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Bridging the Gap between Policy and Science in Assessing the Health Status of Marine Ecosystems

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Human activities, both established and emerging, increasingly affect the provision of marine ecosystem services that deliver societal and economic benefits. Monitoring the status of marine ecosystems and determining how human activities change their capacity to sustain benefits for society requires an evidence-based Integrated Ecosystem Assessment approach that incorporates knowledge of ecosystem functioning and services). Although, there are diverse methods to assess the status of individual ecosystem components, none assesses the health of marine ecosystems holistically, integrating information from multiple ecosystem components. Similarly, while acknowledging the availability of several methods to measure single pressures and assess their impacts, evaluation of cumulative effects of multiple pressures remains scarce. Therefore, an integrative assessment requires us to first understand the response of marine ecosystems to human activities and their pressures and then develop innovative, cost-effective monitoring tools that enable collection of data to assess the health status of large marine areas. Conceptually, combining this knowledge of effective monitoring methods with cost-benefit analyses will help identify appropriate management measures to improve environmental status economically and efficiently. The European project DEVOTES (DEVelopment Of innovative Tools for understanding marine biodiversity and assessing good Environmental Status) specifically addressed these topics in order to support policy makers and managers in implementing the European Marine Strategy Framework Directive. Here, we synthesize our main innovative findings, placing these within the context of recent wider research, and identifying gaps and the major future challenges.

Keywords: environmental status, marine health, status assessment, management, ecosystem approach, socio-ecology

INTRODUCTION

A recent assessment of marine ecosystem ecology identified eight grand research challenges (Borja, 2014): (i) understanding the role of biodiversity in maintaining ecosystem functionality; (ii) understanding the relationships between human pressures and ecosystems; (iii) understanding the impacts of global change on marine ecosystems; (iv) developing integrative assessment of marine ecosystem health; (v) ensuring delivery of ecosystem services by conserving and protecting the seas; (vi) understanding the way in which ecosystem structure and functioning may recover through restoration; (vii) understanding the need for an ecosystem approach and integrated spatial planning in managing ocean use, and (viii) developing better ecosystem models to support more effective management.

These challenges reflect widespread recognition of clear effects of pressures from established and emerging human activities on marine ecosystems (Halpern et al., 2015) and, consequently, the potential of those pressures to alter the ability of ocean ecosystems to provide services that yield societal and economic benefits (Barbier et al., 2012; Turner and Schaafsma, 2015). Given the multiple pressures society places on marine ecosystems and the broad range of services they provide, a holistic assessment (Borja et al., 2016) of the status of marine ecosystems requires scientific evidence-based Integrated Ecosystem Assessments (IEA; Levin et al., 2009). Indeed, the former European Commissioner for Environment, Janez Potočnik, stated during the closing session of Euromares 2010, on the occasion of the European Maritime Day, that: "*We are learning that the* [Marine Strategy Framework] *Directive has a weakness—and that weakness is the lack of knowledge*." With a lack of knowledge "*...these unknown variables pose a real problem for decision-makers. They need to be identified and addressed in a systematic way. And while we need to acknowledge the differences and diversity of our seas, there are some issues which can only be adequately addressed on a European scale.*" These statements capture the desire of policy-makers and managers worldwide to fulfill their moral mandate to conserve and protect the seas (Reker et al., 2015) using evidence-based decision-making. Hence, the vision for clean, healthy, biodiverse, and productive oceans and seas with sustainable resource use requires bridging the gap between policy and science in assessing the status of marine ecosystems by increasing scientific knowledge of marine ecosystems and their functioning, including humans and their role as part of the ecosystem (Borja et al., 2013). Indeed, recent European and national policies enshrine the vision of healthy and biologically diverse seas (e.g., DEFRA, 2002; European Marine Board, 2013). More recently, the European Union and United Nations have tried to address problems associated with exploitation of deep fishing resources and associated impacts on biodiversity (St. John et al., 2016).

The development and implementation of policy and legislation globally demonstrate a significant effort to improve the status of the seas, including an ecosystem approach to ocean use management (Browman et al., 2004; Nicholson and Jennings, 2004; Borja et al., 2008, 2016; Curtin and Prellezo, 2010). In the European Union (EU), the Marine Strategy Framework Directive (MSFD; European Commission, 2008) represents the most comprehensive marine environmental legislation. This Directive aims to achieve Good Environmental Status (GES) by 2020 in the four European Regional Seas (Baltic, North Eastern Atlantic, Mediterranean and Black Sea). The MSFD requires that Member States assess ecosystem characteristics, pressures, and impacts with respect to 11 descriptors related to: biological diversity, non-indigenous species, commercial fish and shellfish, food-webs, eutrophication, seafloor integrity, hydrographic conditions, concentration of contaminants in the environment and in fish and other seafood consumed by humans, marine litter, and introduction of energy including underwater noise. Within these 11 descriptors, the European Commission (2010) then defines 29 criteria and 56 indicators necessary in evaluating environmental status.

The assessment of environmental status, while scientifically challenging (Stanley, 1995), simultaneously offers many opportunities for European marine research to support an ecosystem approach to environmental management, which EU Member States have agreed to implement (Borja et al., 2013). The European project DEVOTES (DEVelopment Of innovative Tools for understanding marine biodiversity and assessing GES, www.devotes-project.eu) was started in 2012 to facilitate MSFD implementation. This project considers these complex, inter-related scientific issues and management needs of the MSFD, as well as the challenges shared by the four regional seas identified within the MSFD. Its main objectives were:

- To improve understanding of the cumulative impacts of human activities on marine biodiversity and variation associated with climate, identifying the socio-economic and legislative barriers and bottlenecks that prevent achieving GES;
- To test indicators currently in use (European Commission, 2010) and develop new assessment options, particularly for biodiversity-related descriptors (i.e., D1. Biological diversity, D2. Non-indigenous species, D4. Food-webs, and D6. Seafloor integrity), at several ecological levels (species, habitat, ecosystems), and characterize and classify status of marine waters;
- To develop, test and validate innovative integrative modeling and cost-effective monitoring tools to strengthen understanding of ecosystem function and biodiversity changes in space and time associated with human impacts, including climatic influences.
- To propose and disseminate strategies and measures for adaptive management of ecosystems, including integrative and holistic tools to assess environmental status.

We therefore set an overall goal of better understanding the relationships between pressures from human activities and climate change, and their effects on marine ecosystems, including biological diversity, in order to support ecosystem-based management and attain GES of marine waters. Our harmonized approach to the four European regional seas tested and validated existing indicators, created new indicators when necessary, developed modeling tools for the assessment of biodiversity, tested new monitoring tools and established an integrative approach for assessing environmental status.

This overview describes how this research has contributed to advancing the state-of-the-art since 2012 in bridging the gap between science and policy in marine environmental status assessment. Specifically, this addresses elements such as human pressures, indicator development, model use, innovative monitoring, and integrative assessment tools), in order to achieve healthy and sustainable ocean use. Here we synthesize key responses to major environmental questions and the lessons learnt. This information will support managers and policy-makers in making decisions for improved management of ocean use.

WHY MUST WE UNDERSTAND IMPACTS OF HUMAN ACTIVITIES AT SEA?

State-of-the-Art

Marine environmental managers primarily aim to protect and maintain natural structure and functioning while simultaneously ensuring that ecosystems provide services, which in turn deliver benefits for society (Atkins et al., 2011; Elliott, 2011). In the management of human activities in the marine environment, it is axiomatic that a regulatory body (i.e., an environmental protection agency, natural conservation body, fisheries body, or marine licensing body), does not have to prove that an activity or its developer (the "user," "polluter"—those undertaking the activity, such as a dredging company, industrial plan, or wind farm operator) causes an adverse impact (Gray and Elliott, 2009). In contrast, the developer must prove they will not cause an impact, hence creating the scientific and statistical challenge of "proving the negative." A second key feature, "the precautionary principle" (PP), assumes a deleterious effect resulting from a given activity in the system unless proven otherwise (O'Riordan and Jordan, 1995). However, detractors criticize the vague definition of PP, and balancing scientific uncertainty and appropriate management measures remains a challenge (Steel, 2014).

The third key feature states that any developer wishing to use the marine system must obtain permission from a regulatory body, hence the importance of sufficient administrative bodies (Boyes and Elliott, 2014, 2015; Elliott, 2014); this encompasses the whole of marine governance, defined as the net result of policies, politics, legislation, and administration (Barnard and Elliott, 2015). The fourth feature, the "polluter pays principle," requires a developer to pay for the costs associated with that use: the licensing of the activity, the monitoring, remediation and mitigation of any damage to the system and, if necessary, compensation. The latter requires integrating natural and economic sciences to enable sustainability within and across generations and it may require developers to compensate affected users, the affected resource (e.g., restocking affected fish), or the affected environment (e.g., by creating new environment; Elliott et al., 2016). However, all of these central features relate to how users use an area of the sea (e.g., dredging, wind farm, fishing, etc.) but superimposing a wider suite of natural and human influences, such as climate change, on all of these activities (Elliott et al., 2015). This complexity demands, as the fifth feature, assessing the anthropogenic change or pressure in question (a "signal") against a background of inherent variability and natural change or wider influences, i.e., the changes emanating externally to the area being managed (the "noise"; Gray and Elliott, 2009; Elliott, 2011). Finally, a sixth key feature requires quantitative and legally defendable detection of such change with a direct feedback into management.

Progress beyond the State-of-the-Art

These key features require a defendable, holistic, underlying framework, accepted, and communicable to marine managers and wider users. That framework must link causes of potential and actual changes to the marine environment, the types of changes experienced and societal responses to mediating or removing the drivers of change or at least accepting change for the benefits provided. Even in the recent past, stakeholders frequently used the DPSIR (Drivers, Pressures, State change, Impact and Response) interlinking framework (e.g., Atkins et al., 2011; Smith et al., 2014), without clearly defining each element. Hence, the wide use of DPSIR model (Gari et al., 2015; Lewison et al., 2016; Patrício et al., 2016a) not only introduced many variants and perpetuated confusion but also made it not-fit-for-purpose in providing management guidance.

Previous studies document the evolution of the DPSIR approach (Smith et al., 2014, 2016), and here we summarize and focus on the evolution from DPSIR to the most recent derivative DAPSI(W)R(M) (Patrício et al., 2016a; Scharin et al., 2016; Burdon et al., in press). This modified approach adds Activities, and relates the Impact to human Welfare and the Responses to the use of Measures (the term preferred by EU Directives). Drivers describe underlying basic human needs, such as for food, security, space, and well-being, which require Activities (fishing, building wind farms, creating navigation routes). These activities then create Pressures, such as scraping the seabed with bottom trawls or building infrastructure that removes space. Pressures are the mechanisms that change the system, potentially causing concern. Those changes encompass both the natural system, including its structure and functioning (the "State change"; Strong et al., 2015), and the human system [the Impact (on human Welfare)]. The term Welfare is used *sensu stricto* to include economic welfare and human and societal well-being (Oxford English Dictionary).

Furthermore, all of the activities and external changes could potentially adversely affect that main aim (the protection of the social and ecological systems), and may thus be considered hazards. If these hazards damage parts of the socio-ecological system we value, they may be termed risks, thus providing a hazard and risk typology used in the DEVOTES project (Elliott et al., 2014). Smith et al. (2016) illustrated DPSIR, using fishing activity and the pressure of trawling from abrasion on the seabed and its impacts on particular components as an example. The challenges were addressed in moving from conceptual models to actual assessments including: assessment methodologies (interactive matrices, Bayesian Belief Networks, ecosystem modeling, the Bow Tie approach, assessment tools), data availability, confidence, scaling, cumulative impacts, and multiple simultaneous pressures, which more often occur in multi-use and multi-user areas (Smith et al., 2016).

Society and environmental managers need to know not only the current status of a marine system, but also whether it has been altered, the cause of that alteration, its significance, and what can be done to reverse that change. Therefore, this requirement creates the need to consider how Pressures result in State change, in the natural system, and a societally relevant Impact of sea use (including the assessment of cumulative pressures and impacts, as shown by Korpinen and Andersen, 2016); hence the need to consider not just Welfare (*sensu* DPSWR in Cooper, 2013) but the Impact (on human Welfare). This need explicitly includes an economic approach and a human health and well-being approach to human-induced changes. Furthermore, while that State change may often relate to the physico-chemical and ecological structure of the marine system, it increasingly requires users to consider the ecological functioning (Strong et al., 2015) especially given that many MSFD descriptors relate to functioning aspects. This "biodiversity-ecosystem functioning debate," regarding the effect of functioning on biodiversity and vice versa, is an important and developing field (Zeppilli et al., 2016).

The detection or prediction of changes to the natural state and impacts on human welfare require action to minimize, mitigate, compensate, remove, or even accept changes through societal Responses (the R in DPSIR). However, based on terminology used in the EU Directives, environmental managers now refer to those Responses as Measures [hence Responses -using Measures- in DAPSI(W)R(M); Scharin et al., 2016]. During the past decade, management has recognized the need to include all measures which therefore, as referred to as the Programme of Measures in the MSFD, should consider aspects of ecology, technology, economy, legislation, and administration. They should also satisfy societal, cultural and moral imperatives while communicating decisions to stakeholders; hence the so-called "10 tenets" for sustainable and successful marine management (Elliott, 2013; Barnard and Elliott, 2015).

The prevailing governance system provides a central control on adverse effects of human activities. The EU arguably represents the pre-eminent proponent of marine environmental legislation and other aspects of governance (Boyes and Elliott, 2014), but the complexity of the marine system, the need for transboundary action and the joint implementation of different systems have produced anomalies, confusion, and a need for an inter-governmental transboundary approach (Cavallo et al., 2016).

Most of the above framework relates to activities and pressures emanating from within a system such as a sea region, under management, for example the Baltic or North Seas (Andersen et al., 2015; Scharin et al., 2016). These may be termed endogenic managed pressures in which the causes and consequences in the region are managed (Elliott, 2011) and under legislative control (Boyes and Elliott, 2014). Exogenic unmanaged pressures (i.e., those aspects emanating from outside a managed system; for example global climate change Elliott et al., 2015) represent the major current challenge; environmental managers cannot control the causes but must respond to the consequences. Climate change offers a primary example, in which human impacts (e.g., ocean acidification, increase in alien species, sea-level rise, temperature regime change; Danovaro et al., 2013; Katsanevakis et al., 2014, 2016) add to internal pressures in an area. Climate change therefore shifts baselines, complicating evaluation change associated with internal activities in a region, but also potentially nullifying the use of quantitative indicators or at least requiring the target values of those indicators to be continually revised. A Member State not meeting legislative controls, such as directives, may therefore cite climate change as a modifying factor but one outside of its control (Elliott et al., 2015). Targets that cannot be reached due to changes caused by climate change effects are not manageable and need to be revised as a part of the 6 years management cycle.

Conclusions

Successful ocean use management relies on adequate and comprehensive monitoring, and identifying appropriate measurements of change. Management response requires a clear understanding of underlying causes and effects of change in the marine environment and their consequences. Hence, the use of conceptual models linking the marine drivers, activities, and pressures can provide that solid foundation to link to state changes, impacts on societal welfare, and the resulting management responses using programmes of measures. Similarly, management relies on the ability to predict and detect future responses of the system to changes with sufficient certainty; prediction requires conceptual, empirical, and deterministic models, whereas detection implies the presence of robust monitoring systems at appropriate spatial and temporal scales. However, the "paradox of environmental assessment" sets the backdrop for this framework whereby increasing national and European legislation (such as the MSFD) requires more understanding and better monitoring but monitoring organizations face reduced budgets (Borja and Elliott, 2013). Therefore, by expanding the concept of DPSIR into DAPSI(W)R(M), understanding the gaps and the Strengths, Weaknesses, Opportunities, and Threats in monitoring, and exploring how climate change could affect GES, DEVOTES has included human welfare in the modified approach, emphasizing the importance for future policy and management measures. Hence, an adequate assessment of marine status can only be achieved through fit-for-purpose monitoring based on sound scientific knowledge.

WHY DO WE NEED BETTER INDICATORS TO ASSESS THE STATUS?

State-of-the-Art

The multifaceted concept of biodiversity encompasses everything from the genetic composition of species to the organization of habitats and ecosystems (CBD, 1992). Despite the widely recognized need to maintain biodiversity, its many interpretations make difficult any comprehensive evaluation and therefore it is necessary to use indicators, or simplified measures, that reflect or synthesize the status of important aspects of ecosystem structure or function. Marine assessments depend upon indicators to detect and evaluate changes in environmental status driven by either natural or human pressures, often in the context of implementing management targets for environmental objectives and measures. Therefore, scientists and managers worldwide seek accurate and reliable indicators that represent all relevant aspects of marine biodiversity either as individual aspects or as surrogates (proxies) for series of changes (for example the use of the breeding health of piscivorous seabirds as a proxy for the whole marine trophic system).

Although, many nations worldwide recognize the need for an ecosystem approach to ocean management, the EU has led in developing specific metrics toward that objective. The European Commission (2010) Decision specifies criteria and methodological standards to evaluate environmental status of marine waters, based upon a set of 56 MSFD indicators. Some indicators used in the assessment of coastal ecosystems under the Water Framework Directive (WFD; European Commission, 2000; Birk et al., 2012) also apply to the MSFD assessment beyond the narrow coastal strip where MSFD and WFD overlap (Borja et al., 2010; Boyes et al., 2016). In practice, during the first phase of the MSFD implementation, EU Member States used different methodological approaches to determine and assess ecosystem status (European Commission, 2014; Palialexis et al., 2014). Data availability, regional specificities, and potentially different interpretations of the EU Commission Decision led to discrepancies within methodologies reported by Member States, increasing the potential for non-harmonized approaches to status determination. Managers require further guidance on criteria for "good" indicators, and assessment of status (Patrício et al., 2014), and such a plan is currently being developed by the EU and its Member States, ICES (International Council for the Exploration of the Sea), EEA (European Environment Agency), and RSCs (The Regional Sea Conventions). Concurrently, the RSCs are developing indicators for holistic marine assessments (e.g., HELCOM, 2013; OSPAR, 2015; UNEP, 2016).

Progress Beyond the State-of-the-Art

Overview of Existing Indicators and Gaps in Relation to MSFD Requirements

To support the MSFD process, we completed a comprehensive overview of existing MSFD biodiversity-related indicators (MSFD descriptors: D1—biological diversity, D2—non-indigenous species, D4—food-webs, and D6—seafloor integrity), identified gaps, and developed/tested new indicators to assess the status in the marine environment (Patrício et al., 2014).

We created an inventory of current MSFD biodiversity indicators, which includes over 600 entries, and developed complementary software (DEVOTool; www.devotes-project.eu/devotool) to help users navigate the metadata. The DEVOTool includes instructions for its use as well as a description of the database contents. Developing the inventory demonstrated that, despite many available marine biodiversity indicators, obvious gaps remain regarding some biotic components and criteria required for the MSFD implementation (Teixeira et al., 2014). Furthermore, information regarding the quality and confidence of the indicators is currently insufficient. Most available operational indicators target coastal and shelf ecosystems and cover WFD biological quality elements, such as macroinvertebrates, fish, phytoplankton, macroalgae, and seagrasses. Major current gaps include ecosystem level and genetic population level indicators, as well as indicators for microbes, pelagic and planktonic invertebrates, reptiles, ice-associated species, and communities, and deep-sea habitats. Most indicators lack regional targets or GES threshold values, and few measure confidence levels or demonstrably link to pressures. Thus, although current indicators may be regarded as operational in the way that they have been used in marine assessments, their applicability to fulfill the criteria of MSFD indicators and to comply with indicator quality criteria (Queirós et al., 2016) has not been assessed.

Development of New Indicators

We developed 16 new indicators and refined another 13 indicators (Berg et al., 2016; **Table 1**) to address gaps in MSFD implementation (Teixeira et al., 2014). These indicators mainly relate to the biodiversity-related Descriptors (D1, D2, D4, and D6), and cover the full range of biological components (i.e., from microbes to seabirds and marine mammals). In addition, we developed indicator quality criteria, which were used to evaluate these indicators (Queirós et al., 2016). For example, we developed four new indicators for microbes (bacteria and cyanobacteria), but their poor score on pressure responsiveness and the potential to set targets indicated a need for further development and validation (Berg et al., 2016). Some phytoplankton biomass indicators, such as chlorophyll-a concentration from satellite measurements, provide valuable assessments of pressures leading to eutrophication, but linking changes in diverse and rapidly fluctuating phytoplankton composition with impacts of nutrient loading has proved challenging (Camp et al., 2015; Carstensen et al., 2015).

Also indicators were developed to address the environmental impacts of invasive non-indigenous species in European regional seas (Minchin and Zaiko, 2013; Zaiko et al., 2014; Katsanevakis et al., 2016). Moreover, the project developed new food-web indicators focusing on primary and secondary producers, both for phytoplankton and fish. Of those, the novel food-web indicator "Phytoplankton community composition as a food-web indicator" was a highly-evaluated indicator and hence it is currently a candidate HELCOM core indicator for holistic ecosystem assessment. An indicator for systematic high-resolution habitat mapping and characterization scored high in the indicator-evaluation as it may be a proxy for many of the 56 MSFD indicators. We also recently developed and tested numerous promising indicators that capture effects of fishing on marine biodiversity, e.g., on the positive effects of fishing effort reduction on the increase of large fish indicator (Engelhard et al., 2015) and on the need of using biodiversity and conservation-based indicators complementarily to ecological indicators of fishing pressure to evaluate the overall impact of fishing on exploited marine ecosystems (Fu et al., 2015; Coll et al., 2016). Furthermore, a newly developed indicator based on DNA metabarcoding assesses genetic diversity of macroinvertebrates

TABLE 1 | Indicators developed or refined within DEVOTES project, in relation to some of the indicators proposed within the Marine Strategy Framework Directive (MSFD).

Marine Strategy Framework Directive requirements			DEVOTES indicators achievements	
Descriptors	**Indicator code**	**Indicator description**	**Indicators targeted**	**New or refined**
1. Biodiversity	1.1.2	Species: Distributional pattern within range	Distribution of herbivorous waterfowl in relation to eelgrass biomass distribution	New
	1.2.1	Species: Population abundance and/or biomass	Microbe biodiversity and indicator species	New
	1.3.1	Species: Population demographic characteristics	Microbe biodiversity and indicator species	New
	1.4.1	Habitats: Distributional range	Lower depth distribution limit of macrophyte species	Refined
	1.4.2	Habitats: Distributional pattern	Distribution of herbivorous waterfowl in relation to eelgrass biomass distribution	New
	1.5.1	Habitats: Habitat area	High resolution habitat characterization	New
	1.6.2	Habitats: Condition of the typical species and communities	Production of phytoplankton	New
			Phytoplankton community composition as a food web indicator	New
			Phytoplankton community composition based on food quality traits as an early warning indicator for food web effects on higher trophic levels	New
			Phytoplankton taxonomic diversity (Shannon95)	Refined
			Phytoplankton taxonomic evenness	New
			Seasonal progression of phytoplankton functional groups	Refined
			Spring diatom/dinoflagellate biomass ratio (Black Sea)	New
			Biomass of copepods	Refined
			Mesozooplankton biomass	Refined
	1.6.3	Habitats: Physical, hydrological and chemical conditions	High resolution habitat characterization	New
2. Non-indigenous species	2.1.1	Trends in abundance, temporal occurrence and spatial distribution	Abundance and distribution range of established Non-Indigenous Species	Refined
			Trends in the arrival of new non-indigenous species	New
			Trends in the arrival of Non-Indigenous Species by pathway of entry	Refined
	2.2.2	Impacts of non-indigenous invasive species	Cumulative impact index of Invasive Alien Species	New
3. Commercial species	3.3.2	Mean maximum length	Mean maximum length of demersal fish and elasmobranchs	New
4. Food-webs	4.2.1	Large fish	Size composition in fish communities (Typical length)	New
			Large fish indicator	New
	4.3.1	Abundance trends of functionally important selected groups/species	Share of cyanobacteria from total phytoplankton biomass as an early warning indicator for food web effects on zooplankton	New
			Production of phytoplankton	New
			Phytoplankton community composition as a food web indicator	New
			Phytoplankton community composition based on food quality traits as an early warning indicator for food web effects on higher trophic levels	New
			Biomass of copepods	Refined
			Mesozooplankton biomass	Refined
			Distribution of herbivorous waterfowl in relation to eelgrass biomass distribution	New

(Continued)

TABLE 1 | Continued

Marine Strategy Framework Directive requirements			DEVOTES indicators achievements	
Descriptors	**Indicator code**	**Indicator description**	**Indicators targeted**	**New or refined**
5. Eutrophication	5.2.1	Chlorophyll concentration in the water column	Surface Chlorophyll-a concentration from satellite measurements	Refined
	5.2.4	Species shift in floristic composition such as diatom to flagellate ratio, benthic to pelagic shifts, as well as bloom events of nuisance/toxic algal blooms caused by human activities	Biomass of N2-fixing cyanobacteria as an indicator for nitrogen load originating from N2-fixing cyanobacteria	New
			Diatom/Dinoflagellate index	Refined
			Spring diatom/dinoflagellate biomass ratio (Black Sea)	New
	5.3.1	Abundance of perennial seaweeds and seagrasses adversely impacted by decrease in water transparency	Lower depth distribution limit of macrophyte species	Refined
6. Seafloor integrity	6.1.2	Extent of the seabed significantly affected by human activities for the different substrate types	High resolution habitat characterization	New
	6.2.1	Presence of particular sensitive and/or tolerant species	Genetic based benthic microbial community condition and functionality assessment	New
			AZTI's Marine Biotic Index (AMBI)	Refined
			Genetic based macrobenthic community condition and functionality assessment	New
	6.2.2	Multi-metric indices assessing benthic community condition and functionality	Multivariate AZTI Marine Biotic Index	Refined
			Benthic quality index	Refined

Note the potential application of some indicators in assessing various MSFD indicators.

and microorganisms (Aylagas et al., 2014, 2016; Carugati et al., 2015; Dell'Anno et al., 2015).

We also applied Signal Detection Theory (SDT) to assess the accuracy, sensitivity and specificity of refined benthic indicators (such as the Benthic Quality Index—BQI) and their response to eutrophication. In general, we found SDT to be a robust and scientifically sound strategy for setting threshold values for indicators (Chuševė et al., 2016). Finally, we introduced a new approach to set indicator targets in relation to ecosystem resilience (i.e., the ability to recover rapidly and predictably from pressures) and to select indicators and their target ranges (Rossberg et al., 2017). This approach is a specific, quantitative interpretation of the concepts of GES and sustainable use in terms of indicators and associated targets. Importantly, it distinguishes between current and future uses to satisfy societal needs and preferences.

Conclusions

Increasing legal challenges of marine and coastal management, both to the EU Member State implementation of Directives and industry compliance with national laws, which hinge upon detecting and demonstrating marine environmental change (Elliott et al., 2015), increases the need for scientifically defensible indicators. Those indicators must be comprehensive, either in covering all relevant aspects of the marine system or as conceptually defensible surrogates that represent a well-defined and well-accepted causal link (e.g., the health of breeding populations of top seabird and fish predators being dependent on the health of seabed populations).

We tested and refined 13 available biodiversity indicators, developed 16 new options for assessment, particularly for biological descriptors (considering species, habitat and ecosystem levels), identified gaps for future research, developed indicator performance criteria, and provided a user-friendly tool to select and rank indicators (**Table 1**). These publicly-available contributions (Berg et al., 2016), support the second phase of the MSFD implementation and assist marine management in Europe and elsewhere.

WHY MODELS ARE NECESSARY IN MARINE STUDIES AND ASSESSMENT?

State-of-the-Art

Understanding how changes in biodiversity link to food-web functioning, anthropogenic pressures, and climate changes requires novel, integrative modeling tools. Similarly, scaling determining change from small to large areas and from the present to future, also requires such modeling approaches. Once validated, modeling tools can elucidate expected risks and rewards for a range of management options, aimed at achieving or maintaining GES. The evidence base from such scenario testing thus provides a suitable platform to enable informed decision-making. Prior to 2012, the proposals for using models in the MSFD implementation were very limited (Cardoso et al., 2010) but now, in the context of using models in assessments, Pinnegar et al. (2014) for example have demonstrated the value of food-web models in assessing potential responses of ecosystems to invasions.

Progress beyond State-of-the-Art

We assessed the capabilities of state-of-art models to provide information about current and candidate indicators outlined in the MSFD, particularly on biological diversity, food-webs, non-indigenous species, and seafloor integrity descriptors (Piroddi et al., 2015; Tedesco et al., 2016). We demonstrated that models could explain food-webs and biological diversity, but poorly-addressed non-indigenous (alien) species, habitats and seafloor integrity (Lynam et al., 2016).

Habitats and Non-Indigenous (Alien) Species

In order to address the key gap related to non-indigenous (alien) species, we developed a method to model the vulnerability of areas to invasions, using the Mediterranean Sea as a case study (Katsanevakis et al., 2016). This conservative additive model accounts for the Cumulative IMPacts of invasive ALien species (CIMPAL index) on marine ecosystems. It estimates cumulative impact scores based on distributions of invasive species and ecosystems, considering both the reported magnitude of ecological impacts and the strength of such evidence.

Theory and New Approaches to Model Ecosystem Function

The theory supporting advanced modeling of food-webs and biodiversity was extended (Rossberg, 2013; James et al., 2015). Through different projects, including DEVOTES, Fung et al. (2015) used this theory to explore links between Biodiversity-Ecosystem Functioning (BEF) in marine ecosystems to fill in a key knowledge gap. Strong et al. (2015), furthermore, showed the importance and potential of such functional indicators. The BEF relationship can change (Mora et al., 2014; Fung et al., 2015), but the protection of fish from predation provided the mechanism in this case, and BEF relationships depended upon species richness and fishing impacts. Previous studies by Danovaro et al. (2008) revealed that the BEF relationships can be exponential and thus extremely sensitive to changes in environmental conditions determining a biodiversity loss. Nagelkerke and Rossberg (2014) also developed a theoretical understanding whereby resource and consumer traits predict trophic space, such that empirical data can be used to determine trophic traits related to food-web functioning (James et al., 2015).

New modeling approaches using mass-balanced models were also developed to identify ecosystem structure, function (including Ecological Network Analyses) and reaction to disturbance (Lassalle et al., 2013, 2014a,b; Niquil et al., 2014; Chaalali et al., 2015; Guesnet et al., 2015).

Habitats and Function

To further understand the role of habitat in regulating function in marine food-webs, and thus link to other descriptors, such as seafloor integrity and biological diversity, we studied marine habitats at local [i.e., Basque coast, Galparsoro et al. (2015); Eastern Aegean Sea, Lynam et al. (2015b); Western Adriatic deep-sea, Zeppilli et al. (2016)], sub-regional (i.e., North Sea, Stephens and Diesing, 2015; van Leeuwen et al., 2015), and regional (i.e., Mediterranean, Katsanevakis et al., 2016) scales. For example, we developed a process-driven characterization of sedimentary habitats for the Basque continental shelf and demonstrated that species richness decreases rapidly with increased sediment resuspension (Galparsoro et al., 2013). Habitat modeling of elasmobranchs in the southern North Sea demonstrated the extirpation of some species such as common skate over time (Sguotti et al., 2016). Modeling spatial distribution of three common seabird species in the southern North Sea demonstrated the importance of habitat type and availability fish prey to seabird distributions (see Lynam et al., 2015a). Additionally, we demonstrated in Stephens and Diesing (2015) the feasibility of predicting substratum composition spatially across a large swath of seabed (North Sea) using legacy grain-size data and environmental predictors. We also demonstrated the suitability of such a quantitative prediction for further analyses of habitat suitability compared to traditional grid cell categorization (Stephens and Diesing, 2015).

We applied Benthic Traits Analysis (Alves et al., 2014; van der Linden et al., 2016a; Van der Linden et al., 2016b) specifically to understand benthic community function in relation to habitat. This analysis identified typological groups of benthic macroinvertebrates in the North Sea, based on response and effect traits, as potential ecological indicators for MSFD Descriptors 1 (Biological Diversity) and 6 (Seafloor integrity; Veríssimo et al., 2015). The creation and analysis of large data set on population genetics in species groups with different dispersal abilities linked genetic variation to constraints in movement within benthic habitats in macroinvertebrates. This finding appears consistent with a "neutral theory" explanation for marine biodiversity spatial patterns (Chust et al., 2013, 2016).

A major challenge in marine management and assessment relates to the ability to link the physico-chemical and ecological systems. For example, for pelagic habitats, we identified distinct physical regimes in the North Sea based on density stratification characteristics, and modeling identified five hydrodynamic regimes (van Leeuwen et al., 2015). These findings are valuable to support assessment at a sub-divisional scale within MSFD subregions. Effective marine management must consider these regimes and their likely biological interactions. These zones form the basis for the OSPAR biodiversity (pelagic habitat) assessment based on lifeforms, together with considering oxygen and eutrophication when assessing primary production for food webs.

Scenario Testing to Inform Management Decisions

Our research demonstrated that fisheries management may enhance biological diversity (such as the size-structure of the fish and elasmobranch community) but potentially produce unintended consequences for other ecosystem components (Lynam and Mackinson, 2015). For example, decreases in bentho-piscivores component. However, the system may nonetheless sustain economic yields with minimal risk of stock collapse (Lynam et al., 2015b) if managed through an ecosystem approach. In the long term, climate change may shift baselines for indicators (Lynam et al., 2015b) and so assessments of GES should recognize these effects (Elliott et al., 2015).

Conclusions

Marine research and assessment require modeling studies that can support the use of indicators in fully encompass the functional linkages between ecosystem components and overwhelming pressures on the marine environment, such as climate change and ocean acidification. Such modeling provides the evidence for setting realistic targets and thus supporting better long-term marine planning. We used case studies to illustrate that modeling can assist in MSFD implementation, contributing to each step of the assessment and management cycle. Modeling can help to develop and refine novel indicators to support indicator-based assessment of GES. Modeling can incorporate indicator trends and responses, incorporating prevailing climatic conditions and anthropogenic pressures and, in this way, support the review of objectives, targets and indicators. Moreover, modeling can both inform adaptive monitoring programmes and be used in scenario testing to inform management decisions.

MONITORING NETWORKS IN EUROPEAN REGIONAL SEAS: IS TRADITIONAL MONITORING SUFFICIENT TO ASSESS THE STATUS OF MARINE ECOSYSTEMS?

State-of-the-Art

Methods traditionally used in marine monitoring to investigate spatial and temporal variation in abiotic and biotic variables are time-consuming, costly and often limited in resolution (de Jonge et al., 2006; Borja and Elliott, 2013; Carstensen, 2014; Fraschetti et al., 2016). These constraints can severely limit our capacity to detect spatial and temporal changes in marine environmental health. In addition, most countries lack the tools to expand marine monitoring to the deep sea (Ramirez-Llodra et al., 2011), severely constraining the expected implementation of the MSFD in the open ocean and deep sea (Zeppilli et al., 2016). Moreover, marine monitoring methods currently limit analyses of some descriptors. For example, detecting cryptic and/or alien species (including those causing harmful algal blooms) will benefit from molecular approaches (Bourlat et al., 2013).

Activities that smoother, abrade or permanently-remove seabed habitat represent the greatest threats to seafloor integrity (Rice et al., 2012). Previous studies used benthic faunal analysis to indicate general seafloor integrity (Pearson and Rosenberg, 1978), drawing on an extensive catalog of methods and approaches for such a fundamental change (Gray and Elliott, 2009), but increasingly together with various visual assessment tools (Solan et al., 2003). Specific benthic faunal indicators exist for trawl abrasion (Jorgensen et al., 2016) but deriving these indicators is time-consuming and expensive to implement. Video inspection of seafloor smothering using Remotely Operated Vehicles (ROV), such as from seabed drilling activities, can visually map the environmental footprint (Gates and Jones, 2012), but we lack data to validate the uncertainty of the method compared to conventional biological sample collection.

The implementation of the assessments of marine environmental status required by the MSFD thus requires development and/or testing of innovative monitoring systems. Despite creating recent methodologies/technologies in DEVOTES, these are not yet used in routine monitoring of the MSFD descriptors. We encourage this through our summary analysis encompassing a catalog of monitoring networks and a wide array of potential tools, including: (i) molecular approaches (e.g., barcoding and metagenomic tools), (ii) remote sensing/acoustic methods, and (iii) *in situ* monitoring techniques.

Progress beyond the State-of-the-Art

We have produced a catalog with the biodiversity monitoring networks, currently available in European Seas, with the aim to: (i) present a critical overview of the monitoring activities in Europe (i.e., the amount and reason for ongoing monitoring, whether it fulfills its objectives and to what pressures it is links), (ii) identify areas where no monitoring occurs, and (iii) recommend the further development and improvements for optimizing marine biodiversity monitoring in the context of the MSFD. Since the publication of the catalog (Patrício et al., 2014), new material has been added so that it currently identifies 865 monitoring activities corresponding to 298 monitoring programmes. A gap and SWOT (Strengths, Weaknesses, Opportunities, and Threat) analysis of the catalog (Patrício et al., 2016b), highlights uneven distributions of monitoring across regional seas (i.e., more monitoring activities in the North Eastern Atlantic and Mediterranean). Specifically, we note uneven monitoring effort between descriptors (e.g., more monitoring for Descriptor 1 on Biological diversity and Descriptor 4 on Food webs), between biological components (e.g., monitoring emphasis on fish and phytoplankton) and between pressures (e.g., high level of monitoring of organic matter enrichment across all regional sea). In addition, we consider whether monitoring networks are fit-for-purpose or sufficient for adequate implementation of the MSFD within the context of the need for better coordination, harmonization of methodologies, and cost-effectiveness considerations (Patrício et al., 2016b). This allowed us to explore different innovative monitoring approaches. Below we discuss these new approaches in terms of their potential applications to some of the 11 descriptors of the MSFD investigated by DEVOTES, in order to evaluate their broader applicability to future marine environmental monitoring.

Descriptors 1 (Biological Diversity) and 2 (Non-indigenous Species)

Future monitoring is increasingly likely to use molecular tools to complement classical taxonomic techniques in providing timely and inexpensive results (Bourlat et al., 2013). Classical biodiversity assessment is time-consuming and requires diverse taxonomic expertise. Metabarcoding could expedite biodiversity assessment, especially for microscopic organisms (either algae or animals) for which morphological identification is difficult (Carugati et al., 2015). For example, Dell'Anno et al. (2015) provided the first comparison of different DNA extraction procedures and their suitability for sequencing analyses of 18S rDNA of marine nematodes. They subsequently analyzed intra-genomic variation in 18S rRNA gene repeats and reported that morphological identification of deep-sea nematodes matches the results obtained by metabarcoding analysis only at the order-family level. These results illustrate the importance of metabarcoding for exploring the diversity of benthic metazoans, but currently available databases have a limited coverage in quantifying the species encountered. Metabarcoding studies should therefore carefully consider these limitations in quantitative ecological research and monitoring programmes of marine biodiversity (Aylagas et al., 2016).

The routine use of microarrays for rapid detection of specific phytoplankton taxa, and particularly the presence of harmful algal blooms, requires further development to increase reliability and reduce associated time and expense. Nonetheless, monitoring strategies should include different molecular approaches [e.g., quantitative, *in situ* Polymerase Chain Reaction (PCR)] as these approaches offer far greater sensitivity to detect the presence, for example, of pathogenic bacteria compared to traditional approaches.

In addition to the above molecular tools, comparing biodiversity across different habitats and seas represents a critically important aspect of marine biodiversity monitoring, which metabarcoding can address. For example, in order to use metabarcoding to investigate the benthic biodiversity colonizing identical structures in different habitats, we deployed and later recovered Autonomous Reef Monitoring Structures (ARMS), initially developed by NOAA for coral reefs, after 12 months on hard bottoms at shallow depths at three sites (triplicates) within different regional seas (Baltic Sea, English Channel in the NE Atlantic, Adriatic Sea, Black Sea, and Red Sea). This highly reproducible approach allows a standardized comparison of colonizing biodiversity in different systems.

In parallel, molecular tools allowed us to identify aspects of biodiversity that classical tools could not, such as identifying microbial assemblages as indicators of biodiversity (Caruso et al., 2016), monitoring picoplankton (Ferrera et al., 2016), an early detection of invasive species (Ardura et al., 2015; Zaiko et al., 2015a,b), a census of meiofauna (Carugati et al., 2015), identifying functional gene diversity and plankton phylogeny (Reñé et al., 2013, 2015; Ferrera et al., 2015), revealing benthic eukaryotic diversity (Pearman et al., 2016a,b), or assessing the status of benthic macroinvertebrates (Aylagas et al., 2014).

The MSFD recognizes spatial changes in species and population distributions as key indicators. Numerous DEVOTES studies demonstrated the value of combining seabed geological information with biological variables (e.g., Galparsoro et al., 2013, 2014). However, whilst multiple needs drive the collection of such geological data (e.g., safety of navigation, renewable energy infrastructure, planning), mapping the entire marine area will require considerable time (although perhaps less than a decade with existing capabilities). Despite this potential, even after a comprehensive baseline survey, further monitoring for change will always be necessary. Existing monitoring programmes have enabled collection of high-resolution multibeam sonar data over a large area and extrapolation of these properties across 100,000 km^2 in the western English Channel. Only by addressing and interrogating environmental variables at scales and a resolution relevant to the biota will we understand the context of local ecosystem change and status.

Descriptor 3 (Commercial Fish Species and Shellfish)

At present, other than acoustic surveys that lack taxonomic resolution and exceed the science capability of developing nations, we lack novel approaches to replace traditional surveys and stock recruitment assessment in fish population studies. However, emerging molecular tools can identify connectivity among fish populations and help elucidate the role of connectivity in maintenance of fish stocks.

Descriptor 4 (Food-Webs)

Researchers can now cost-effectively monitor the functioning at the base of the food-web (i.e., primary and secondary production) using ferrybox systems [such as the Continuous Automated Litter and Plankton Sampler -CALPS-, developed on the RV Endeavor CONISMA, 2013] on research vessels and ships of opportunity. The zooplankton data collected by CALPS identifies broad geographic patterns in abundance and diversity and can be integrated within existing multidisciplinary surveys at minimal extra cost. As another example, semi-automated classification of zooplankton samples usefully provided data for a range of food web related indicators even in the northern Baltic Sea, where the generally small-bodied zooplankton is difficult to be classified using semi-automated methods (Uusitalo et al., 2016a). The OSPAR-led EU project "Applying an ecosystem approach to (sub) regional habitat assessments" (EcapRHA, www.ospar.org/work-areas/bdc/ecaprha) has further investigated this approach. Monitoring of phytoplankton community composition (i.e., ratio between diatoms and flagellates) by a combination of remote sensing, microscopy, and bio-optical methods can clarify food-web effects on higher trophic levels (Goela et al., 2015).

Descriptor 5 (Eutrophication)

Current instruments that can analyze chlorophyll-a from *in situ* sampling can ground-truth satellite image analysis for monitoring of phyto-pigments concentrations in surface waters (Cristina et al., 2014, 2016) or assess aquaculture impacts (Mirto et al., 2010, 2014; Luna et al., 2013; Bengil and Bizsel, 2014). In addition, pigment color analysis (particularly *in situ* flow cytometry) can provide insights on phytoplankton biodiversity (Goela et al., 2015), estimate and calculate time series of annual gross primary production, and support MSFD implementation (Cristina et al., 2015). We also investigated the influence of benthic trophic state on meiofaunal biodiversity and found that the benthic trophic status based on organic matter variables is not sufficient to provide a sound assessment of the environmental quality in marine coastal ecosystems. However, the integration of the meiofaunal variable allows providing robust assessments of the marine environmental status (Bianchelli et al., 2016).

Descriptor 8 (Contaminants)

Andrade et al. (accepted) developed a high frequency non-invasive (HFNI) bio-sensor as a potential tool for marine monitoring which uses the biorhythmic gaping behavior of clams (such as the Icelandic scallop *Chlamys islandica* and the Pacific oyster *Crassostrea gigas*) in response to environmental cues such as day length. These innovative microsensors measure the distance between the valves of bivalves held in underwater baskets at strategic locations, and can operate unattended for several years. Measurements every 1.6 s are telemetered from the field to the laboratory and further transferred to a "big-data" storage system for analysis. Minimal operational costs and online, real-time data availability offer major advantages of the system once installed.

Beyond biorhythm research (including growth and spawning behavior) in relation to climatic factors, the method has potential for monitoring marine contamination. Exposure to stressors such as sudden changes in water quality, temperature increases (e.g., around power plants), toxic algal blooms, or a plume of water-borne contaminants, interrupts otherwise regular gaping behavior. The automated, real-time detection could provide an early-warning system, with potential applications including monitoring of water quality at swimming beaches, harbors, petroleum installations (produced water and unintentional spillages), and aquaculture sites. This "talking clam" method can improve cost-efficiency by alerting users to periods of potential risk, narrowing the need for more labor-intensive physical sampling, as long as it is assumed that normal gaping behavior reflects good water quality status.

Conclusions

As indicated above, we currently face a "paradox of environmental assessment"—with increasing monitoring requirements set against a backdrop of decreasing budgets. This paradox ensures the need for more cost-efficient and effective monitoring, and may eventually produce cheaper traditional monitoring, especially where monitoring requirements span large areas, as in the MSFD. The paradox requires wide-scale and rapid surveillance techniques, including innovative tools such as genomic approaches, remote sensing and acoustic sensors.

WHY DO WE NEED AN INTEGRATIVE ASSESSMENT OF STATUS?

State-of-the-Art

The European Commission (2010) identified 56 indicators to consider when evaluating environmental status, but at least an order of magnitude more indicators already exist (Berg et al., 2015). Despite this, many of these indicators are variants on similar themes and hence measure related attributes, and are often geographical derivations, for example the health of seabed communities. The relevance and availability of indicators vary substantially among regional seas and their subdivisions; however, the MSFD provides no guidance on integration principles, despite multiple approaches to aggregating indicators whose selection may produce highly diverging results (Borja et al., 2014). These choices challenge the scientific community to develop harmonized approaches for integrating these indicators to compare across different assessment areas.

The Ocean Health Index (OHI; Halpern et al., 2012) was developed to assess the consequences of human impacts as well as societal benefits by calculating a weighted average of scores for pressure, status and resilience goals in different areas globally. Borja et al. (2011) were the first to address specifically the challenges of the MSFD, using weighting averaging principles for integrating indicator information. The MARMONI (Innovative approaches for MARine biodiversity MONItoring and assessment of conservation status of nature values in the Baltic Sea) assessment tool (Martin et al., 2015) then used an aggregation principle based on the hierarchical structure laid out by the European Commission (2010), rather than using aggregation approaches based on the structures of marine ecosystems. Nevertheless, all assessment methods standardize indicators to a common scale prior to aggregation (Borja et al., 2016). This standardization relies upon defining of targets or reference states, which MSFD describes as targets for GES (Borja et al., 2013). The OHI uses the relative deviation from a reference state, whereas the MARMONI tool uses a binary scoring system to determine whether GES has been achieved (score of 100) or not (score of 0). However, these standardization approaches do not always achieve translating indicator values to a common scale. A relative deviation from a reference state of 50% could indicate a minor human disturbance for one indicator but a major human disturbance for another. Similarly, a binary standardization approach does not differentiate between whether minimal attainment or high status level of GES was achieved.

Progress beyond the State-of-the-Art

We developed and released software for NEAT (Nested Environmental status Assessment Tool; freely available at: www.devotes-project.eu/neat), to overcome some of the deficiencies of current integrated assessment tools (e.g., aggregation of multiple indicators at multiple temporal and spatial scales; absence of uncertainty determination, etc.) NEAT is loosely based on previous tools (Andersen et al., 2014, 2016) and translates indicator values to a common scale ranging from 0 (worst possible status) to 1 (best possible status), with 0.6 defining GES or the good-moderate boundary according to the WFD. Similarly, NEAT also allows users to set boundaries representing high-good status (value of 0.8), moderate-poor status (value of 0.4), and poor-bad status (value of 0.2). It also employs stepwise linear interpolation between these fixed points to produce transformations with a high degree of flexibility spanning the entire scale (0–1) and in which 0.6 always represent GES. In comparison with the OHI and MARMONI tool, this transformation produces a more comparable scale for integrating standardized indicator values. NEAT also employs weighted averaging of standardized indicators, but bases averaging on ecosystem features to represent the whole ecosystem. The approach primarily divides the entire ecosystem into multiple Spatial Assessment Units (SAU) that are nested to define a hierarchy of SAUs. Habitat information and relevant indicators according to organism groups are used to describe the environmental status which the given habitat may enter at different levels of the hierarchy, depending on the spatial representativity of the indicator and organism. First, averaging aggregate indicators at the organism level to produce a more even representation of relevant organism groups, i.e., to avoid an assessment biased by many indicators for the same organism group, before aggregating across habitats and SAU (Clark et al., 2011). Spatial information of the different SAUs, if provided, is used for weighting and habitats can be prioritized to weight complex habitats such as vegetated sea bottoms more heavily than deep, muddy sediments. In addition, NEAT indicators are associated with the different MSFD descriptors, supporting assessments based on various descriptor combinations (essentially from one to all).

Application of NEAT to 10 case studies across European marine waters with very different challenges, environmental conditions, and scales (Uusitalo et al., 2016b) highlights its flexibility adapting to these very different cases. This also highlighted the need for careful evaluation of the indicator set, their GES boundaries, and the selection of the SAUs, all of which can increase the accuracy of the GES assessment.

Finally, NEAT includes an uncertainty assessment at all levels of integration based on the propagation of errors (uncertainties) associated with the provided indicator information (Uusitalo et al., 2015). Therefore, assessing the confidence in the integrated assessment requires including an indicator value with an estimate of the standard error of that indicator value. Noting that few studies report or even determine the standard error of an indicator value, Carstensen and Lindegarth (2016) provide a framework for quantifying indicator uncertainty to enable such calculations. Knowing the distributions of the indicator estimates enables the calculation of the distribution of the standardized indicators as well as their aggregated values.

Conclusions

A true ecosystem approach for ocean use management requires an integrative assessment of marine water status. In this way, NEAT provides a second-generation, integrated assessment tool that builds on the hierarchical structure of marine ecosystems and the organisms inhabiting different compartments within this structure, thereby improving upon previous tools. Such a hierarchical approach allows users to interrogate the results to understand the reasons for the failure or success at achieving GES. However, the integrated assessment is only as good as indicator information allows, and missing or omitting information on specific groups (e.g., biological components or descriptors relevant to the assessed area) can bias the assessment results. Therefore, managers should produce guidelines stipulating indicator minimum requirements [e.g., type, coverage (ecosystem components, area, etc.), number] and the integrated assessment tool should clearly indicate if there is non-compliance with such guidelines. Moreover, because NEAT includes a comprehensive uncertainty assessment, researchers should incorporate this information as part of their interpretation of outcomes and decision support, thus needing guidelines for confidence levels of decisions.

In conclusion, environmental managers must assess the status of marine waters, not only to comply with current legislation (i.e., MSFD, WFD), but also to determine how far from targets marine ecosystems may be. Such information will allow managers to make informed decisions on sustainable resource use and the adequate restoration of degraded systems.

WHAT ECONOMIC AND SOCIAL DIMENSIONS AFFECT MARINE MANAGEMENT?

State-of-the-Art

Inevitably, new legislative framework directives bring about unforeseen challenges to the different stakeholders who need to be involved in their implementation, particularly when first applied. Managers already apply the MSFD, which is itself complex, to complex, heterogeneous, and dynamic environments. Furthermore, initiation of the MSFD coincided with a period of a growing, global economic crisis. The numerous objectives can potentially conflict with one another from the perspective of different government departments within the Member States and also between Member States sharing a regional sea. The MSFD legal status and implementation deadlines demand that scientists and decision makers ensure a collaborative and multidisciplinary approach to deliver multi-sectoral objectives that test the abilities of existing institutions. The rapid identification of the issues, and the problems that they can create, can help those responsible for MSFD implementation to consider best how to address such issues and ensure that the MSFD can provide the intended sustainable environmental benefits.

The introduction of complex and integrative environmental legislation such as the MSFD also inevitably incurs additional costs, such as establishing new monitoring and improving existing monitoring of multiple indicators across European seas. This demand can be economically challenging. Policy makers and regulators in all EU countries are obliged to manage their resources carefully and hence they will seek to comply with the MSFD in the most cost-effective way. Yet they have many choices on which types of monitoring to apply as they select the approaches that best comply with the legislative needs within the limits of their budgets (Veidemane and Pakalniete, 2015). Although the MSFD does not require consideration of the socio-economic aspects of monitoring, Borja and Elliott (2013) noted that limited financial resources represent the most significant threat to ensuring adequate monitoring.

Furthermore, the law requires that EU countries determine whether they need new management measures and monitoring schemes to enable them to achieve GES and, if so, to implement them. Here, the socio-economic analysis of the use of marine waters, the cost of present-date degradation of the marine environment, and the cost-benefit analysis of implementing monitoring and new management measures required under the MSFD could motivate Member States to achieve GES. However, whilst a dominant tool of all governments, economic analysis approaches to achieve such analyses specifically for the MSFD in relation to the marine environment and its management were not developed at the start of the MSFD process.

Progress Beyond the State-of-the-Art

Barriers to Achieving Good Environmental Status

A comprehensive review of the documented barriers to achieving GES indicated that Member States have encountered and reported legislative, governance, and socio-economic barriers during this first phase of implementing the MSFD (Boyes et al., 2015, 2016). Barriers include ambiguity in the text of the Directive resulting in different interpretations by Member States, creating uncertainty, and different levels of conformity and governance complications. For example, GES [Article 3(5)] is neither well defined nor quantitatively described (Boyes et al., 2016), not easily understandable, and requires specific guidance to achieve common understanding and to enable coherent practices between the Member States and across regional seas. The next revision of the European Commission (2010) Decision regarding MSFD implementation will provide more guidance on GES definition (for example the operational definition proposed by DEVOTES; Borja et al., 2013), and thus the input from different stakeholders, including the scientific community, will be extremely important. The effectiveness with which MSFD can achieve GES partially relates to the success of other EU legislation [e.g., the WFD, the reformed Common Fisheries Policy (CFP), Maritime Spatial Planning Directive (MSP), Integrated Maritime Policy (IMP)], acknowledging the ambiguity of the role and contribution of each individual piece of legislation. Despite limited reference to specific policies in the MSFD, it provides a framework that can incorporate earlier and future legislation to ensure that legislation provides spatially and temporally complete coverage for the protection of marine environment. The MSFD article 6 is quite clear on the purpose and role of RSC: "*... Member States shall, where practical and appropriate, use existing regional institutional cooperation structures, including those under Regional Sea Conventions...*" and "*...Member States shall, as far as possible, build upon relevant existing programmes and activities developed in the framework of structures stemming from international agreements such as Regional Sea Conventions....*" However, in the absence of clear guidance on how this objective should be implemented or the actual competence of the RSCs, Member States have not adopted the regional coordination and integration to achieve MSFD objectives. Boyes et al. (2015, 2016) offer recommendations to address these legislative and governance barriers, such as "*continued clarification and harmonization of the definitions and methodologies within and between Member States and the different RSCs*." The aims of other directives should be consistently included in considerations for GES together with clear reference to MSFD and other existing, forthcoming and amended directives. Systematic use of standards that already used within other EU legislation must be applied as minimum requirements. Implementation of the MSP Directive particularly provides measures that will support delivery of the goals of MSFD by facilitating a balance with blue growth objectives (Boyes and Elliott, 2014; Boyes et al., 2016). The RSC must have a mandate supported by their contracting parties in order to ensure that the measures implemented in EU countries are supported and complemented by respective measures also in non-EU countries. Achieving RSC aims requires continuous cooperation in regional seas between EU-Member and non-Member States in the context of RSCs (Cavallo et al., 2016).

Socio-economic barriers include a lack of appropriate biological, environmental, and socio-economic data, a limited application of the ecosystem-based approach and of economic impact analyses by Member States. Effective use of the findings of EU funded projects and pilot projects (involving both non-EU countries and Member States) can both boost the evidence and knowledge required. It can also provide a vehicle to improve and support regional coordination and encourage the coherent implementation of the MSFD in regional sea areas, and ensure engaging non-EU countries in programmes that enable measures to achieve true regional GES.

Discussions with stakeholders showed that often public and stakeholder consultations on the programmes of measures were only open for limited periods of 1–2 months, and stakeholders in most Member States, particularly NGOs, felt that they were not sufficiently involved in the MSFD process, with only limited integration of their feedback (Boyes et al., 2015). In recognizing the complexity of marine ecosystems, the existence of multiple stakeholders with imperfect and impartial knowledge, as well as resource constraints, we developed a workshop approach "to engage and share different perspectives, and develop models of the system under consideration that are seen to be valid and useful aids to decision making" (Boyes et al., 2015). This multi-stakeholder workshop based modeling approach, which focused on Causal Loop Diagrams (CLD) to describe and understand the case site, was developed and then trialed in a case study site in England (Boyes et al., 2015). Managers should consider this approach, which effectively engaged stakeholders in understanding the complex environment associated with GES and the barriers and opportunities for its achievement, is exemplary for moving forward in MSFD implementation.

Cost-Effectiveness of Monitoring

Building on the ecological criteria for monitoring developed in Queirós et al. (2016), we developed an approach that uses multi-criteria-decision-analysis (MCDA) for cost-effectiveness analysis incorporating both ecological and economic criteria as attributes of monitoring systems. This approach encompassed a standardized scoring system for each of the different attributes, readily adaptable to the analysis undertaken with the attributes and the scores used as input to the MCDA. The cost-effectiveness of a given monitoring approach can be determined using the Rapfish software (www.rapfish.org), a non-parametric multivariate analysis tool, developed and tested in different contextual case studies of MSFD monitoring in Finland, Spain, and the UK. We also developed flow charts to help users identify the different elements of operational costs during monitoring. The tool can be applied to examine both the cost-effectiveness of the different monitoring elements and whether the monitoring programmes satisfy the requirements of the MSFD monitoring objectives. The tool has demonstrated, for example, a mixed ability of current monitoring programmes in Bay of Biscay to comply with the need to monitor changes in quality and quantity of different MSFD Descriptors. In addition, monitoring open sea areas in the Gulf of Finland becomes more cost-efficient when combining monitoring with research cruises on scientific vessels, which make up the largest single monitoring cost.

Cost-Benefit Analysis of New Management Measures to Achieve GES

By 2015, EU Member States had to define the Programme of Measures, including new measures if any, required to achieve GES. Oinonen et al. (2016a) stated that "the specific application of methods and uptake of resulting information are currently still evolving in the ecosystem-based and adaptive management framework that the Directive stipulates." They further recommend the use of environmental economics delivered through interdisciplinary research to support the needs of MSFD.

Three different case-studies showed interdisciplinary approaches to the cost-benefit analysis of management measures to achieve GES. In Finland, a quantitative cost-effectiveness analysis of implementing different management measures, based on opinion of interdisciplinary experts, identified the costs, and most cost-effective measures. Researchers estimated economic benefits of the management measures based on existing valuation studies (i.e., willingness to pay) on the benefits of improving the state of the Baltic Sea; these analyses connected the benefit estimates directly to the change in the status of the GES descriptors (Oinonen et al., 2016b). Extending from this analysis into a full cost-benefit analysis, the net value of achieving GES for indicators of biodiversity, food webs, and eutrophication alone in 2020 is placed at ∼2 bn € (although the planned management measures will not achieve GES of these Descriptors by 2020).

Alternative approaches to cost-benefit analysis of management measures were developed and applied in the Bay of Biscay and the East Coast of England Marine Plan Areas (ECE). These approaches built on research to determine changes in ecosystem services and the benefits that identified, mapped and modeled ecosystem services, and considered valuation of their benefits (e.g., Hattam et al., 2014, 2015; Galparsoro et al., 2014; Borja et al., 2015; Kleisner et al., 2015; Laurila-Pant et al., 2015).

The Bay of Biscay approach examined the links between ecosystem services and their benefits and management measures to control the development of maritime activities creating those benefits. We used the Fishrent bioeconomic model (Salz et al., 2011) to quantitatively assess the impacts, in terms of percentage changes in net present value, of implementing some of the measures under the European Common Fisheries Policy (CFP) expected to support attainment of GES.

The ECE approach used structured analysis of changes in ecosystem services and benefits arising from potential new management measures (ballast water treatment, underwater noise reduction) to identify the benefits of achieving GES alongside the costs of implementing the measures. Insufficient availability of valuation data, needed to quantify ecosystem benefit impacts in monetary terms, precluded the possibility of extending the analysis into a quantitative cost-benefit analysis.

Conclusions

Ensuring that Member States implement sufficient and non-overlapping measures to achieve GES will require the continuous review of legislation and policy, and the assessment of its implementation (Boyes et al., 2016). Furthermore, effective stakeholder engagement is likely to facilitate the acceptance of the measures and associated costs. The effective application of the MSFD requires knowledge and databases but these currently are limited by economics (Borja and Elliott, 2013). It remains to be seen how the different Member States identify the additional measures needed to improve the marine environment toward GES and close the gap between current status and GES in 2020. However, Member States must use existing budgets carefully to avoid further economic hardship resulting from financial penalties due to legal infraction proceedings in the European Court. For example, reduced funding for monitoring, if not guided toward more effective monitoring tools (see Section Monitoring Networks in European Regional Seas: Is Traditional Monitoring Sufficient to Assess the Status of Marine Ecosystems?), can reduce the quality of monitoring (e.g., by reducing spatial and/or temporal coverage). Such reduction can ultimately entail a greater cost than investment in monitoring as inaccurate evaluation could increase the risk of decision-making errors, potentially resulting in reduced ecosystem services and a devaluation of ecosystem benefits. Political decision makers may consider other aspects of monitoring as societally important, such as maintaining a bank of knowledge, technological development, professional skill and experience development and enhancing public engagement. Tools for determining the cost-effectiveness of monitoring and of management measures, as well as use of the ecosystem service approach to determine ecosystem benefits in cost-benefit analysis can support decisions on activities undertaken to comply with the MSFD. However, many member states implementing the MSFD lack both the data required to underpin rigorous economic analysis of costs of monitoring and the valuation data for assessing changes in ecosystem benefits from improvements in ecosystem services. Furthermore, the relationship between MSFD indicators and ecosystem services still requires better understanding and the implementation of the MSFD still urgently requires such data and information.

FILLING IN THE GAP BETWEEN SCIENCE AND POLICY

Some of the challenges in marine ecosystems ecology identified by Borja (2014) relate to socio-ecological topics, especially given the recognition of humans (and the activities they perform and pressures they pose in the oceans) as an integral part of the marine ecosystem in recent decades. The human dimension of marine systems remains poorly documented, and discussions

TABLE 2 | Progress beyond the state-of-the-art achieved by DEVOTES, within the different topics addressed by the project, and gaps bridged in science-policy.

Topic addressed	State in 2012	Progress in 2016, after DEVOTES	Gaps bridged in science-policy by DEVOTES	Challenges for the future
Understanding of human impacts at sea, including climate change	-DPSIR framework and derivatives - Scarce knowledge on climate change effects on MSFD	-DAPSI(W)R(M) approach Expansion of the framework to accommodate multiple activities, multiple pressures and mechanisms - Potential effects of climate change on the MSFD known - Matrices of pressure/impact for European regional seas	-Better understanding of the effects of human impacts at sea and the endogenic and exogenic pressures that can or cannot be managed	-Managing multiple pressures under climate change
Use of indicators in the assessment	-indicators identified to be needed for holistic ecosystem based approach for assessment of GES (European Commission, 2010) - No clear criteria for the selection of indicators - Lack of overview what indicators are currently available and well suitable for MSFD assessment	- DEVOTool available - >600 indicators collated and evaluated for their applicability for MSFD assessment - Gaps identified to further improve and develop indicators to cover needs of MSFD assessments - Criteria to develop and select ecologically relevant and robust indicators for MSFD assessments - 29 indicators developed or refined as a contribution to support concise indicator based assessment ecological status	- Availability of operational and scientifically sound criteria to select suitable indicators depending of the needs of the users - Availability of a suite of new and refined indicators to assess the status of marine waters, based on the gaps identified and to supplement the needs of the users - Publicly available user-friendly tool to select and rank indicators, depending on the operational needs of the marine managers in different regional seas, and available also for other stakeholders to evaluate GES assessments	- Develop environmental targets and reference conditions for some of the new indicators (and refine those of the old ones) to make them comparable across regional seas - Keep the DEVOTool database updated, and to provide support (help desk) for end-users of the tool
Modeling of marine systems	- Little use of models within the MSFD	- List of models suitable for the MSFD - Additive model for cumulative impacts of alien species - New developments in model ecosystem functioning - New approaches using mass-balanced models - Habitat modeling for different species - Models of connectivity developed	- Modeling studies support the use of indicators and functional linkages between ecosystem components and overwhelming pressures on the marine environment, such as climate change and ocean acidification, are more fully grasped and can be used in management - A series of case studies illustrating that modeling can assist the implementation of the MSFD, contributing in each step of the assessment and management cycle.	- Need of more integrative models at ecosystem level, covering all European seas - Need to better communicate to managers the usefulness and need of using modeling tools to implement the MSFD - Need to take uncertainty into consideration
Monitoring of marine systems	- Little knowledge regarding marine biodiversity monitoring networks on place at Pan-European scale - Traditional monitoring undertaken by EU Member States	- Catalog with information on marine biodiversity monitoring networks on place in the four European Regional Seas and their sub-regions - New molecular tools used to monitor and assess the status in microbes, plankton, meio- and macrofauna - Use of ARMS and ASUs to monitor hard-bottom - New applications of remote sensors to assess eutrophication - New biosensor as early warning of contamination	- Information on monitoring networks compiled and publically available - Identification of gaps and needs for further monitoring by European regional sea and marine sub-regions Traditional monitoring, regarded as too expensive to cover large areas, has been complemented with wide-scale and rapid surveillance techniques, useful for assessment and management	- Achieve coordinated monitoring within regional seas - Need to cooperate with non-EU countries, particularly in the Black and Mediterranean Seas - Need to optimize resources and apply the new monitoring tools under routine monitoring frameworks

(Continued)

TABLE 2 | Continued

Topic addressed	State in 2012	Progress in 2016, after DEVOTES	Gaps bridged in science-policy by DEVOTES	Challenges for the future
Assessment of marine systems	- Lack of an operational definition of GES - Little knowledge on aggregation methods - No integrative assessment tools available	- Proposal of an operative definition of GES - Proposal of different methods for aggregation - New integrative assessment tool (NEAT)	- Provision of the necessary basis to better understand what GES mean, when it is achieved and how can it be assessed, for a better management	- Integrate the assessment of ecosystem services in NEAT - Make assessments across regional seas comparable and harmonized
Economic and social dimensions	No knowledge of the barriers to implementing MSFD No tools to consider the cost-effectiveness of marine monitoring No approaches for undertaking cost-benefit analysis of management measures to improve the marine environment	Understanding of the initial governance, legislative and socio-economic barriers Systemic modeling approach to consult with stakeholders to overcome barriers Tool to undertake analysis of cost-effectiveness of monitoring Approaches to undertake cost-benefit analysis of management measures to achieve GES	Decision support on best use of limited resources for monitoring and for development of management measures Approaches to reveal the benefits of achieving GES enabling cost-benefit analysis of management measures that support decision making on approaches to achieve GES, potentially including motivation to do so.	Requirement for economic data on: - Costs of monitoring - Costs of implementing management measures - Valuation data to apply to benefits from ecosystem services - Bioeconomic modeling to support economic analysis of marine environmental benefits

DPSIR and DAPSI(W)R(M): D, drivers; A, activities; P, pressures; S, change of state; I, impact; W, human wellbeing; R, responses; M, management; MSFD, Marine Strategy Framework Directive. GES, Good Environmental Status; NEAT, Nested Environmental status Assessment Tool; ARMS, Autonomous Reef Monitoring Structures; ASU, Artificial Substrate Unit.

on ecosystem-based management of seas often minimize the importance of social sciences (Fréon et al., 2009), despite the explicit role of humans in implementing the Ecosystem Approach since its adoption in the Convention on Biological Diversity (CBD, 1992). Despite progress in recent years in connecting natural and social sciences, the gap between science (social and natural) and policy remains large in marine research (Nicholson et al., 2012). Europe has made efforts to close the research project-policy circuit in relation to the WFD (Oliver et al., 2005; Quevauviller et al., 2005; Hering et al., 2010), although until recently, few attempts have been made to close such a circuit for the MSFD (Borja et al., 2010).

Many challenges remain in bridging the gap between science and policy to support improved policy decisions in marine management (von Winterfeldt, 2013; Choi et al., 2015). As noted by Rodwell et al. (2014), improvement would require identifying: (i) the gap or perceived gap between marine science and policy; (ii) the obstacles that prevent us from bridging the gap, and (iii) the possible solutions.

More than 30 years ago, Sebek (1983) identified some of the reasons for marine public policy failure in incorporating scientific knowledge, but researchers since have removed some of the impediments (**Table 2**). Specific examples include:

(i) Lack of international regulation encompasses both EU and non-EU countries adjacent to the regional seas, which the different RSCs and, especially, the WFD and MSFD has overseen in recent years. DEVOTES brought together different pieces of legislation, identified gaps and overlaps and provided advice on future needs for the satisfactory implementation of the MSFD for the new Commission Decision expected in the coming months (Patrício et al., 2014);

(ii) Although monitoring increased after enacting the WFD and should continue to improve during the MSFD implementation (Patrício et al., 2014; Patrício et al., 2016b), it remains insufficient. DEVOTES contributed by identifying, testing and validating multiple innovative tools for monitoring and modeling large areas;

(iii) Independent scientific input into international conferences provided a means to organize multiple stakeholder meetings and offer training courses and sessions at international conferences aimed at disseminating and making project findings operational;

(iv) Incorporating scientific advice into regulations requires political compromise and we contributed by developing tools to assess environmental status (NEAT) that we hope will be incorporated into the implementation of the environmental quality directives (e.g., MSFD and WFD). Furthermore, a series of workshops and webinars with key stakeholders and end-users (e.g., policy-makes, relevant Member State representatives, RSC, etc.) has accompanied this development for all to understand the basis, capacities and functioning on this tool;

(v) Insufficient use of economic analysis to assess and support implementation of MSFD exacerbated a lack of appropriate monitoring costs, impacts and valuation data relevant to the assessment of marine ecosystems, their services and benefits. We developed new approaches to undertake cost effectiveness and cost- benefit analysis of monitoring and management measures, respectively, in the context of MSFD. Furthermore, we explored linkages between

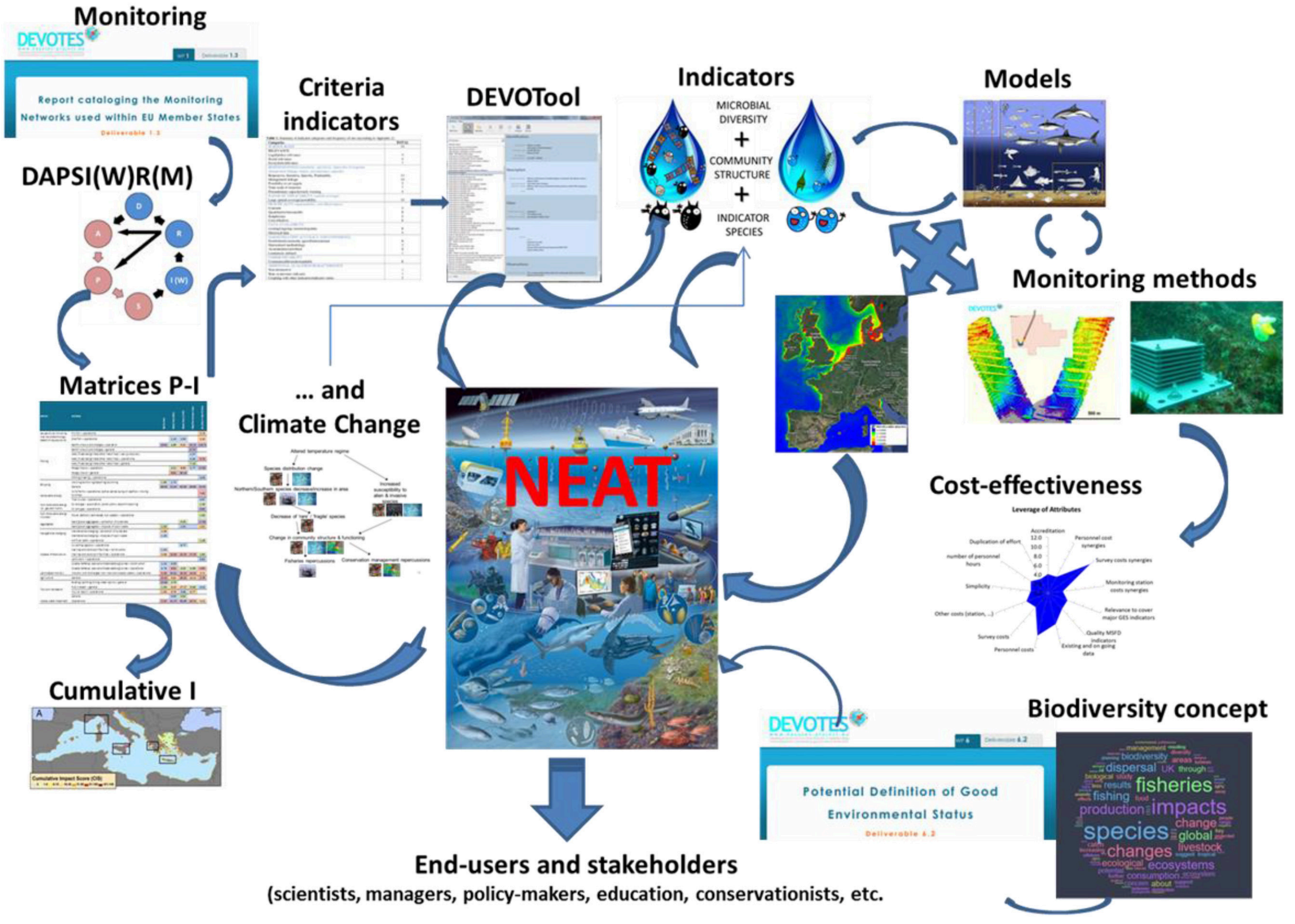

FIGURE 1 | Synthesis of the knowledge generated within the DEVOTES project, to assess the status of marine waters in an integrative manner. D, drivers; A, activities; P, pressures; S, change of state; I, impact; W, human wellbeing; R, responses; M, measures. NEAT, Nested Environmental status Assessment Tool. The central plate, about NEAT, was drawn by Alberto Gennari.

ecosystems and provision of ecosystem services as well as between management measures and ecosystem services.

DEVOTES was conceived as an integrative project that aimed to expand and merge natural and social sciences, enable the natural scientists to understand the economic and legal requirements and economic and governance specialists to understand the limitations of natural science. **Figure 1** encapsulates the work done and the integration of pieces to assess the status and respond to multiple stakeholders and end-users (i.e., scientists, policy-makers, managers, industry, conservation organizations, and society). Hence, our outputs not only increased knowledge of marine assessment and assisted marine managers, but also communicated these findings to increase stakeholder uptake.

In connection with the development of the MSFD programme of measures, Oinonen et al. (2016b) developed a pragmatic approach to holistic cost-effectiveness analysis. This allows users to select a cost-effective set of candidate measures in order to reach the multidimensional environmental objectives of the MSFD. They concluded that the major challenge in applying cost-effectiveness analysis was in assessing the current state of the environment and the multiple effects of different measures in evaluating marine ecosystem components rather than in the concepts of economic analysis. Despite this, economics helped to determine socially optimal level of marine protection.

Many challenges remain despite the body of work undertaken over the last 4 years (**Table 2**). These challenges include, among others: (i) understanding how multiple pressures act in marine ecosystems, and managing those pressures in the context of climate change; (ii) identifying key indicators and setting targets and reference conditions for those indicators so they can be used in assessments, noting the need for comparability across regional seas, and recognizing scenarios of climate change that shift baselines; (iii) the need to develop models capable of operating at an ecosystem level, with powerful computational capacities able to handle big data; (iv) getting EU Members States to consider adopting new monitoring tools routinely, and coordinating monitoring activities within regional sea research activities; (v) the need for intercomparable and harmonized assessments across regional seas that include ecosystem services in the assessment, and (vi) the urgent need for a harmonized framework under which indicator development follows specific rules and aligns with specific criteria to readily use in an integrative assessment tool.

GENERAL CONCLUSIONS

Defining, attaining and maintaining the GES of the seas spans from the technical details of monitoring and indicator implementation to major social and economic issues of how to optimize the long-term delivery of ecosystem goods and services, and how to govern society fairly in relation to use of the sea. It requires integrating natural and social sciences, horizontal integration across stakeholders, and vertical integration through governance, and feedback between monitoring, measures, and management. The MSFD aspires to bring all these aspects under the same umbrella, an ambitious and highly relevant objective.

DEVOTES advanced the state-of-the-art and identified major gaps within various aspects of MSFD implementation, contributed to filling these gaps, and identified additional scientific and development needs. The further development and validation of marine biodiversity indicators requires improved data with better spatial and temporal coverage, based on novel and cost-efficient monitoring methods. Better ecological relevance and indicator responsiveness to pressures will require experimental research on different levels of biological organization from the cell to the ecosystem. Such research will also enable incorporation of indicators into models in order to extrapolate marine assessment results to larger spatial and temporal scales. Each of these aspects requires comprehensive and integrated natural and social sciences which cross international boundaries and regional seas.

AUTHOR CONTRIBUTIONS

AB conceived the paper and wrote the first draft; ME, AB contributed to the pressures section; TB, SC, MM, AH, JP, LU contributed to the indicators section; CL, CW contributed to the modeling section; RD, AB, AN, JP, SC, PS, MU contributed to the monitoring section; JC, AB, TB, SC, MU contributed to the integration section; MA, MU contributed to the socio-economic area; all authors contributed equally to the discussion and conclusions, AB, ME, SG, PS, MU made a revision of the whole text.

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