweeds in both their natural habitats (De La Fuente et al., 2019b) as well as in artificial habitats used as 'gardens' where their natural habitat is under threat (Perkol-Finkel et al., 2012).

Marine restoration practice and governance are still in their infancy both in terms of research as well as political, legal and economic support (Abelson et al., 2020; Bayraktarov et al., 2016). The challenge of safeguarding ecosystem services is especially prominent for the Mediterranean Sea, where knowledge of marine ecosystems status and dynamics is still fragmented (Airoldi and Beck, 2007; Gianni et al., 2013). Yet, significant research is emerging, aiming at identifying both the feasibility and self-sustainability of restoration efforts as well as adequate techniques and spatial layouts (Claudet and Fraschetti, 2010). Concerning rocky habitats, most of these research efforts have focused on the recovery of macroalgal stands (Guarnieri et al., 2020; Orlando-Bonaca et al., 2021; Savonitto et al., 2021; Verdura et al., 2018). Recent efforts have also focused on the restoration of populations of invertebrate species, such as the scleractinian coral *Astroides calycularis* (Musco et al., 2017), the bryozoan *Pentapora fascialis* (Pagès-Escolà et al., 2020), and the limpet *Patella ferruginea* (Ferranti et al., 2021), with many novel technologies and approaches emerging, such as or the use of electro-mineral accretion for enhancing the settlement of the red coral *Corallium rubrum* (Benedetti et al., 2011). Increasing research has also focused on the bioenhancement of artificial habitats by increasing surface topographic complexity, or by using more environmentally friendly construction materials, with some successful examples but also uncertainties about the consistency of the benefits (Strain et al., 2021).

There is real interest and critical opportunities to support marine restoration actions in the Mediterranean sea for the benefit of people and nature. Large-scale, long-lasting test projects are needed to nurture the most innovative ideas, overcome the barriers to scaling and address some technical challenges. This restoration, however, will rarely, if ever, result in a return to a historical state, forcing us to actively consider what we think those ecosystems should consist of.

5. Next challenges and perspectives in ecological research

Understanding how rocky reef communities persist in the face of intensifying climate change and escalating cumulative anthropogenic disturbances is a research priority to preserve the structure and functioning of these systems and to promote informed conservation policies. Persistence is generally understood in terms of components of stability, such as resistance and resilience to perturbations and adaptation (Donohue et al., 2016; Hillebrand et al., 2018). Despite increasing research efforts to elucidate the effects of natural and anthropogenic disturbances on rocky reef communities, a clear understanding of the mechanisms underpinning stability and adaptation has remained elusive.

Regime shifts in macroalgal forests are a case in point. Several studies have documented the collapse of these systems in response to pollution, urban development and degrading environmental quality more generally (Benedetti-Cecchi et al., 2001; Strain et al., 2014; Wernberg et al., 2011). Experiments and models have shown how these responses may involve nonlinearities and thresholds, implying abrupt transitions (regime shifts) towards alternative states, often characterized by algal turfs or barren habitats (Benedetti-Cecchi et al., 2015; Rindi et al., 2017) (see Fig. 3). The occurrence of nonlinear dynamics implies the existence of reinforcing (feedback) mechanisms that stabilize the system in one state or the other (Scheffer, 2009). For example, successful recruitment is more likely to occur nearby dense stands of canopy species with limited dispersal capabilities (e.g., Capdevila et al., 2018). Hence, an expanding patch of algal canopy can reinforce itself because it will produce larger and larger numbers of propagules as it grows. Similarly, an expanding patch of canopy algae can become increasingly resistant to dislodgement owing to the coalescence of an increasing number of holdfasts, as observed in some canopy-forming algae (Gonzáles et al., 2015). Reinforcing mechanisms should also be at work to stabilize the alternative states. In principle, established mats of algal turfs may persist by inhibiting the recruitment of canopy algae (Benedetti-Cecchi and Cinelli, 1992) and by reducing desiccation stress through water retention in intertidal habitats. Both mechanisms are expected to strengthen as algal turfs grow and develop into thick mats.

These runway mechanisms have been invoked to explain the nonlinear dynamics observed in *Ericaria amentacea* (Benedetti-Cecchi et al., 2015; Rindi et al., 2017). However, the limited dispersal of zygotes in this species has been inferred mostly from laboratory studies and the extent to which coalescence of holdfasts increases stability remains unquantified (Clayton, 1992). Similarly, the stabilizing mechanisms proposed for algal turfs have been rarely tested. All these reinforcing feedbacks involve density-dependent processes as a common underlying cause. Density-dependent processes are pervasive in ecological communities and similar feedbacks may occur generally across species and habitats (Aubier, 2020). For example, mechanisms similar to those described for algal canopies may stabilize benthic communities dominated by suspension feeders, such as gorgonian forests. To the best of our knowledge, no single study has investigated these mechanisms on rocky shores and linked them to stability. We believe the lack of empirical testing of essential stabilizing mechanisms is a critical knowledge gap that hampers our ability to anticipate the response of rocky reef communities to environmental change.

Understanding the mechanisms underpinning variation in species tolerance to changing climates will be key to preserving the biodiversity and functioning of coastal rocky systems through informed restoration and conservation (e.g., MPA networks, genetic rescue) practices. This will require the coupling of common garden and reciprocal transplant experiments with cutting-edge genomic and transcriptomic techniques (Johnson et al., 2021). In common garden experiments, the exposure of offspring and adults from different populations to a common set of environmental conditions, including extreme events, such as heatwaves, would allow assessing variation in their performance and fitness across populations. Aquatic mesocosms appear as the elective playground for this kind of experiments. While the advantages of a fine control of environmental conditions in artificial settings are undisputable, field experiments offer the opportunity to assess species response to changing conditions while embedded into the complex web of species interactions.

In particular, reciprocal transplant experiments in the field would represent a powerful tool to identify genetic versus phenotypic plasticity adaptation of populations in natural settings. These experiments will be particularly valuable when studied populations span broad environmental gradients (Johnson et al., 2021). This implies taking into account variations in key environmental and climatic variables over a hierarchy of spatial scales, from geographic to local. The relevance of assessing variations in a species tolerance to warming conditions among populations at edges of its latitudinal distribution is widely acknowledged (Bulleri et al., 2018b; Hampe and Petit, 2005). However, latitudinal gradients are not always linearly correlated with seawater and air temperature and, even less, with the degree of mean change or the intensity and frequency of extreme events (Burrows et al., 2011; Helmuth et al., 2002). For example, viable populations from areas that have been, historically, exposed to extreme events of larger intensity and/or more frequently can be expected to exhibit a greater tolerance to adverse climatic conditions (Coleman and Wernberg, 2020). Thus, maps of past climatic conditions may be of aid in selecting relevant populations for tolerance/adaptation studies.

Dispersal potential of target species represents another key aspect to take into account while attempting to assess variations in local adaptation since connectivity among populations is paramount for sustaining climate-readiness of restoration activities and MPA networks. Assessing local adaptation across fine-scale gradients in environmental conditions appears as crucial in short-dispersal species. In the Mediterranean, canopy-forming macroalgae are often distributed from the surface to depths below the seasonal thermocline and individuals only a few m apart are, thus, exposed to very different thermal environments. Likewise, substrate topography, orientation and slope can create a fine-scale thermal mosaic in intertidal environments. Reciprocal transplants of individuals, possibly both adults and offspring, from different depths, heights on the shore or from intertidal microhabitats characterized by benign versus adverse environmental conditions (i.e., desiccation, temperature) would provide an insight into local adaptation within populations and, hence, into their potential to persist in the face of change.

Genomic tools can complement the information generated by field and mesocosm experiments providing a mechanistic understanding of the genetic basis of local adaptation. Progressive reduction of costs of next-generation sequencing techniques has fostered the production of genomic information and is giving momentum to conservation genomics of marine forests (Mamo et al., 2021). For instance, Wood et al. (2021) characterized neutral and adaptive genetic diversity in the brown seaweed *Phyllospora comosa* and how it correlates with temperature, generating an insight into genetic vulnerability under warming climates, crucial information for climate-proof restoration of this species. In addition, improvement of transcriptomic analyses can allow assessing how relevant environmental variables influence gene expression, fostering a mechanistic understanding of species physiological response to changing climates (Li et al., 2016).

A research agenda on ecological persistence and adaptation should develop following state-of-the-art approaches and methodologies. For example, distributed experiments might be used to assess the generality (or lack thereof) of dispersal limitation and density-dependent processes along geographic gradients and in contrasting environmental conditions. The Mediterranean provides an invaluable model system for this purpose. New technological tools such as environmental DNA should be calibrated and used to capture phenological events, such as massive reproductive outputs of algae and invertebrates. Novel approaches that combine observational and experimental data in the same analytical framework have been proposed to increase the scale and inferential strength of ecological studies (Benedetti-Cecchi et al., 2018). The implementation of these approaches is facilitated by the increasing availability of open datasets and by joint collaborative efforts among researchers. Our final recommendation is that a research agenda on persistence and adaptation should focus primarily on habitat-forming species, since these contribute most to the structure and functioning of rocky reef communities.

6. The fate of Mediterranean rocky reefs

While representing less than 1% of the world's oceans, the Mediterranean Sea accounts for 20% of world annual gross marine product (Hoegh-Guldberg et al., 2015). Due to the intense exploitation rates, increasing demography, isolation, and high vulnerability to climatic alterations, pressures accumulate like in few other areas of the global ocean (Halpern et al., 2008).

The fate of Mediterranean rocky reefs remains highly uncertain, as is the fate of the entire basin, but current trends in cumulative human pressure and climate change do not bode well for a bright future. Next years will be decisive for the persistence of Mediterranean rocky reef ecosystems as we have known them so far. Most probably, we will see a relatively fast process of oversimplification of their communities, both in terms of structure and functioning, accompanied with a depletion of biodiversity and an increased biotic homogenization driven by opportunistic native species and NIS. Bioconstructions in the mediolittoral zone, such as vermetid reefs, which already have limited extension in the basin and are highly fragile and fragmented, will drastically reduce or disappear being more exposed to climate-related disturbances. Infralittoral algal forests will continue to shrink, being replaced by less structured communities dominated by smaller erect algae, algal turfs and crusts. Deeper communities in the circalittoral zone will be less affected by climate change, at least in the short-medium term. However, acidification and other interacting human stressors, sooner or later, will start to mine the growth rates of coralligenous outcrops enhancing bioerosive processes (Ponti et al., 2018). MHWs and MMEs, increased sedimentation and deoxygenation will contribute to simplify coralligenous communities, making them more similar to fouling assemblages. The loss of long-living ecosystem engineers, like gorgonians and large sponges, will trigger a gradual, and probably irreversible, process of habitat degradation, increasing the opportunity for NIS to spread and leading to less complex assemblages.

Changes will not be uniform over the entire Mediterranean Sea, but slower and smaller in areas less compromised by human impacts and less affected by climate-driven alterations. Rocky reefs in the eastern basin will become more and more tropicalized, losing their Mediterranean identity, whereas this progression will be delayed in the other regions, although early signals of change might also occur in previous cold-temperate areas (e.g., the northern Adriatic Sea). However, in the western Mediterranean Sea, the higher rates of intensification of fishing effort, spread of new pollutants, and of artificialisation of rocky coasts will further undermine the resilience potential of reef ecosystems, making them more exposed to bioinvasions and more prone to collapse in the face of future climatic anomalies. In both regions, the process of reorganization (*sensu* Holling, 2001) of rocky reef ecosystems will probably be slower than current and future rates of disruption, altering, if not dismissing, the provision of essential goods and services for a long period. This will pose serious concerns (and, indeed, they are already raising) on the ability of socioeconomic systems of Mediterranean coastal areas, which largely rely on rocky reef integrity especially for tourism and small scale fisheries (UfMS, 2017), to adapt to these ecological changes.

The substantial expansion of the coverage and improvement of effectiveness of Mediterranean MPAs through the implementation of the European Biodiversity Strategy and the Green Deal, and the development of efficient conservation strategies, which beyond the structure may also allow preserving the functional diversity of reef communities (Bevilacqua and Terlizzi, 2020), are expected to contribute in decelerating or even reversing the declining trend of the ecological status of rocky reef ecosystems. Nevertheless, a number of challenges may compromise the effectiveness of future conservation strategies, and MPAs alone cannot be a panacea (Lubchenco et al., 2003). Climate change and biological invasions can keep increasing stress to reef ecosystems, and forthcoming socioeconomic pathways can lead to a wide range of plausible futures, with a varying effect in shaping priorities in marine policies and conservation (Roura-Pascual et al., 2021; van Vuuren et al., 2014). Progresses in ecological restoration will certainly be of help in contrasting the degradation of rocky reefs in the next years, although the intrinsic difficulties of restoration techniques and constraints to their application over large areas (Falace et al., 2018; Guarnieri et al., 2020) will probably relegate restoration to an ancillary role in their conservation or recovery. Moreover, hysteretic behaviour of reef ecosystems could vanish the attempts to restore their integrity in the absence of management strategies aiming at enhancing the wider environmental context (Anthony et al., 2015).

In 2012, the European Commission launched the Blue Growth Strategy (COM/2021/0494, 2012), identifying the European seas and oceans as the frontier for future sustainable socioeconomic development. The working concept of sustainable blue growth defines it as an economy that '…promotes economic growth, social inclusion and improved livelihoods while ensuring the environmental sustainability of the natural capital of the oceans and seas' (CINEA, 2021). This is not an easy task that requires balancing often conflicting needs within marine socioecological systems, implementing development strategies carefully tuned to match local contexts, and monitoring their effectiveness through specific indicators to ensure timely adaptations to environmental changes (CINEA, 2021). Given the current status, the pace of ongoing degradation of Mediterranean rocky reefs and future projections, any further use of their resources seems to be unrealistic. Therefore, at least for these coastal systems, the importance of the two elements composing the concept of blue growth should be reversed, emphasizing the need for a healthy status of reefs over the rush for new economic opportunities.

Major efforts in policies and regulations specifically tailored for Mediterranean rocky reefs are urgently required to make the integrity of these habitats a priority for conservation and management at European and basin scale, and try to give the chance for a less troubled future to Mediterranean coastal ecosystems.

Author contribution

S.B. outlined and led the manuscript drafting. All authors equally contributed to intellectual contents, writing and critical review of the manuscript.

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CHAPTER TWO

Human impacts on deep-sea sponge grounds: Applying environmental omics to monitoring

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Contents

Abstract

Sponges (Phylum Porifera) are the oldest extant Metazoans. In the deep sea, sponges can occur at high densities forming habitats known as sponge grounds. Sponge grounds can extend over large areas of up to hundreds of km^2 and are biodiversity hotspots. However, as human activities, including deep-water hydrocarbon extraction, continue to expand into areas harbouring sponge grounds, understanding how anthropogenic impacts affect sponges and the ecosystem services they provide at multiple

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biological scales (community, individual and (sub)cellular levels) is key for achieving sustainable management. This chapter (1) provides an update to the chapter of *Advances in Marine Biology* Volume 79 entitled "Potential Impacts of Offshore Oil and Gas Activities on Deep-Sea Sponges and the Habitats They Form" and (2) discusses the use of omics as a future tool for deep-sea ecosystem monitoring. While metagenomics and (meta)transcriptomics studies have contributed to improve our understanding of sponge biology in recent years, metabolomics analysis has mostly been used to identify natural products. The sponge metabolome, therefore, remains vastly unknown despite the fact that the metabolome is a key link between the genotype and phenotype, giving us a unique new insight to how key components of an ecosystem are functioning. As the fraction of the metabolome released into the seawater, the sponge exometabolome has only just started to be characterised in comparative environmental metabolomic studies. Yet, the sponge exometabolome constitute a unique opportunity for the identification of biomarkers of sponge health as compounds can be measured in seawater, bypassing the need for physical samples which can still be difficult to collect in the deep sea. Within sponge grounds, the characterisation of a shared sponge exometabolome could lead to the identification of biomarkers of ecosystem functioning and overall health. Challenges remain in establishing omics approaches in environmental monitoring but constant technological advances and reduction in costs means these techniques will become widely available in the future.

1. Introduction

Sponges are important benthic organisms that filter large quantities of seawater and fulfil multiple ecosystem services including enhanced bentho-pelagic coupling (transfer of energy and nutrients from the benthos to the water column; Bart et al., 2021). In the deep sea, sponges can occur at high densities and form habitats known as sponge grounds, which support high levels of biodiversity (Maldonado et al., 2015). In 2018, we published a review paper, which described the impact of offshore oil and gas activities on deep-sea sponges and sponge grounds. The review found that effects of hydrocarbon production activities on sponges should be considered at all biological scales, from cellular to habitat levels. The review also highlighted that many research gaps persisted in our understanding of sponge biology and ecology and these gaps hindered our ability to predict how these important filter-feeding organisms are impacted by human activities.

Since the publication of our review in 2018, our knowledge of sponge biology and ecology has improved greatly, thanks to (1) the completion of large international research projects such as the EU Horizon 2020 ATLAS (https://www.eu-atlas.org/) and SponGES (http://www.deepseasponges.org/) projects and (2) the release of new datasets such as the one delivered by the Sponge Microbiome Project (Moitinho-Silva et al., 2017). These advances have contributed to a substantial increase in the number of papers published on sponges, especially from deep-sea and polar regions. The use of omics approaches (see Box 1) have also played a significant role in further

BOX 1 Omics

The term omics first appeared in the scientific literature in 1999 but has since become a common word (Leung, 2018). Omics techniques are molecular methods that analyse the DNA, RNA, proteins and other small molecules synthesised in an organism or among a community (e.g., Aguiar-Pulido et al., 2016). Common omics approaches rely on new technologies such as next generation sequencing as well as mass spectrometry or nuclear magnetic resonance (NMR) to produce large datasets requiring complex bioinformatics processing (Faure and Joly, 2015; Maikkara et al., 2020). As the overall costs of omics analysis have decreased in recent years and with the continued development of big data analysis capabilities, omics tools are now widely used in marine ecology (Faure and Joly, 2015). This is especially true in the field of marine microbiology where omics methodologies have contributed to revolutionise our understanding of microbial communities present in the oceans (Karsenti et al., 2011).

There are over a thousand omics field in biology to date (Bahk, 2020) but the most common omics approaches considered in ecology are:

- (Meta-)Genomics, which mostly refers to the sequencing of DNA fragments (often 16S/18S ribosomal RNA genes) to identify taxa (Maikkara et al., 2020).
- (Meta-)Transcriptomics, which pertains to the sequencing of mRNAs to identify gene expression profiles of a sample at a given time, often in response to a stressor (e.g., Aguiar-Pulido et al., 2016).
- Metabolomics, which is the study of the metabolites (small intra- or extracellular molecules produced mostly through enzymatic reactions) present within an organism (e.g., Goulitquer et al., 2012; Maikkara et al., 2020; Villas-Bôas et al., 2005) and which we will discuss further in this review. As the production of metabolites can change depending on gene expression as a response, for example, to environmental conditions, the metabolome of an organism constitute a key link between genotype and phenotype (Fiehn, 2002; Goulitquer et al., 2012).
- Proteomics and lipidomics, which respectively describe the study of all proteins and lipids encoded by a genome and can be considered as a sub-fraction of the metabolome.

The suffix meta-in metagenomics and metatranscriptomics refers to the identification of a panel of microbial organisms/genes expression profiles within a community populating a sample.

revealing the functioning of sponges and of the sponge microbiome (Pita et al., 2018 and references therein). Just like their shallow-water counterparts, deep-sea sponge holobionts (sponges and their microbiome) participate in the cycling of nutrients including carbon (Bart et al., 2020, 2021; de Kluijver et al., 2021) and nitrogen (Rix et al., 2020; Rooks et al., 2020) and transferred nutrients to associated fauna through their deep-sea sponge host (Bart et al., 2020). At the wider habitat level, many recent studies have explored the spatial distribution of sponge grounds and the factors that control their occurrences (Davison et al., 2019; Dijkstra et al., 2021; Hanz et al., 2021; Kazanidis et al., 2019; Puerta et al., 2020; Roberts et al., 2021). Temperature and salinity have been found to significantly influence the distribution of deep-sea sponges (Davison et al., 2019; Dijkstra et al., 2021) and deep-sea sponge grounds are predicted to occur in areas where different water masses mix (Hanz et al., 2021; Kazanidis et al., 2019; Puerta et al., 2020; Roberts et al., 2021).

In addition to oil and gas extraction activities, deep-sea ecosystems, including sponge grounds, are now facing multiple anthropogenic pressures. Deep-sea fishing is known to cause habitat damage and loss, fish-stock depletion, and disruption of food webs (Clark et al., 2016a; Koslow et al., 2000; Vieira et al., 2020). Furthermore, the prospect of seabed mining moving from phases of exploration to exploitation means that many more deep-sea species and habitats could soon be at risk from this new anthropogenic activity (Leray and Machida, 2020; Ramiro-Sánchez et al., 2019). Seabed mining is widely predicted to cause extensive habitat loss and fragmentation, generate sediment plumes which disrupt feeding and smother animals, as well as expose organisms to noise pollution, electromagnetic disturbance and potentially chemical pollution (Hauton et al., 2017; Niner et al., 2018). In addition to local anthropogenic impacts, the complex implications of climate change on deep-sea ecosystems continue to be revealed (Levin and Le Bris, 2015). Climate change projections for the deep sea include up to a 4.41 °C bathyal temperature increase, a 0.37 pH decrease, a $0.05\,\mathrm{mL\,L^{-1}}$ decrease in dissolved oxygen, and a $13.73\,\mathrm{mg\,C\,m^{-2}\,d^{-1}}$ decrease in seafloor particulate organic carbon (POC) flux by 2100 (Sweetman et al., 2017). But despite this, the impacts of climate change on sponges and sponge grounds remain poorly understood (Guihen et al., 2012; Strand et al., 2017). Modifications of major oceanographic currents due to climate change could lead to significant shifts in the spatial distribution of sponge grounds (Puerta et al., 2020). However, some sponge species seem resilient to climatic variability and sponge grounds may therefore be less vulnerable to climate change (Beazley et al., 2018, 2021) than other habitat forming organisms such as cold-water corals (Hennige et al., 2020). Although sponges might be more resilient to climate change (Bell et al., 2018), modification to the sponge holobiont and specifically its associated microbial community could lead to alteration in the sponge metabolism (Pita et al., 2018) and ultimately transform deep-sea sponge grounds from nutrient sources to nutrient sinks (Rooks et al., 2020). This would mean that global change could significantly alter the ecosystem services provided by sponge grounds and any climate change resilient sponge grounds might not support similar levels of biodiversity.

As sponge grounds are exposed to multiple stressors emerging at both local and global scales, assessing the impacts of one anthropogenic activity—oil and gas production—on sponges should no longer be explored in isolation. Novel biomarkers of ecosystem health are urgently required to efficiently monitor deep-sea ecosystems and omics approaches are expected to become a key constituent of future environmental monitoring efforts (Martyniuk, 2018). Sponges have long been identified as potential marine sentinels (Tlili and Mouneyrac, 2021; Veldhoen et al., 2012) due to their ability to bioaccumulate contaminants (Berthet et al., 2005; Gentric et al., 2016; Mahaut et al., 2013; Orani et al., 2018a,b, 2020). Omics approaches here give an exciting new avenue of research that could reveal the complexity of sponge functioning and help us assess the health of sponges when exposed to environmental stressors. In this present "roadmap" chapter, we will provide a brief update to Vad et al.'s, 2018 review on oil and gas impacts on deep-sea sponges. We will then go beyond the remit of the 2018 review and discuss the advancement made in the use of omics approaches in sponge-targeted studies as well as consider the role of environmental omics and especially metabolomics approaches to identify biomarkers of sponge and sponge ground health.

2. Brief update on 2018 review

The lifetime of an oil field can be divided up into stages of discovery and appraisal, development, production and decommissioning. Each stage is characterised by different activities (e.g., drilling, installation/removal of infrastructures) and therefore by different environmental impacts (e.g., resuspension of sediments, release of drill muds and cuttings) on the local ecosystems (Fig. 1; Vad et al., 2018). Any accidental release of hydrocarbons during an oil spill along with other chemicals such as dispersants should also

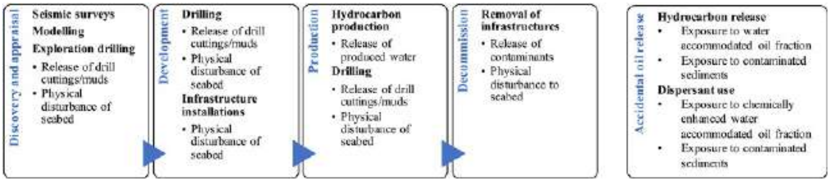

Fig. 1 Flow chart of oil field development divided in four phases and main activities associated with each phase. *Reproduced from Vad, J., Kazanidis, G., Henry, L.A., Jones, D.O.B., Tendal, O.S., Christiansen, S., Henry, T.B., et al. 2018. Potential impacts of offshore oil and gas activities on Deep-Sea sponges and the habitats they form. In: Advances in Marine Biology, pp. 33–60. https://doi.org/10.1016/bs.amb.2018.01.001.*

be studied when reviewing the impacts of oil and gas activities on marine ecosystems (Fig. 1; Vad et al., 2018). A summary of the progress made in our understanding of the impacts of hydrocarbon extraction activities on deep-sea sponges and sponge grounds can be seen in Table 1.

2.1 Sub-individual and individual level impacts of oil and gas activities on sponges

Since 2018, several studies have explored the impact of sediment and drilling waste on deep-sea sponges (Fang et al., 2018; Grant et al., 2018; Scanes et al., 2018). *In-situ* exposure to sediments led to sponges halting their feeding activity, diminishing their metabolism, suppressing the uptake of silicate and increased cellular instability (Grant et al., 2018; Scanes et al., 2018). When combined with thermal stress, the effects of sedimentation led to higher respiration and nitrogen excretion rates, highlighting the complex interplay often seen in multi-stressor experiments (Galic et al., 2018; Scanes et al., 2018). When exposed to drill cuttings, oxygen consumption decreased by up to 33% which led to a drop in tissue oxygenation levels in three sponge species (Fang et al., 2018). In turn, this caused a change in microbial activity, decreasing the holobiont nitrite/nitrate releases (Fang et al., 2018). As our understanding the sponge holobiont increases, these results are starting to reveal how impacts at sub-individual and individual level could trigger ecosystem-wide effects by altering the important role sponge holobionts play in benthic nutrient cycling.

In addition to sediment resuspension, drilling leads to releases of drill cuttings and muds which contain contaminants such as hydrocarbons and heavy metals. Since 2018, several laboratory studies have examined the effects of heavy metals on sponges. Specifically, the bioaccumulation and bioremediation of metals and metalloids by sponges have been further

Table 1 Overview of major impacts of offshore oil and gas activities on deep-sea sponges and deep-sea sponge grounds at community, individual, cellular and molecular levels and throughout oil field development.

		Exploration and appraisal	Field Development	Production	Decommissioning	Deep-sea oil spill
Community level	Main concern	Physical disturbance of seabed and increase sedimentation		Discharge of drill muds and cuttings	Removal of structure	Exposure to high hydrocarbons and dispersant concentrations
	Impacts				🟥 Benthic habitat destruction.	🟥 Changes in benthic community abundance, age structure and trophic interactions.
		🟩 Diminished benthic community.		🟩 Benthic community diversity/abundance decrease.	🟩 **Changes to benthic community distribution**	🟩 **Sponge mortality. Low recovery.**
Individual Level	Main concern	Seismic survey and increase sedimentation	Increase sedimentation	Discharge of produced water	Release of chemical contaminants	Exposure to high hydrocarbons and dispersant concentrations
	Impacts	🟥 Larval development delay and malformations.				🟥 Health decline, hydrocarbon bioaccumulation.
		🟨 Changed respiration rate and reproduction capacities. Decreased growth rate.		🟨 **Bioaccumulation of PAH and heavy metals. Mortality.**		🟨 **Larval settlement and metamorphosis disturbance. Hydrocarbon bioaccumulation. Paused filtration. Shift in sponge microbiome.**
		🟩 **Paused filtration. Diminished oxygen consumption. Diminished metabolism.**				
Cellular & Molecular levels	Main concern	Discharge of drill muds and exposure to chemicals via release of produced water				Exposure to high hydrocarbons and dispersant concentrations
	Impacts	🟥 Decrease immune system function.				🟥 Decreased immune system function.
		🟨 Activation of MAPKs and cytochrome P450 pathways. Oxidative stress.				🟨 **Activation of MAPKs and cytochrome P450 pathways. Oxidative stress.**
		🟩 **Decrease of lysosomal membrane stability.**				

Impacts described in deep-sea sponge species are highlighted in green. Impacts described in shallow-water sponge species but not yet confirmed for deeper species are highlighted in orange. Impacts described in other benthic organisms but not yet investigated in any sponge species are highlighted in red to emphasise remaining knowledge gaps. Bold font has been used to draw attention to impacts discovered or further investigated since the 2018 review.

investigated (Ferrante et al., 2018; Orani et al., 2018a,b, 2020). These studies have confirmed the potential role sponges could play in biomonitoring programmes due to their ability to efficiently bioaccumulate contaminants (Ferrante et al., 2018; Orani et al., 2018a,b, 2020). One study did, however, highlight the relatively low resilience of sponges to heavy metal exposure, once more revealing their vulnerability to human activities (Ferrante et al., 2018).

2.2 Habitat level impacts of oil and gas activities on sponge grounds

At habitat level, the role of oil and gas infrastructure in shaping the spatial distribution of deep-sea sponge grounds was investigated in one study published in 2020. Focussed on the Faroe-Shetland Channel, a key area for oil and gas activities in the North Atlantic, this study found that oil and gas infrastructures changed the distribution of sponge grounds at a local spatial scale (tens of metres) while fishing activities structured deep-sea benthic communities in the area at large spatial scales (tens of kilometres; Vad et al., 2019). Furthermore, motile megafauna associated with the sponge grounds were found to accumulate near oil and gas infrastructures such as pipelines and manifolds (Vad et al., 2019). These findings will need to be considered in the context of the decommissioning debate (Fowler et al., 2020) and contribute to show that removal of offshore infrastructure near sponge grounds could lead to strong negative environmental impacts (Fortune and Paterson, 2020; Fowler et al., 2018, 2020). However, as multiple human activities often take place within an area (as seen within the Faroe-Shetland Channel), leaving man-made structures *in-situ* might not always constitute a viable option (Rouse et al., 2020).

2.3 Impacts of a deep-sea oil spill on sponges and sponge grounds

Since 2018, our understanding of the impacts of oil spills on sponges has improved, in part thanks to experimental studies using shallow-water sponge model species. For example, exposure to hydrocarbons in the temperate sponge model *Halichondria panicea* led to a significant decrease in sponge pumping rate and severe changes in the sponge gene expression profiles (Vad et al., 2020). Genes involved in detoxification processes and oxidative stress were differentially expressed in samples exposed to oil and dispersant contaminated seawater. These results align with a study conducted on the tropical sponge *Rhopaloeides odorabile* (Luter et al., 2019). In addition, exposure to oil-contaminated seawater also decreased sponge larval settlement and metamorphosis and led to a shift in the sponge microbiome in *R. odorabile* (Luter et al., 2019).

Our understanding of the consequences of accidental releases of oil and dispersants on deep-sea marine ecosystems has also increasing with the emergence of long-term investigations into the impacts of the Deepwater Horizon oil spill (Girard and Fisher, 2018; McClain et al., 2019; Schwing et al., 2020). In the Gulf of Mexico, evidence of low recovery since the spill was identified in impacted areas with, for example, coral colonies still displaying signs of injury 7 years after the spill (Girard and Fisher, 2018). Very limited information is available on the impact of the spill on sponges specifically. However, remotely operated vehicle surveys conducted in 2017 revealed that glass sponges often found in control areas are absent from contaminated sites 7 years post-spill, highlighting the low resilience of sponges to hydrocarbon exposure (McClain et al., 2019).

3. Understanding sponge biology and ecology through omics

3.1 Using omics to unravel sponge holobiont biology

Omics approaches include a wide range of techniques, which offer exciting avenues to investigate the biology of marine organisms. Applied to sponges, omics have increased our understanding of the sponge holobiont (Fig. 2). Metagenomic analysis has revealed the complex structure of the sponge microbiome. Indeed, one study recently described the global sponge-microbiome network revealing that microbial communities associated with sponges formed distinct functional modules. These modules are connected by sponge species that share microbial taxa with other species around the world (Lurgi et al., 2019). Vertical transmission of symbionts from a parent sponge to its larvae does occur but such transmission is irregular, meaning that a sponge larva is as likely to share vertically transmitted microbes with another sponge species than other member of its own species (Björk et al., 2019). So, while biotic factors will define the core species of microbes associated with a sponge, abiotic factors play an important role in shaping the peripherical microbial taxa present within the sponge holobiont (Busch et al., 2020; Lurgi et al., 2019; Schellenberg et al., 2020). The composition of the sponge microbiome is therefore the product of both evolutionary and ecological processes (Björk et al., 2019; Lurgi et al., 2019). Complementing metagenomics studies, metatranscriptomics approaches have revealed that

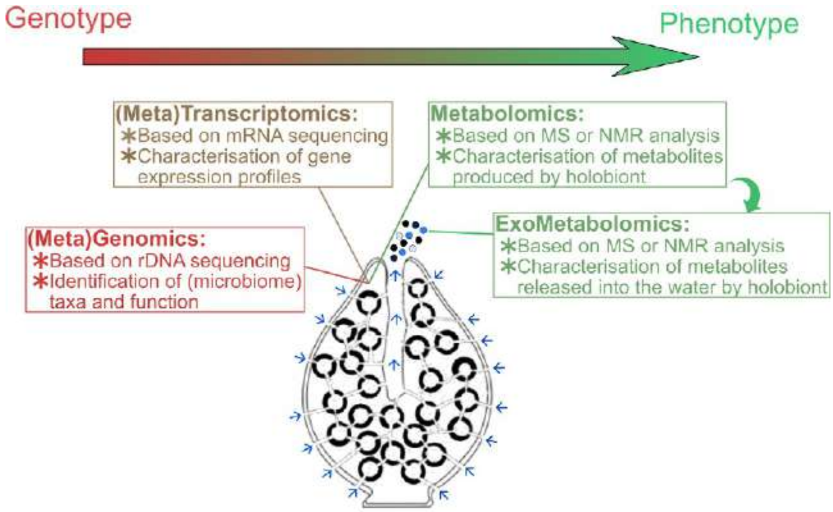

Fig. 2 Schematic overview of omics application to sponge biology. *Sponge drawing adapted from Hentschel, U., Piel, J., Degnan, S.M., Taylor, M.W. 2012. Genomic insights into the marine sponge microbiome. Nat. Rev. Microbiol. 10 (9), 641–654. https://doi.org/10.1038/nrmicro2839.*

gain of symbionts due to changes in environmental conditions can translate to a gain of new functions for the holobiont, further demonstrating the critical importance of the microbial community in the survival of the sponge host (Britstein et al., 2020; Schellenberg et al., 2020). Transcriptomic and metatranscriptomic investigations have also identified molecular pathways involved in the response of the sponge holobiont to a disturbance (e.g., Koutsouveli et al., 2020; Luter et al., 2019, 2020; Vad et al., 2020) as well as characterising the sponge immune response (e.g., Pita et al., 2018).

While metagenomic and (meta)transcriptomic studies have increased our understanding of the functioning of the sponge holobiont, metabolomic and proteomic studies have mostly been focussed on the identification of natural products, i.e., secondary metabolites which hold interesting properties such as antibiotic effects (Indraningrat et al., 2016; Mehbub et al., 2014; Paul et al., 2019; Pawlik, 2011). In fact, sponges have received considerable attention in the field of chemical ecology which routinely applies metabolomic approaches (Paul et al., 2019). Sponge holobionts produce a very diverse array of metabolites and natural products and sponge species can even be identified based on their metabolomic profiles (e.g., Fagundes et al., 2021; Núñez-Pons et al., 2012; Paul et al., 2019; Vohsen et al., 2019). While over then thousand natural products have been isolated from sponges, the ecological role of these compounds is largely unknown (Avila, 2020; Paul et al., 2019; Pawlik, 2011). One ecological function that is better understood is the role that some natural products play in chemical defence against predation, competition, fouling or disease (e.g., Blunt et al., 2018). While a large proportion of secondary compounds identified in sponges are in fact produced by their microbial counterparts (e.g., Mohanty et al., 2020, 2021), chemical defence molecules might be synthesised by the sponge host at high energetic costs. Indeed, sponge species that lack chemical defences appear to grow faster than species rich in chemical defence compounds. In overfished regions, this means that some sponges are able to outcompete other species, highlighting the importance of the metabolome in shaping community composition (Loh and Pawlik, 2014; Marino et al., 2017; Pawlik, 2011; Puglisi et al., 2019). More recently studies have started to use comparative metabolomics to reveal the temporal and spatial intraspecific variability of sponge metabolomes (Bayona et al., 2020; Reverter et al., 2016, 2018; Villegas-Plazas et al., 2019). Results showed that sponge metabolomes can vary depending on physiology (reproduction) but mainly shifted as a response to environmental factors such as a rise in temperature (Reverter et al., 2016, 2018; Ternon et al., 2016). However, while intraspecific differences were found by Reverter et al. (2018), these were smaller than across sponge species and correlated closely with the sponge microbiome (Mohanty et al., 2020, 2021). In addition to producing a large variety of metabolites, sponges are also known to release part of it metabolome into the seawater (Thompson, 1985; Walker et al., 1985). The role of the sponge exometabolome, i.e., the portion of metabolites expelled by the sponge into the water column is rarely understood. Nevertheless, in areas where sponges are found at high concentration such as sponge grounds, the shared exometabolome could create a chemical signature or seascape that may play a significant role in the functioning of the whole ecosystem and contribute to shape the biodiversity it supports.

3.2 Exploring the sponge exometabolome

It has long been known that natural products released into the water column can act as important signals in intra- and interspecific biological interactions that ultimately contribute to regulate community structure (Avila, 2020; Pawlik, 1993, 2011). For example, chemical cues are heavily involved in reproduction, larval settlement and larval recruitment in many marine organisms (see Harder et al., 2018 for a review), including shallow-water sponges (Hunting et al., 2009). But chemical cues (beyond defence compounds discussed above) can also change the behaviour of motile species (e.g., Ashur and Dixson, 2019; Tricarico et al., 2011) and in the deep sea, an environment largely deprived of light, the assumption is that chemical cues could be even more important to communication than in shallower settings (Skropeta, 2008). Sponge grounds are habitats that hosts vast numbers of organisms and it is very likely that chemical cues play an important role in the interactions between sponges and associated species (Avila, 2020). However, very little is known about the role of the sponge exometabolome. Sponges' exhalant water is enriched in compounds which influenced the chemical profile of the dissolved organic matter they expelled (Fiore et al., 2017; Olinger et al., 2021). Furthermore, some sponge exometabolites can be discharged through spherulization, a process by which compounds are stored in specialised spherulous cells ready for release, calling attention to the role of exometabolites in sponge biology (Ternon et al., 2016). In addition, there is anecdotal evidence that motile fauna may be attracted to sponge-dense areas (for example, sea caves) through a shared sponge exometabolome (Santonja et al., 2018) and signals of exposure to pollutants can be identified from sponge exometabolites (Bojko et al., 2019). These could constitute first hints of the role of the sponge exometabolome in wider ecological processes and how the study of the exometabolome could reveal new biomarkers of sponge health.

4. Environmental omics as biomarkers of sponge and sponge ground health

4.1 Environmental omics as a monitoring tool

To date, deep-sea habitat monitoring has typically relied on gathering images and physical samples from the seabed (see Box 2). However, these traditional methods struggle to monitor changes in ecosystem functioning. Classically, omics techniques have been applied in controlled laboratory conditions, but the development of environmental omics has changed this approach by aiming at identifying organism or community responses in natural environments (Bahamonde et al., 2016; Bundy et al., 2008). While the use of omics in environmental management and ecotoxicological assessment programmes remains limited, environmental omics approaches have received increasing attention in recent years (Canonico et al., 2019; Leung, 2018; Prat and Degli-Esposti, 2019). Efforts have been made to include environmental omics into marine observatories (Canonico et al., 2019).

A good example of environmental omics is the use of environmental DNA (eDNA) metabarcoding to monitor biodiversity in marine habitats as an alternative to benthic sampling (Taberlet et al., 2012). Based on high-throughput amplicon sequencing of DNA molecules extracted from water or sediment samples, eDNA metabarcoding holds real promise as a fast and cost-effective way to survey marine biodiversity (Cordier et al., 2017; Taberlet et al., 2012). This is especially true with the development of new bioinformatic tools based on machine learning to minimise the proportions of unassigned sequences (Cordier et al., 2017) and promising novel automatic sampling technologies (Doi et al., 2017; McQuillan and Robidart, 2017; Scholin et al., 2017; Yamahara et al., 2019). For example, samplers mounted on autonomous underwater vehicles (AUVs) can collect samples at high spatial and temporal resolution and allow complex biological processes such as spawning events to be followed *in-situ* (McQuillan and Robidart, 2017; Yamahara et al., 2019). Interestingly, marine sponges have been showed to be effective eDNA samplers themselves thanks to their filtering activities (Mariani et al., 2019).

BOX 2 Sponge grounds monitoring

Traditional monitoring approaches to study deep-sea habitats can be divided into two categories: video-based *versus* sampling-based methods. These methods allow for assessment of species abundance, community composition as well as diversity and can be used in repeated sampling designs to establish level of change over time. Sampling-based methods include epibenthic sledges, beam trawls and grabs (Clark et al., 2016b). These classical methods of sampling are very intrusive and destructive but allow for samples to be collected for further analysis. For deep-sea sponges, this could for example allow for species level identification through spicule determination. Video-based methods include towed camera systems, human-occupied vehicles, remotely operated vehicles, and autonomous underwater vehicles (Bowden and Jones, 2016). These systems enable the gathering of high-quality images of the seafloor, which can help determine the spatial distribution and potential diversity of deep-sea habitats. However, none of the methods mentioned here offer the ability to measure individual organism or whole ecosystem health. There is therefore a recognised urgent need to move beyond measurement of community diversity and species abundance and omics approaches will play a key role in this shift (Bell et al., 2017).

4.2 Environmental metabolomics and sponge exometabolites as biomarkers of sponge ground health

By targeting molecules that are ubiquitous across taxa (as opposed to individual genes), metabolomics offers a significant advantage for environmental monitoring over genomics and transcriptomic-based studies (Bahamonde et al., 2016). In addition, metabolomic analyses are often more cost-effective than sequencing and therefore, are more suitable for monitoring as they allows for many more samples to be processed. Furthermore, environmental metabolomics could become a key tool in future monitoring efforts as shifts in the metabolome of an organism reflect changes in fitness, and the metabolome can therefore be an effective bioindicator (Bahamonde et al., 2016; Pomfret et al., 2019). Environmental metabolomic approaches have already been applied, among others, in studies on mussels (Cappello et al., 2013; Kwon et al., 2012), clams (Campillo et al., 2015) and fish (Goode et al., 2020) to determine how these organisms interact with their environments and to identify metabolites as indicators of habitat quality. In these examples, metabolites were measured within tissues and exometabolites were not targeted. However, investigating the exometabolome for biomarkers of organism health has significant advantages over traditional metabolomic studies in that it is non-invasive and does not require physical samples to be collected. Recently, new protocols have emerged which allow for efficient measurement of metabolites in seawater, even when compounds are present at low concentrations (Bojko et al., 2019; Sogin et al., 2019). These methods include the use of solid phase microextraction membranes and fibres, which allow for rapid, simple, and cost-effective metabolite extraction from seawater and have proved to be effective in collecting sponge exometabolites (Bojko et al., 2019). Where sponges are present at high densities, analysis of the shared sponge exometabolome could therefore be an exciting new way of identifying biomarkers of ecosystem functioning and health.

4.3 Remaining challenges

Several challenges remain before omics approaches such as (exo)metabolomics can be used to monitor sponge grounds and other deep-sea ecosystems. The further development of cost-effective sensor technologies is key to widen the use of omics in surveys (McQuillan and Robidart, 2017). AUV mounted samplers such as the ones developed for eDNA show great promise (Doi et al., 2017; McQuillan and Robidart, 2017; Scholin et al., 2017; Yamahara et al., 2019) and similar samplers for exometabolite characterisation could make metabolomic surveys possible. Omics approaches including metabolomics generate vast datasets, requiring complex bioinformatic analysis and storage on long-term FAIR-compliant (Findable, Accessible, Interoperable, Reusable) repositories (Canonico et al., 2019; Cordier et al., 2017; Longnecker et al., 2015). Despite the existence of repositories such as PubChem (Bolton et al., 2008) and METLIN (Tautenhahn et al., 2012), identification of marine metabolites remains difficult due to the overall paucity of annotations in comparisons to the diversity of compounds found (Sogin et al., 2019). Beyond the continued development of sensors, bioinformatic analysis capacities and databases, it is also essential to develop standard collection and survey protocols to establish best practices and ensure the quality of omics data produced and cross-survey comparability (Bahamonde et al., 2016; Beger et al., 2019; Pawlowski et al., 2018). For example, defining baselines is a vital step before any new monitoring technique can be established, especially in deep-sea environments (Kazanidis et al., 2020). In the context of metabolomics, characterising normal metabolome variability and identifying significant change (critical effect size) to define a meaningful biological response to a stressor is required before the approach can be used in environmental monitoring (Bahamonde et al., 2016; Canonico et al., 2019; Martyniuk, 2018; Prat and Degli-Esposti, 2019). Thus, understanding normal variability in metabolomes will ideally require multi-stressor experimental approaches in controlled mesocosm conditions ground-truthed with field-based studies.

5. Conclusion

The sustainable use of marine resources depends upon preventing marine ecosystem deteriorating, maintaining healthy habitats, and efficiently monitoring marine environments. Benthic megafaunal assemblages, and especially habitat-forming ecosystem engineers, should be included in monitoring efforts and variables that allow the measurement of ecosystem health should be prioritised (Danovaro et al., 2020). Efficient monitoring of ecosystem health is also key to the success of deep-sea ecological restoration (Da Ros et al., 2019; Danovaro et al., 2021; Van Dover et al., 2014). Efforts to incorporate environmental omics approaches into monitoring should be prioritised, and by understanding sponge exometabolomes, we have the potential of linking impacts of stressors at individual sponge levels to habitat-wide effects for the first time. As such, exometabolomics could become a tool that directly answers the need for ecosystem health biomarkers and contribute to establishing a new generation of efficient monitoring practices. In conclusion, the present short review can be summarised in four key points:

- Since our 2018 review, impacts of oil and gas activities on deep-sea sponges and sponge grounds have been further investigated. At habitat level, oil and gas infrastructure can alter sponge distribution at local spatial scale (while other human activities such as deep-sea fishing will shift sponge distribution at large spatial scale). At individual and sub-individual levels, exposure to re-suspended sediment and drill cuttings negatively impact deep-sea sponges by altering their physiology and metabolism. Finally, there is now mounting evidence from both experimental and field-based studies that sponges are highly vulnerable to hydrocarbon exposure and deep-sea oil spills like the one seen following the Gulf of Mexico Deepwater Horizon incident will lead to pronounced sponge mortality.
- As deep-sea ecosystems are exposed to multiple anthropogenic threats and pressures ranging from fishing, mineral extraction, global warming and pollution, it is key that new biomarkers of ecosystem health are developed. Omics methodologies offer new approaches to study marine systems and could help establish sponges as sentinels of ecosystem function in the deep sea.
- Specifically, investigating the sponge exometabolome could be key to further understand the role of sponges in shaping local biodiversity. Furthermore, studying the existence of a shared exometabolome across sponge grounds could provide valuable opportunities to identify exuded metabolites as biomarkers of ecosystem health. By only requiring water samples to be collected, exometabolite monitoring through environmental metabolomics could constitute a significant non-invasive tool to assess sponge ground ecosystem health.
- Advancement in sampling methods including AUV mounted samplers and the development of efficient solid-phase metabolite microextraction fibres and membranes could contribute to make environmental metabolomics an indispensable tool for future monitoring surveys.

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CHAPTER THREE

From an economic crisis to a pandemic crisis: The need for accurate marine monitoring data to take informed management decisions

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Contents

Abstract

It is axomatic that a system cannot be managed unless it is measured and that the measurements occur in a rigorous, defendable manner covering relevant spatial and temporal scales. Furthermore, it is not possible to predict the future direction of a system unless any predictive approach or model is supported by empirical evidence from monitoring. The marine system is no different from any other system in these regards. This review indicates the nature and topics of marine monitoring, its constraints in times of economic austerity, the sequence of topics subject to monitoring and the amount of monitoring of various topics carried out as indicated by the number of publications and researchers. We discuss the way in which the nature of monitoring is decided and we use examples to comment on the way monitoring leads to and responds to marine management and governance.

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1. Introduction

In the 50 years spanning between 1870s and 1920s, many marine biological stations were founded, and many oceanographical surveys organized, setting the scene for modern marine ecology (Egerton, 2014). However, most of these institutions did not start systematic marine monitoring, with the exception of those related to the management of fishing resources (Watson and Tidd, 2018).

Marine monitoring comes in many shapes and sizes—originally perhaps just the surveillance of a set of features—but more precisely it includes the survey of physical, chemical and biological ecosystem components for a defined purpose and against a defined end-point (Borja and Elliott, 2013; McLusky and Elliott, 2004). That aim could be the detection of a trend or the noncompliance with a threshold, standard, trigger value or baseline, thus leading to a well-defined (and agreed in advance) policy action (de Jonge et al., 2006). Perhaps the greatest reason for monitoring is either to decide what management measures are required or to check the efficacy of the management measures once carried out.

In this way, aquatic and marine legislation worldwide requires monitoring at different spatial and temporal scales (Borja et al., 2008). There appears to be 10 types of monitoring (Box 1), covering everything from wide surveillance (for which a pre-determined endpoint may not have been defined), through operational monitoring (by an industry wanting to know or demonstrate its performance), to investigative monitoring (also called diagnostic monitoring, which is better regarded as applied research possibly to find the cause of a measured effect), as described by Borja and Elliott (2013). Although making the concepts of monitoring more complex, but also more comprehensive, each of these 10 types has been defined for a purpose and indeed is mentioned in legislation such as European Directives or national laws and guidelines—again with an intent to aid in management, to provide relevant and timely information, and/or to check the efficacy of management against accepted standards and indicators. Under the 'polluter pays principle' or perhaps the more correctly named 'developer debt principle', many if not all of these types of monitoring have to be funded by an industry or, failing that, a conservation body, even if they are required by a statutory regulator.

Similarly, Elliott (2011) indicates the 18 characteristics of monitoring programmes and the indicators of change detected during those programmes. Hence, the need for a rigorous, and scientifically and legally defendable

BOX 1 Types of monitoring (expanded and modified from Elliott, 2011).

Type	explanation
Surveillance monitoring	A 'look-see' approach which is started without deciding what are the end-points and often followed by a post hoc (a posteriori) detection of trends and then linked to a suggested management action.
Condition monitoring	Used by nature conservation bodies to determine the present status of a 'conservation objective', an area, a habitat or a species; it could be linked to the biological valuation of those features (e.g. Derous et al., 2007).
Operational monitoring	Used by industry for business reasons to check their operations meet their needs (e.g. for a dredging scheme linked to the reason for the dredging, the aims for management and to determine if an area requires further dredging).
Compliance monitoring	Originally regarded as 'true monitoring'; used by industry and linked to licence (or permit/authorisation/consent) issued by an environmental regulator, for example in setting conditions for effluent discharge, disposal at sea, planning permission, etc.; often showing compliance with indicators and deviation from a baseline or reference condition which are set a priori.
Self-monitoring	Being carried out by the developer/industry under the 'polluter pays principle' (or more aptly the 'developer debt principle') but often sub-contracted to an independent and quality-assured/controlled laboratory; again, used to check any environmental damage cause by the operations.
Check monitoring	Where an Environmental Protection Agency then checks the self-monitoring to ensure that a developer is performing appropriate monitoring and the data produced can be trusted, especially if the results are subject to legal proceedings.
Toxicity monitoring and testing	As a predictive approach needed for licence setting (to determine the level of contaminants suitable for discharge), or used by regulators to determine compliance of the licence conditions with required standards.

Continued

BOX 1 Types of monitoring (expanded and modified from Elliott, 2011).—cont'd

Type	explanation
Investigative monitoring	Applied research on cause-and-effect, to explain any deviation from perceived or required quality, by focussing on certain elements, species, habitats etc.
Diagnostic monitoring	Determining effects on biological elements but with a link to the cause for change, synonymous with investigative monitoring; to determine the signal: noise ratio.
Feedback monitoring	Real time analysis, linked to predetermined action; e.g., monitoring during dredging on condition that the activity is controlled/prevented/stopped if a deleterious change is observed; this relies on an acceptance that any early-warning signal will be related to an ultimate affect.

approach and resulting information and data is clear. For example, most monitoring required by statutory agencies, especially that linked to conditions stipulated in licences, permits, consents or authorizations, have to stand up to statutory or legal scrutiny otherwise there will be legal challenges either to the developer (the industry or pollution discharger) or the regulator issuing the permissions to operate. As such, for example, an industry will be given an authorization to operate an effluent discharge which will list the contents or concentrations of contaminants discharged (termed Uniform Effluent Standards), the toxicity of those elements (such as Direct Toxicity or Whole Effluent Testing), or the permissible characteristics once the toxicants are discharged to the receiving environment (the Environmental Quality Standards, Environmental Quality Objectives, desirable biological features) (van Dam et al., 2019).

The importance of monitoring in marine waters has been largely emphasized (Borja and Elliott, 2013; Pearce, 1998; Sukhotin and Berger, 2013; Tanabe, 1993; Wells and Sheppard, 2007) and it is recognized that marine monitoring is expensive, especially when done well. For example, if monitoring is to answer specific questions and to give statistically robust outcomes, such as the BACI-PS approach (before-after-control-impact paired series, Gray and Elliott, 2009) then it requires suitable replications.

This was illustrated by Franco et al. (2015) who, in analysing the amount of benthic monitoring required to test deviation from a baseline and compliance with a reference condition, found that most surveys of offshore wind farm environmental impact assessments did not have sufficient replication, probably because of the cost. This emphasized that although the monitoring was considered to be important for obtaining planning permission for the wind farm and for detecting adverse change, it was unlikely to achieve these aims.

Despite this importance, the global financial and economic crisis of 2007–2008, and the subsequent recession, led many countries (and industries) to reduce their statutory monitoring budgets or try to pass them to industry (Borja and Elliott, 2013). During almost a decade after the crisis, the ways to obtain this saving by governments included reducing monitoring programmes and cutting the operational budgets of statutory bodies (e.g., Environmental Protection Agencies (EPA), Environmental and Nature Conservation Ministries, etc.) (Borja and Elliott, 2013; National Research Council, 2015). Indeed, for those EPA, such as in the UK, whose remit includes both environmental quality monitoring and public safety aspects of flooding and erosion control, then the public safety aspects have to take precedence over the environmental quality monitoring when budgets are cut. Usually cutting budgets results in reducing the elements to be sampled, the number of sampling locations and number of samples (de Jonge et al., 2006), frequency of sampling (Abramic et al., 2012) or requires cheaper monitoring (Lampadariou et al., 2005) and assessment (Pawlowski et al., 2018) methods, and a reduction in core science (National Research Council, 2015). The result of this may be that while the remaining monitoring makes the regulators and industry feel as though it is valuable, it does not fulfil any of the criteria mentioned above and hence is open to challenge.

However, after the financial crisis, the need for monitoring remains, to accomplish implementation of the various national, regional and international legislation (Borja et al., 2008), and significant gaps in expertise and resources still persist. For example, this applied in Europe, for the Marine Strategy Framework Directive (MSFD; 2008/56/EC) monitoring in which Member States had to provide their Monitoring Programme to Brussels otherwise they would be in breach of the Directive (Palialexis et al., 2021). Likewise, there is an increasing need to respond to the main challenges that the environment in general, and the ocean in particular is facing, e.g., climate change (IPCC, 2019), biodiversity loss (Worm et al., 2006), or assessing the ocean health status (United Nations, 2021), all of which require accurate and comprehensive long-term monitoring data.

Indeed, we have previously identified the paradox in marine assessments (Strong and Elliott, 2017) (Box 2)– that there is an increasing marine governance and management, and this is dependent on acquiring greater data across larger spatial scales and greater time-series (Borja et al., 2016a) and yet the bodies responsible for data collection are subject to significant resource limitation (Borja and Elliott, 2013). For example, ambitious legislation, such as the EU MSFD and the US Oceans Act (see Borja et al., 2008), are making greater demands from the assessment process, with the current trends including: (i) the evaluation of health over large spatial scales; (ii) increasingly defendable and repeatable measurements of status; (iii) responsiveness to management measures, and (iv) cost-effective implementation (Borja and Elliott, 2013).

In addition, the COVID-19 disease, and its rapid spread across the world as a pandemic (Wang et al., 2020), has revealed the need for data to take rapid management decisions, but also the close links of nature and biodiversity (including marine) and conservation (Bates et al., 2020; Hentati-Sundberg et al., 2021) with human health (Pouso et al., 2021). This puts the focus again on the need to obtain rigorous and scientifically defendable data, under a long-term basis to take marine management decisions (Borja et al., 2016a), but also using cost-efficient monitoring methods (Hyvärinen et al., 2021; Strong and Elliott, 2017).

BOX 2 The marine assessment paradox—'That there are more and more initiatives requiring assessments (below, with reference to European Directives) but there is less funding for achieving them (or the funding burden is put onto industry)'

- Catchment quality (e.g., Water Framework Directive, Clean Water Act)
- Habitat and species conditions (e.g., Habitats Directive, Conservation legislation)
- Appropriate Assessment (e.g., Habitats and Wild Birds Directives)
- Marine regional quality (e.g., Marine Strategy Framework Directive, Oceans Acts)
- Cumulative impacts assessment (e.g., Cumulative Impact/Effects Assessment Directive)
- Strategic environmental assessment (e.g., Strategic Environmental Assessment Directive)
- Environmental Impact Assessment (e.g., EIA legislation worldwide)
- Permit conditions for industry and marine activities

(modified from Strong and Elliott, 2017).

In addition to the above, it is apparent that marine monitoring and assessment is moving to a global framework in contrast to much previous monitoring which was aimed at addressing local, national or regional questions. For example, monitoring to give a status assessment is given throughout the proposals for the recently started UN Decades of Oceans Science for Sustainable Development (Pearlman et al., 2021; Ryabinin, 2020) and of Ecosystem Restoration (Fischer et al., 2021; Waltham et al., 2020), the recently issued World Oceans Assessment II (United Nations, 2021), the Quality Status Reports from the UNEP Regional Seas Conventions such as OSPAR (OSPAR Commission, 2010) and HELCOM (HELCOM, 2010), the fulfilling of the Sustainable Development Goals, especially SDG14 Life Below Water (Cormier and Elliott, 2017), and the implementation of the G7 FOSI (Future of Oceans and Seas Initiative). In addition, the UNEP recently announced GEMS Oceans (Global Environmental Monitoring System) is aiming for a partnership of those involved in marine monitoring, thereby hoping to give a coordinated view.

As described above, the plethora of monitoring types, the increasing statutory requirement for monitoring, the reasons for its achievement, the use of its outputs in management, the emphasis in global initiatives and the concomitant pressure in funding, all indicate the need for an interrogation of the monitoring literature. Hence, in this context we consider that a review of marine monitoring publications will provide lessons for future monitoring and in particular the means of reconciling the challenges indicated above. In this, we aim to consider the types and extent of marine monitoring, the main proponents and the outcomes of that monitoring. This then allows us to comment on whether the existing marine monitoring is fit-for-purpose.

2. Methodology

In order to undertake an in-depth study of the topic, a search in Scopus using the terms ‘marine’ AND ‘monitoring’, was made on 27th April 2021. A total of 37,400 references was found, for the period 1956–2021. However, to study complete years, those from 2021 were discarded, and the remainder were exported to EndNote. After removing incomplete references and some duplicates, 36,272 were used in the study.

The bibliometric study is based on the research profiling method (Porter et al., 2002) and using science network mapping methods (Zupic and Cater, 2015). The methods of science network mapping include: citation analysis, co-citation analysis, bibliographic coupling, co-author analysis, and co-word analysis (Lis et al., 2020; Zupic and Cater, 2015). For that, we have used VOSviewer software, version 1.6.16 (van Eck and Waltman, 2010, 2020), which allows the user to employ keywords co-occurrence analysis, which is similar to the co-word analysis, to identify leading and emerging topics. Lis et al. (2020) considered that *'co-word analysis is a content analysis technique that uses patterns of co-occurrence of pairs of items (i.e., words or noun phrases) in a corpus of texts to identify the relationships between ideas within the subject areas presented in these texts'*.

The software allows a co-author analysis, showing the links between lead authors and research groups, taking into account the papers and topics published. Subsequently, it is possible to measure the strength of relationships between different items (i.e., keywords, authors) clustered into groups, showing the co-occurrence frequency of items, and displayed in bibliometric network maps. A cluster is a set of closely related nodes where each node (representing an item, such as an author, or keyword) is assigned to exactly one cluster. In knowledge domain maps, each node and the links between them indicates their collaborative relationships. A link is a connection or a relation between two items (e.g., coupling between publications, co-authorship, and co-occurrence between terms). The strength of a link may, for example, indicate the number of cited references two publications have in common, the number of publications two researchers have co-authored, or the number of publications in which two terms occur together (van Eck and Waltman, 2020). In some cases, there are keywords with high number of occurrences, but not useful for the analysis, e.g., 'article', 'priority journal', 'review', etc., or even are implicit in the research (e.g., 'monitoring'). In other cases, several different keywords, with the same meaning, can be grouped into a single term, for a more accurate analysis, e.g., 'coastal area', 'coastal ecosystems', 'coastal environments', 'coastal water', 'coastal waters', 'coastal zone', and 'coastal zones', can be grouped under the term 'coast'. In order to remove those not useful terms or merging those similar keywords, we built a 'thesaurus file' as described in the software manual (van Eck and Waltman, 2020). VOSviewer uses a*.ris* file exported from EndNote for the analyses.

VOSviewer has been used in multiple scientific topics, including sustainability (Lis et al., 2020; Rosato et al., 2021), human health and environment interactions (Spano et al., 2020), marine spatial planning (Chalastani et al., 2021), or general scientific research achievements (UNESCO, 2015).

Building on the analysis initially performed in Borja and Elliott (2019), we have also studied the evolution of some selected topics, obtained from those identified in the clusters mapped with VOSviewer. The information contained in the EndNote file was used to undertake such a study,

Table 1 Search in EndNote (containing the basic information of 'marine monitoring') and several selected topics, to track the evolution in their publication

Basic information	Boolean term	Selected topics	Name used
Marine monitoring	AND	Waste* OR Waste water OR Wastewater* OR Waste discharge*	Waste
		Radioact* OR Radiact*	Radioactivity
		Toxic* OR Ecotoxi*	Toxicity
		Noise OR Sound	Noise
		Metal*	Metal
		Oil-spill* OR Oil spill*	Oil-spill
		Eutroph*	Eutrophication
		Organic pollut*	Organic pollution
		Biomonitor*	Biomonitor
		Pharmaceut*	Pharmaceuticals
		Plastic*	Plastics
		TBT	TBT
		Litter*	Litter
		Biodiversity	Biodiversity
		Microplast* OR Nanoplast*	Micro-nanoplastics

combining the terms included in Table 1, and extracting the number of papers published per topic each year. Then, to normalize the number of papers published by topic, the ratio between those papers, and the total papers published on marine monitoring by year, was calculated.

3. Results

3.1 Publications and journals

From the 36,272 papers identified in this study, the number of papers published before 1970 was very low (<6 papers year^{-1}) (Fig. 1). After the publication of the USA Clean Water Act (CWA) and the USA Coastal Zone Management Act, in 1972, and the formation of the UNEP Regional Seas Conventions such as the Oslo, Paris and Helsinki Conventions in

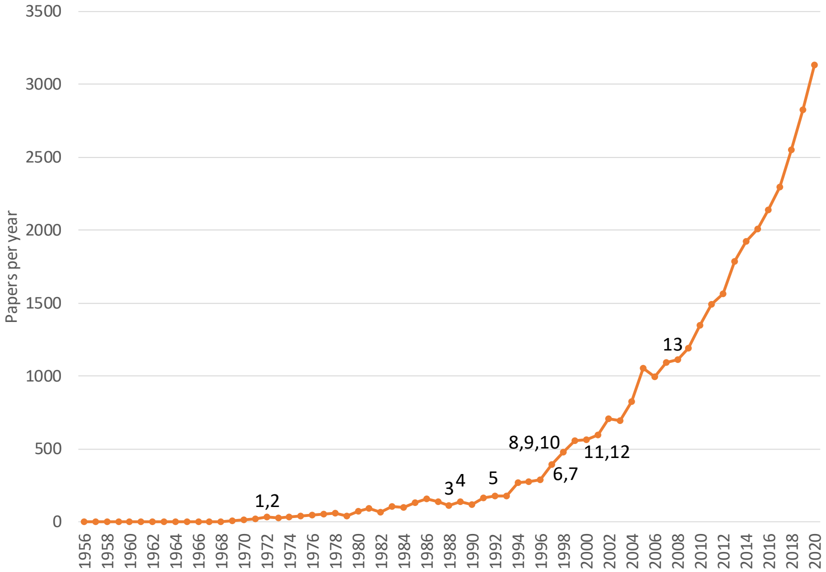

Fig. 1 Number of papers published per year on 'marine monitoring' (1956–2020). Numbers refer to the year of publication of important national or international legislation, implying monitoring implementation: (1) USA Clean Water Act; (2) USA Coastal Zone Management Act; and Oslo, Paris and Helsinki UNEP Regional Seas Conventions; (3) China Law on Water; (4) China Environmental Protection; (5) United Nations Convention on Biological Diversity; (6) Oceans Act, Canada; (7) China Sea Water Quality; (8) Oceans Policy Australia; (9) South Africa National Water Act; (10) USA Harmful Algal Blooms and Hypoxia Research and Control Act; (11) European Union (EU) Water Framework Directive; (12) USA Oceans Act; (13) EU Marine Strategy Framework Directive.

the 1970s, the number of papers started to increase slowly, until ≈140 papers year^{-1}, around the mid-1980s (Fig. 1). From then, and coinciding with several new legislative instruments, there is another increase until ≈300 papers year^{-1}, around the mid-1990s. Between 1997 and 2000, there was much marine legislation implemented in Canada, China, Australia, South Africa and the European Union, among others, showing an inflection point, with a large-scale increase in the number of papers published annually, now reaching >3000 papers year^{-1} (Fig. 1). This also coincided with an increasing number of researchers and an increasing number of authors per paper.

From the total of papers identified, 49.1% have been published by only 80 journals, which have each published at least 50 papers on marine monitoring in the whole studied period (Table 2). From those 17,829 papers, the top-five publishing journals are *Marine Pollution Bulletin* (founded 1970, 24.1% of the papers), *Science of the Total Environment* (1972, 7.8%),

Table 2 Rank of the journals publishing most papers on 'marine monitoring' (only those with at least 50 papers in the period 1956–2020).

Journal	Papers	Journal	Papers	Journal	Papers
Marine Pollution Bulletin	4300	Scientific Reports	138	Journal of Marine Systems	70
Science of the Total Environment	1397	Hydrobiologia	133	Marine Biology	67
Environmental Pollution	817	Journal of Envir. Monitoring	130	PeerJ	67
Envir. Sci. and Tech.	773	Water, Air and Soil Pollution	126	Atmospheric Chemistry and Physics	66
Marine Environmental Research	760	Remote Sensing	122	Int. Journal of Remote Sensing	66
Envir. Monit. and Assess.	708	Aquatic Conserv.: Mar. & Freshw. Ecosyst.	120	Marine Engineers Review	65
Chemosphere	544	Journal of the Mar. Biol. Assoc. of the UK	116	Journal of Chromatography A	64
Plos ONE	487	Marine Technology Society Journal	105	Bulletin of Marine Science	63
Envir. Sci. and Poll. Res.	388	Ecotoxicology	104	Remote Sensing of Environment	62
Envir. Toxicol. and Chem.	278	Journal of Geophysical Research	103	Comparative Biochem. and Physiol.	61
Journal of Envir. Radioactivity	276	Journal of Environmental Management	102	AMBIO	60
Marine Ecology Progress Series	253	Journal of the Acoustical Soc. of America	101	Deep-Sea Res. Part II: Top. Stud. in Oceanog.	60
Archives of Envir. Cont. and Toxicol.	242	Sensors (Switzerland)	99	Applied and Environmental Microbiology	59

Continued

Table 2 Rank of the journals publishing most papers on 'marine monitoring' (only those with at least 50 papers in the period 1956–2020).—cont'd

Journal	Papers	Journal	Papers	Journal	Papers
Frontiers in Marine Science	229	Ecological Applications	94	Huanjing Kexue/ Environmental Science	59
Marine Policy	223	Journal of Exper. Mar. Biol. and Ecol.	93	Aquaculture	58
Ecotoxicol. and Envir. Safety	212	Harmful Algae	90	Int. Journal of Envir. Res. and Public Health	58
Atmospheric Environment	199	Environmental Research	88	Journal of Envir. Science and Health	58
Ocean and Coastal Management	174	Water, Science and Technology	80	Journal of Environmental Sciences	58
Bull. of Envir. Cont. and Toxicol.	169	Nature	78	Polar Biology	57
Ecological Indicators	164	Fisheries Research	76	Marine Mammal Science	56
Journal of Coastal Research	163	Revista de Biología Tropical	76	Conservation Biology	55
Estuarine, Coastal and Shelf Science	160	Biological Conservation	75	Analytical and Bioanalytical Chemistry	54
ICES Journal of Marine Science	157	Marine and Freshwater Research	75	Journal of Marine Science and Engineering	54
Sea Technology	154	PNAS	74	Marine Drugs	53
Aquatic Toxicology	152	Environmental Management	73	Endangered Species Research	50
Water Research	147	Science	73	Regional Studies in Marine Science	50
Environment International	138	Progress in Oceanography	71		

Environmental Pollution (1980, 4.6%), *Environmental Science and Technology* (1967, 4.3%), and *Marine Environmental Research* (1978, 4.3%) (Table 1). The years of founding of these journals reflects the increasing environmental awareness and governance of the marine environment in the 1970s. It is of note that high-impact journals, such as Nature, Science and PNAS, do not publish many papers on marine monitoring, since none of them has published more than 80 papers in the period studied (Table 2).

3.2 Authors and citations

The analysis shows that a total of 89,633 authors have published at least one paper on marine monitoring. For the co-author analysis, those having published at least 15 documents were selected. This selection yielded 641 authors, of which 25 were totally disconnected to any others, leaving 616 for the analysis. These authors have been grouped into 13 clusters, ranging from 3 to 97 authors each (Fig. 2, Table 3).

Since author groupings are based on the publication links, there is a strong association between authors researching in China (clusters 1, 2, 7, 10, and 11), the remaining groups are more dispersed (i.e., Japan, Korea, Europe, North America, Australia) and grouped around different research topics (Fig. 2, Table 3). However, dominance of a few common surnames in China complicates the analysis and may mean attributions of papers is not always accurate (Table 3). It is also of note that authors in one geographical area tend to cite authors from that area, including their own groups.

From the 36,272 papers, only 17 have been cited more than 1000 times (Table 4). The main topics investigated and attracting more attention are plastics and microplastics (6 papers, all of them published in the last 10 years), biodiversity 'sensu *lato*' (4), and climate change (3). All but one of these 17 papers have been published after 2000 (Table 4). Six out of the 17 most cited papers have authors who do not belong to any of the above-mentioned clusters. From the remainder, 4 papers are from cluster 3, 4 from cluster 4, and one from clusters 2, 6 and 8, respectively (Table 4).

3.3 Topics investigated

A total of 123,861 keywords were identified, and for the analysis the 784 terms with a minimum of 75 co-occurrences were selected. In total, six clusters were identified (Fig. 3, Table 5), with the most populated being Cluster 1, with 280 items. This large group seems more related with monitoring of coastal ecosystems, mainly with ecological topics and biodiversity, including impacts, the quality of the system (i.e., health) and management, including conservation-protection and climate change (Table 5).

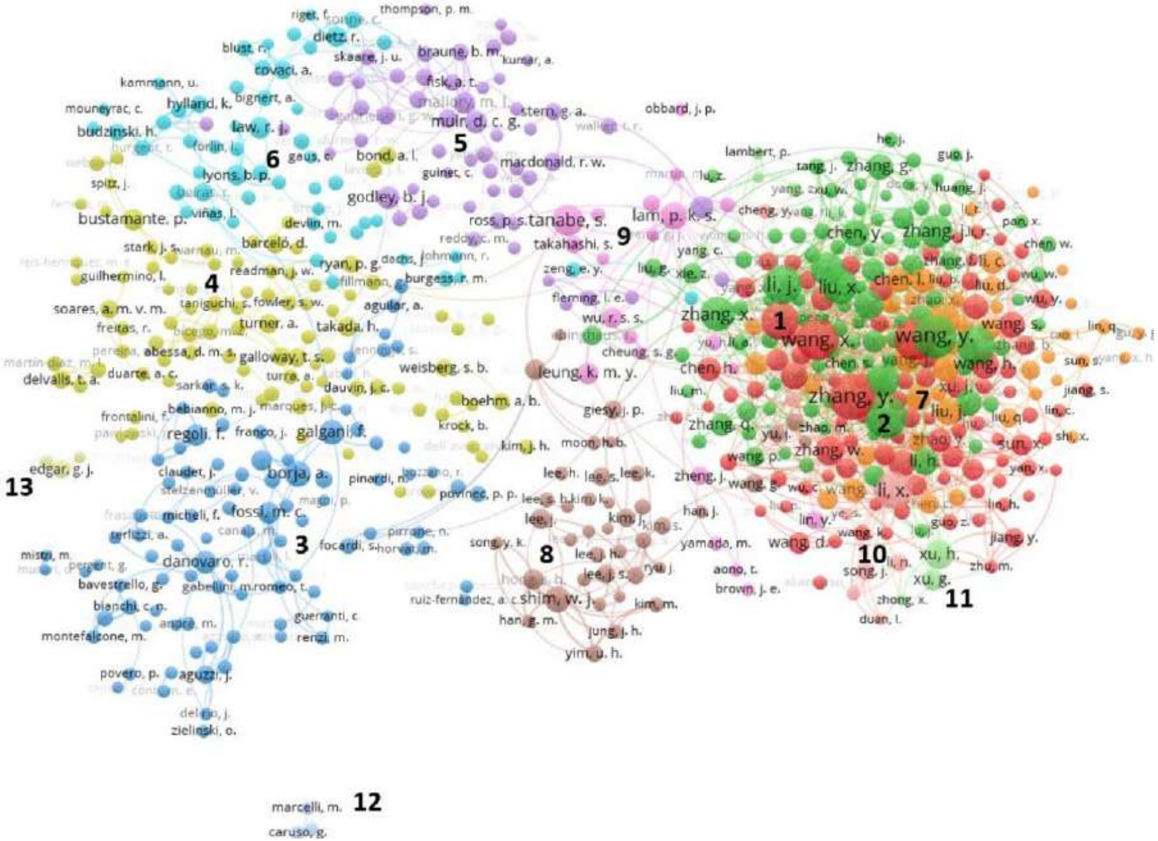

Fig. 2 Clusters (bubbles in same colour, identified by numbers) of authors having published at least 15 papers on marine monitoring, together with the links among them (lines in same colour).

Table 3 Three main authors within each cluster identified in Fig. 2, by number, colour and number of items (authors within the cluster).

Cluster	Colour	Items	Name	Papers	Links	Name	Papers	Links	Name	Papers	Links	Main Topics	Area
1	Red	97	Zhang, Y.	200	506	Wang, X.	175	489	Li, Y.	163	400	Organic pollutants	China
2	Green	96	Wang, Y.	180	497	Wang, J.	175	449	Zhang, H.	112	275	Biology and chemistry	China
3	Dark Blue	95	Borja, A.	67	68	Galgani, F.	62	61	Danovaro, R.	49	88	Indicators and policy	Europe
4	Yellow	93	Bustamante, P.	47	42	Barceló, D.	39	21	Turner, A.	38	4	Bioindicators and accumulation	Europe
5	Purple	57	Muir, D.C.G.	52	89	Godley, B.J.	52	56	Mallory, M.L.	46	74	Trends and biomagnification	Arctic
6	Blue	54	Law, R.J.	44	22	Dietz, R.	43	74	Lyons, B.P.	42	63	Organic pollutants and bioaccumulation	North Europe
7	Pale brown	41	Zhang, L.	100	262	Liu, J.	73	172	Zhao, J.	66	180	Technologies	China
8	Dark brown	40	Shim, W.J.	64	170	Lee, J.	43	66	Hong, S.H.	40	113	TBT, microplastics, etc.	Korea
9	Rose	21	Tanabe, S.	93	100	Lam, P.K.S.	73	188	Leung, K.M.Y.	45	56	Trends and bioaccumulation	Japan
10	Pale red	8	Li, X.	131	378	Song, J.	33	106	Li, N.	29	94	Organic pollutants	China
11	Pale green	8	Xu, H.	84	180	Xu, G.	44	90	Lambert, P.	17	30	Plankton, hydrocarbons, etc.	China, Pacific
12	Pale blue	3	Caruso, G.	22	19	Zappalà, G.	20	22	Marcelli, M.	17	17	Microbial pollution	Italy
13	Pale yellow	3	Edgar, G. J.	32	24	Barrett, N. S.	21	14	Stuart-Smith, R. D.	15	19	Conservation, protection	Australia

For each author, the number of papers published about marine monitoring and the total link strengths are shown. For each cluster, the main topics and main research area are shown.

Table 4 References cited >1000 times in marine monitoring, authors cluster in which they are associated (as in Fig. 2), and topics investigated.

Citations	Cluster	References	Years since publication	Topic
3169	2	Chen et al. (2003)	18	Quantification of dissolved organic matter
2344	None	Tilman et al. (2001)	20	Global environmental change
2216	None	Andrady (2011)	10	Microplastics
2127	None	Akyildiz et al. (2005)	16	Acoustic sensors
1802	4	Cole et al. (2011)	10	Microplastics
1775	8	Giesy and Kannan (2001)	20	Distribution of perfluorooctane sulfonate
1752	3	Orth et al. (2006)	15	Seagrass crisis
1545	4	Browne et al. (2011)	10	Microplastics
1505	3	Eriksen et al. (2014)	7	Plastic pollution
1478	4	Hidalgo-Ruz et al. (2012)	9	Microplastics identification methods
1428	4	Wright et al. (2013)	8	Microplastics impacts
1294	None	Anderson et al. (2006)	15	Beta diversity
1182	6	Hobson (1999)	22	Stable isotopes
1176	None	Pörtner and Knust (2007)	14	Climate change and fish
1168	None	Hare and Mantua (2000)	21	Regime shifts
1039	3	Coll et al. (2010)	11	Biodiversity
1017	3	Borja et al. (2000)	21	Biotic index to assess ecological status

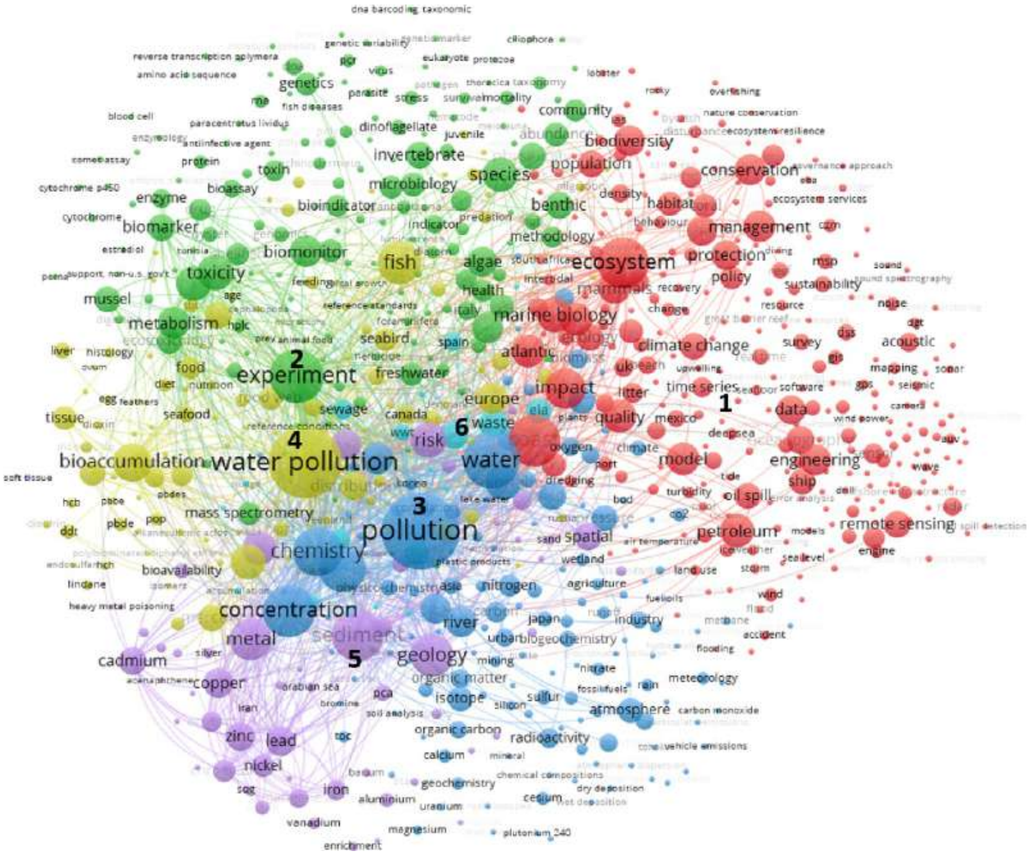

Fig. 3 Clusters (bubbles in same colour, identified by numbers) of keywords co-occurring at least 75 times, together with the links among them (lines in same colour).

Table 5 Top-10 keywords with more occurrences and links, within each cluster defined in Fig. 3).

	Cluster 1	**Cluster 2**	**Cluster 3**	**Cluster 4**	**Cluster 5**	**Cluster 6**
Colour	Red	Green	Dark blue	Yellow	Purple	Pale blue
Items	280	163	145	113	61	22
Keyword 1	Coast	Experiment	Pollution	Water pollution	Sediment	Waste
Occurrences	5466	5844	11,739	10,430	5204	1679
Links	86,255	102,791	183,059	175,932	87,473	27,447
Keyword 2	Ecosystem	Toxicity	Water	Fish	Geology	Plastic
Occurrences	5187	2537	6184	3754	3650	1574
Links	74,447	43,218	96,081	54,080	65,766	23,197
Keyword 3	Impact	Mollusc	Concentration	Bioaccumulation	Metal	EIA
Occurrences	3309	2404	5355	2926	3415	1320
Links	51,666	39,420	99,771	55,749	63,927	22,208
Keyword 4	Marine biology	Species	Chemistry	Organic pollutant	Risk	Discharge
Occurrences	2514	2354	4861	2458	2535	1302
Links	34,794	37,053	84,385	42,573	41,642	22,778
Keyword 5	Quality	Metabolism	Analysis	Europe	Lead	Microplastic
Occurrences	2261	2053	4258	1928	1839	886

Links	33,028	36,106	78,549	29,856	41,466	13,801
Keyword 6	Management	Biomonitor	Seasonality	Distribution	Copper	Sewage
Occurrences	2066	2047	2429	1531	1809	819
Links	24,433	31,599	40,371	26,863	40,299	14,806
Keyword 7	Biodiversity	Biomarker	Sampling	Exposure	Estuary	Spain
Occurrences	1950	1521	2079	1505	1768	675
Links	27,363	25,906	34,246	27,477	31,056	10,834
Keyword 8	Conservation/ Protection	Physiology	River	Mercury	Zinc	WWT
Occurrences	1903/1797	1432	1864	1505	1643	573
Links	23,797/23447	22,104	32,136	29,633	37,622	9410
Keyword 9	Ecology	Ecotoxicology	Temperature	Biochemistry	Cadmium	
Occurrences	1518	1230	1445	883	1624	
Links	23,157	22,401	21,549	18,187	36,350	
Keyword 10	Climate change	Phytoplankton	Atmosphere	Pesticide	Spatial	
Occurrences	1472	1135	1318	786	1578	
Links	16,953	16,605	17,998	14,203	24,654	

The colour and number of items within each cluster are indicated. EIA: Environmental Impact Assessment; WWT: Wastewater Treatment.

Cluster 2, with 163 items, seems related to experimental approaches especially monitoring toxicity and doing ecotoxicological experiments, using biomonitors (especially of ecological taxonomic components, e.g., molluscs and phytoplankton) and biomarkers, including the physiology and metabolism of species (Fig. 3, Table 5). Cluster 3, with 145 items, is related to monitoring water quality and pollution in waters, probably coming from land run-off, rivers and atmosphere, from a sampling and analytical point of view (e.g., chemistry, concentrations, seasonality, etc.) (Fig. 3, Table 5).

Cluster 4, with 113 items, is also dealing with monitoring water quality and pollution, especially the biochemistry and bioaccumulation (as contamination) in some components (i.e., fish), mainly focusing on the exposure to organic pollutants, mercury and pesticides (Fig. 3, Table 5). In turn, Cluster 5, with 61 items, focuses on monitoring sediments, including the biogeochemistry of specific elements, geology and estuaries, studying the spatial distribution and risks mainly of trace and heavy metals (i.e., lead, copper, zinc and cadmium, among others) (Fig. 3, Table 5). Finally, Cluster 6, with only 22 items, is dealing with monitoring sewage, point-source discharges and wastes (including waste-water treatment), as well as plastics and microplastics (Fig. 3, Table 5).

3.4 Evolution of selected topics

It is of value to compare the monitoring of what may be termed 'classical topics', i.e., those studied over many decades, with 'emerging topics', i.e., those in recent years. 'Classical topics' were considered those with the first paper published before 1980, whereas 'emergent topics' were those which started to be published mainly after 1980. The trajectories of the published papers per classical and emergent topics and total papers published by year are compared in Fig. 4, standardized as a ratio of papers published against total papers, using terms selected from the clusters in Fig. 3.

Within the classical group, the highest ratio has been usually that of 'metals', but since mid-1990s the topic started to decrease from ratios of approx. 0.18 to ratios currently approx. 0.12 (Fig. 4). The generic term 'waste', which had very high ratios at the beginning of the series, was decreasing from early 1980s to 2015, with a sharp increase afterwards, presenting now the highest ratio of all words (Fig. 4). The ratio for 'toxicity' increased from the early 1970s to 2003, with a slight decrease or becoming stable until now (Fig. 4). The term 'noise', which presented some high ratios

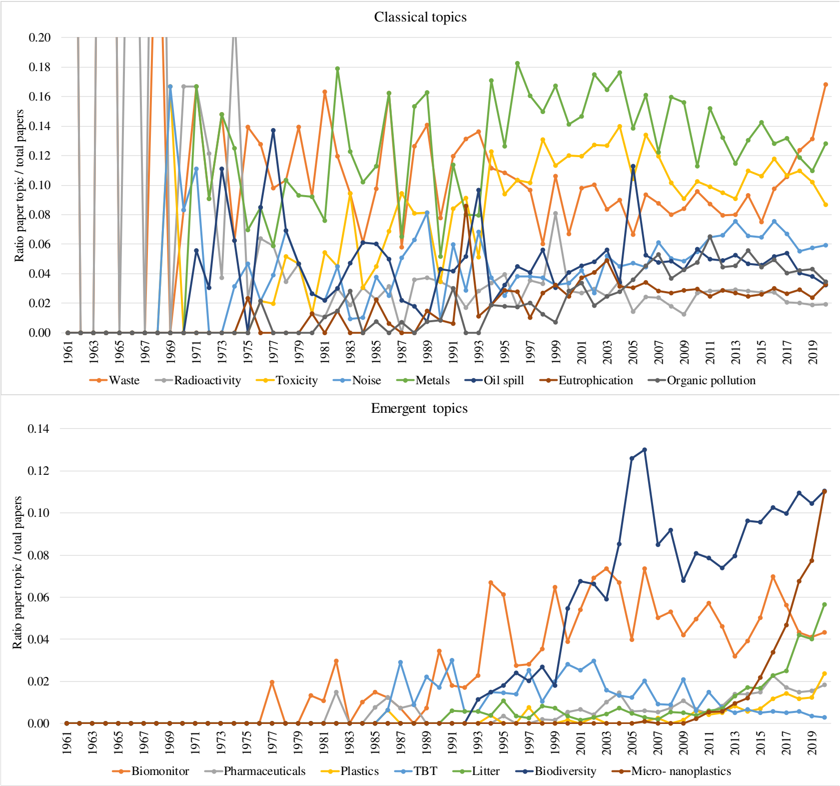

Fig. 4 A comparison of the trajectories of published papers per topic (given as a ratio with total papers) published by year, for 'classical' (above) and 'emergent' topics (below).

very early, then decreased and has been increasing progressively and slightly from the 1990s to now (Fig. 4). The remaining terms (radioactivity, oil-spill, eutrophication and organic pollution) present some stable ratios, especially in the last 20 years (Fig. 4), although there is some 'peakedness' of these topics associated with major marine events such as high-profile oil-spills and nuclear accidents.

In turn, most of the emergent topics present important increases in their ratios, especially biodiversity (after 1999), and litter and micro-nanoplastics (after 2011); others present some stability or slight increases (e.g., biomonitors, pharmaceuticals and plastics), and only TBT has decreased since 2000 (Fig. 4). The most notable and order of magnitude increase is that of micro-nanoplastics, from a ratio of 0.01, in 2013, to 0.11 in 2020 (Fig. 4).

4. Discussion

This review shows a clear relationship between the legislation, either national or international (driving the need for assessing the status of aquatic systems, after Borja et al. (2008)) and marine monitoring publication, due to the need to undertake some controls on pollutants. This is particularly noticeable after the publication of the US CWA and the UNEP Regional Seas Conventions, in the 1970s. However, the highest increase was after the publication of several legislative instruments in Canada, USA, and Europe, at the end of the 1990s and early 2000s, which integrate different ecosystem components (i.e., physico-chemistry, phytoplankton, macroalgae, macroinvertebrates, fishes, mammals, etc.), under an ecosystem-based approach (Borja et al., 2008). A particular example is the large and integrated amount of marine legislation in the European Union, covering all areas of competence from fisheries to alien species and nutrient to renewable energy (Boyes and Elliott, 2014). This integrated approach required innovative monitoring approaches (Danovaro et al., 2016; Mack et al., 2020) and represented an inflection point in the number of publications on marine monitoring.

Most of the monitoring papers are published in journals established in the 1970s (e.g., *Marine Pollution Bulletin, Science of the Total Environment, Environmental Pollution, Environmental Science and Technology, Marine Environmental Research*), partly in response to the increasing interest in monitoring pollution, but at the same time reflecting and stimulating the interest in these topics (Sheppard et al., 2021). This also seems to reflect a ‘snowballing’ effect in which a topic which is in vogue creates an increase in publications in that topic. However, it is of note that high-impact journal editors (e.g., in *Nature, Science*) seem not to be interested in marine monitoring, despite the fact that most systematic information for global analyses (i.e., climate change, conservation, pollution issues, etc.) comes from monitoring (Lamborg et al., 2014; Smetacek and Cloern, 2008). Paradoxically, monitoring appears to be not regarded by some editors as cutting-edge science and is merely repeating analyses in other areas. Because of this, it is of note that journals have been set up dedicated to regional approaches, such as *Regional Studies in Marine Science*, set up by Elsevier in 2015 to take geographical case-studies for which there was either no space in their other journals or where the papers were deemed by the Editors-in-Chief of those other journals to be of local interest; however, while those papers provide valuable data for comparison, they do not give ground-breaking fundamental concepts. Again, it is of note that, in the case of *Marine Pollution Bulletin*, in order to publish such monitoring datasets, it introduced *Baseline* in 1982 (Sheppard et al., 2021). In contrast to the attitude of high-impact journals, new open-access journals are being successful in publishing papers on marine monitoring, such as *Plos ONE*, which ranks 8th publishing on this topic (the journal was set up in 2006), and *Frontiers in Marine Science*, fully devoted to marine topics, which was launched in 2014 and ranks 14th. Finally here, we emphasize that due to the perception that 'monitoring is not real science' then most monitoring and the assessment from it will be in grey literature and usually carried out by regulatory bodies and industries, for whom publishing in peer-reviewed journals is not an important task.

Despite the large number of authors publishing in marine monitoring (near 90,000), only a relatively low number of them (616) have published regularly on the topic (i.e., at least 15 papers). The most prolific authors, with >100 papers, have Chinese names (e.g., Zhang, Wang or Li, see Table 3). However, when looking in detail to the papers published, it seems that some of them are in fact two or more different persons, since the themes and affiliations are too disparate. This is possibly because there are thousands of Chinese surnames, yet the 129 most common ones are used by about 87% of the people (Hui, 2007). Unfortunately, we were not able to obtain the ORCID or other researcher identifier numbers of the authors, which could solve this problem.

There has been an increase in numbers of authors per paper with research now being team-based or project-based with the need to credit all of those involved in the research, no matter how small a role (Baethge, 2008). Most of the authors' groups identified here are related to prolific projects, e.g., DEVOTES www.devotes-project.eu, MESMA www.mesma.org, or VECTORS www.marine-vectors.eu/, which join authors in cluster 3, around marine management and assessment (see Borja et al., 2016b); or GLOBAQUA www.globaqua-project.eu and SOLUTIONS www.solutions-project.eu, around the pollutants topic, in cluster 4 (Fig. 2, Table 3). Hence, collaborative projects across nations have greatly enhanced the publication links among authors with diverse affiliations, allowing to an internationalization of marine monitoring research.

It is interesting to note that, from the 104 authors participating in the 17 papers most cited in marine monitoring, only 21 are within the 857 authors in the top 2% of scientists most cited in the field of Marine Biology through their whole careers (Ioannidis et al., 2020). This indicates that marine monitoring is not a topic attracting much attention from most highly-cited scientists, with the exception of a few cases. It is also interesting to note that these highly-cited authors are mainly based on Spain (6 authors), USA (5 authors) and Italy (2 authors), while in Saudi Arabia, UK, South Africa, Chile, Canada, Israel, New Zealand and France, there are one author per country, and none in China, despite the high number of authors there. In most cases, these authors are related to the implementation of some European legislation (e.g., Water Framework Directive (WFD; 2000/60/EC) or MSFD), which have required an increasing effort in marine monitoring and assessment (Borja et al., 2010).

The clusters of topics identified, as well as their trajectories, are intimately related. Hence, early in the 1960's radioactivity was one of the hottest topics, after the tests of atomic bombs in some Pacific atolls and the advent of the first nuclear power plants. The destruction of habitats and biodiversity, as well as the introduction of long-term effects of contamination by radioactivity, attracted the interest of the scientific community, with none of the other topics, except metals at that time. Furthermore, the high profile of the main nuclear accidents (Three Miles Island, in 1979; Chernobyl, in 1986; and Fukusima, in 2011), led to increases in the ratio of publications within a few years of the accident (Lin et al., 2015).

Another early topic was that on oil-spill pollution monitoring, as prompted by the Torrey Canyon wreck (1967), releasing 119,000 t, and then after each major oil-spill accident (especially in the 1970's and the 1980's, with at least 15 major accidents releasing 2.2 million tons of oil to the seas) there has been an increased awareness (Borja and Elliott, 2019). With better safety and ship-design measures, and perhaps with a reduced movement of oil, there appears to have been a reduction in the very large oil-spills and in turn monitoring of hydrocarbons in the environment.

Eutrophication monitoring started to increase at the end of the 1960's, when untreated wastewater discharges from coastal cities started to produce the adverse signs and symptoms from organic matter inputs and production: anoxia, bad smell, fish kills, harmful algal blooms or bathing water bad quality, among other problems (e.g., Orive et al., 2002). This topic peaked around the 1990s, probably due to the adoption of different legislation worldwide addressing this problem, with the obligation for monitoring and assessment (CWA in USA, in 1972; the Nitrates Directive, Urban Waste-water Treatment Directive and WFD, in Europe, in 1991, 1991 and 2000, respectively) (Elliott and de Jonge, 2002).

Metal contamination started to attract attention after the 1956 Minamata disease problem in Japan with mercury, increasing the ratio of publication until 1995–2003 and decreasing or stabilizing after those dates.

Perhaps Minamata disease was the first attempt to link inputs of the contaminant to levels in the environment and then the biological repercussions throughout various ecological components ended in health problems and deaths for the human population eating contaminated seafood (Kessler, 2013). This indicates the move from monitoring to detect the contamination in waters and biota, to investigative monitoring to determine cause-effect pathways of risk, to determining pollution per se (as adverse biological responses, Rodrigues et al. (2021)) and then to management responses. This and other environmental catastrophes involving metal spillages (such as those in the Doñana National Park in southern Spain, in 1998, Riba et al., 2002), together with the development of the Atomic Absorption Spectrophotometer, allowing contaminants to be accurately monitored, enhanced the need for and ability to achieve the monitoring. Furthermore, there was an increase in national and regional legislation requiring contaminants to be monitored (e.g., CWA, WFD, MSFD, and Priority Substances Directive (PSD), in 2013) (Borja and Elliott, 2019). The European Dangerous Substances Directive in 1976, together with its ‘Daughter’ Directives on mercury, pesticides, other organohalogens, etc. (all of which were absorbed into the WFD) also gave impetus to monitoring and, for the first studies working on such problems, the ability to get the work published in international journals. This again indicates that novel monitoring is worthy of publication whereas subsequent studies would not be recorded in a publication analysis as they would probably be reported only in the grey literature (thereby contributing to the 2.4 million articles identified currently by GoogleScholar under the search for ‘marine monitoring’).

Persistent organic pollutants leading to sublethal effects, detoxification mechanisms and biological anomalies have attracted monitoring attention since the 1980s and increasing until now. This was particularly noticeable in the high-profile case of tributyl-tin (TBT), used in boat paintings to avoid encrusting organisms, and the monitoring of its main effects such as imposex in neogastropods (e.g., in dog-whelks) or golf-ball shape in oysters. The first papers appeared in the early 1970s (Blaber, 1970), which then led to the ban introduced by the International Maritime Organization (proposed in 1999, approved in 2003 and entering into force in 2008) (IMO, 2008), perhaps the best example of monitoring science leading to a global change in the use of chemicals. In addition, the subsequent monitoring led to excellent examples of the science having an immediate effect on the use of chemicals, with extensive reduction in the impacts on the environment (Schøyen et al., 2019; Wilson et al., 2015). However, the interest on TBT monitoring research has decreased dramatically in recent times, after achieving the objectives of impact reduction with some journals, such as *Marine Pollution Bulletin*, taking an editorial decision to reduce the acceptance of papers on TBT and imposex (Dr Charles Sheppard, Pers. Comm.). This was possibly due to the rise of what has been called '*me too* papers' in which the marine monitoring research was investigating the same effects but on new species and new places.

The decreasing interest in some 'classical' monitoring topics (such as radioactivity, metals, oil-spills, TBT) has been replaced by other topics, such as noise, pharmaceuticals, biodiversity, litter and (micro)plastics. In some cases, this is due to their inclusion in legislation, such as the MSFD or the PSD, making compulsory their monitoring and assessment (Galgani et al., 2013; Patrício et al., 2016). That increase started with the topics being raised by the public, media, environmental non-governmental organizations, industry or regulators.

The plastics contamination and pollution constitute a particularly unique example. The study of plastic and litter pollution at sea started as early as at the end of the 1960s (Coe and Rogers, 1997); however, it was in 1981 and 1987 (Wolfe, 1987), respectively, in which the studies on these pollutants started to be regularly published. Despite this, the latest in vogue topic is micro- and nanoplastics, which started to be studied on a regular basis in 2009 (Barnes et al., 2009), interestingly after the approval of the European MSFD, in 2008, which includes among the eleven descriptors to be monitored and assessed one on marine litter/microplastics (European Commission, 2008). After 2014, this topic has experienced an exponential publication trend, and micro- and nanoplastics, together with ocean litter, are shown as the most downloaded papers in many marine journals. In fact, 6 out of 17 most cited papers on marine monitoring are related to plastics and microplastics. In the case of the journal publishing more papers on marine monitoring (*Marine Pollution Bulletin*) the first and second most cited papers are reviews on microplastics (Andrady, 2011; Cole et al., 2011), with the third being a review on marine litter and plastics (Derraik, 2002).

When referring to marine monitoring, many of the earlier papers seem to be concerned more with 'contamination', as the presence of the materials in the environment, rather than 'pollution' per se, as the biological and environmental effects of that contamination (Borja and Elliott, 2019). However, there are notable changes in recent years, focusing more on experimental-based approaches (Rodrigues et al., 2021), and especially on topics related to the Ecosystem Approach and Ecosystem-based Management (Kirkfeldt, 2019), climate change, and holistic approaches to monitoring (Elliott and Whitfield, 2021; Sheppard et al., 2021). This includes the effects of different human pressures on ecosystems, and not only considering pollution as the main driver of marine monitoring (Halpern et al., 2008). It is of note that the highest priorities in marine management are now described as non-indigenous species and habitat loss as well as overfishing (Pörtner et al., 2021). The Ecosystem Approach can be summarized as 'the ability to maintain and enhance the ecological structure and functioning while at the same time ensuring the seas to deliver ecosystem services from which society derives goods and benefits' (e.g., Elliott et al., 2020). This is leading to more papers linking the natural and social sciences and so eventually to joint monitoring of natural environmental and socio-economic features, as epitomized by the growth in studies on ecosystem services and societal goods and benefits (Turner and Schaafsma, 2015). This emphasizes that solutions to marine problems require a multidisciplinary approach involving natural and social sciences.

Despite the increasing number of publications on marine concerns, and the importance of marine monitoring to address current important topics, such as biodiversity loss, climate change or pollution (United Nations, 2021), economic crises have led many monitoring bodies to reduce budgets (Borja and Elliott, 2013). These reduced budgets result in several evident ways to obtain savings, such as reducing the number of sampling elements, locations and samples (De Jonge et al., 2006), a reduced frequency of sampling (Abramic et al., 2012), and looking for cheaper monitoring (Lampadariou et al., 2005) and assessment (Pawlowski et al., 2018) methods, or suppressing core science (National Research Council, 2015). Also, in some cases, the retirement of the scientists involved can compromise the continuity of the long-term monitoring (Beukema and Dekker, 2020)—with the loss of those 'champions' then it is easier for environmental managers and funders to reduce the monitoring. However, there are less-evident ways in which monitoring bodies have saved money, but at the same time reducing the quality of the information collected. For example, we earlier (Borja and Elliott, 2013) identified some of them: (i) use of presence/absence of an ecological component instead of abundance (Bates et al., 2007); (ii) use of high taxonomic levels (a lower taxonomic separation, e.g., family instead of species) (Warwick, 1988); (iii) reducing biological samples (which require people with skills instead of machines); (iv) resistance to adopting analytical quality assurance/quality control (AQC/QA) for biological analyses (Elliott, 1993; Gray and Elliott, 2009); and (v) the paradox of the precautionary principle, e.g., a developer may be required to detect an impact of a given magnitude which, because of the inherent variability in the system, may require a large degree of replication but budgets will dictate that so few replicates are taken that there is no chance of detecting an effect (Franco et al., 2015; Gray and Elliott, 2009).

As we commented in Borja and Elliott (2013), these examples imply a 'short termism' and could be costly in coming years. Reducing monitoring information could result in an inability to detect both near- and far-field effects of an activity and the absence of adequate data to implement new requirements (e.g., use of functional traits, long-term monitoring series to track biological invasions, climate change or trends towards baselines). The disruption of consistent monitoring over the long-term or larger areas will eventually prevent spatial and temporal patterns being interrogated, with a resulting uncertainty in the form and efficacy of management measures (Borja et al., 2016a).

Despite this panorama, unexpectedly the COVID-19 disease could be an ally to problem-orientated and coherent marine monitoring. In fact, the COVID crisis has demonstrated that science can advance faster in solving problems if previous information is available, if scientists and managers cooperate and the knowledge is open to society (Belli et al., 2020). The demonstration that there are close links of nature and marine biodiversity (Bates et al., 2020; Hentati-Sundberg et al., 2021) and human health (Pouso et al., 2021), can move the scientific system towards a research agenda requiring more and better marine monitoring (Borja et al., 2020b, 2020a). This will ensure that rigorous and scientifically defendable data are obtained, under a long-term basis to take marine management.

5. Conclusions

The analysis here has demonstrated that marine monitoring has provided an important role in quantifying the spatial and temporal extent and magnitude of marine concerns, and it has produced data which both indicate the need for marine management as well as showing the effectiveness of that marine management. Indeed, in any field, it has been said that 'you cannot manage something unless you can measure it'. Similarly, one cannot predict the trajectory of a pressure and response unless one has the empirical data on which to base predictive and descriptive models.

The patterns here have allowed us to propose the conceptual model (Fig. 5) which aims to show the sequence at which marine problems arise,

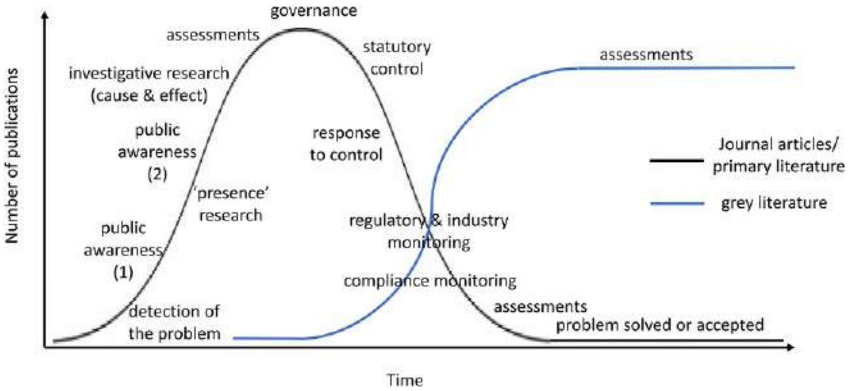

Fig. 5 Conceptual model showing the sequence of marine problems and concerns, their monitoring and the resulting journal and grey literature publications (see text).

are subjected to certain types of monitoring, investigation and assessment and then lead to regulation and control before being removed, in some cases, from public consciousness.

This model separates monitoring as it appears in journals and primary literature, as carried out often by research laboratories and academia, from that which then is only reported in the grey (unpublished but publicly available) literature such as reports from environmental protection agencies, industry and non-governmental organizations. The model indicates that public awareness sometimes raises the topic of concern which can then be studied and monitored (for example radioactivity, case 1, in Fig. 5) but also that, for example in the case of litter, that research and monitoring is responsible for raising the topic in the media and then in public minds (case 2, in Fig. 5). We suggest that assessments can be made at various places—both as research and also as the result of fulfilling legal requirements for reporting the status of the seas. As shown by the examples for TBT, this process then ends with the marine problem being solved—an optimistic conclusion given the nature, extent and magnitude of marine problems which require to be monitored. Unfortunately, an alternative to the problem being solved is that society accepts and adjusts to the problem and tolerates the status of the seas.

In any case, we conclude and emphasize that long-term marine monitoring, although neglected by some highly-rated journals and editors in accepting papers devoted to this topic, has demonstrated its high value when addressing most of the problems that ocean is facing, created by human activities and pressures at sea. Hence, with this research we emphasize the importance of maintaining and expanding these long-term monitoring networks as the most important way to solve these problems, by identifying and assessing them, and proposing the adequate management measures to achieve healthy seas—the overall aim of several global ocean-related initiatives for the next decade.

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