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Essential ocean variables for global sustained observations of biodiversity and ecosystem changes

Patricia Miloslavich[1,2,3,4] (iD) | Nicholas J. Bax[1,5] | Samantha E. Simmons[6] |
Eduardo Klein[2] | Ward Appeltans[7] | Octavio Aburto-Oropeza[8] | Melissa Andersen
Garcia[9] | Sonia D. Batten[10] | Lisandro Benedetti-Cecchi[11] (iD) | David M. Checkley Jr.[12] |
Sanae Chiba[13,14] | J. Emmett Duffy[15] | Daniel C. Dunn[16] | Albert Fischer[17] |
John Gunn[3] | Raphael Kudela[18] | Francis Marsac[19,20] | Frank E. Muller-Karger[21] |
David Obura[22] | Yunne-Jai Shin[19,23]

[1]Institute for Marine and Antarctic Studies, University of Tasmania, Hobart, Tas., Australia

[2]Departamento de Estudios Ambientales, Universidad Simón Bolívar, Caracas, Venezuela

[3]Australian Institute of Marine Science, Townsville, Qld, Australia

[4]Oceans Institute, University of Western Australia, Crawley, WA, Australia

[5]CSIRO, Oceans and Atmosphere, Hobart, Tas., Australia

[6]Marine Mammal Commission, Bethesda, MD, USA

[7]Intergovernmental Oceanographic Commission of UNESCO, IOC Project Office for IODE, Oostende, Belgium

[8]Marine Biology Research Division, Scripps Institution of Oceanography, La Jolla, CA, USA

[9]National Oceanic and Atmospheric Administration (NOAA), Office of International Affairs, Washington, DC, USA

[10]Sir Alister Hardy Foundation for Ocean Science (SAHFOS), Nanaimo, BC, Canada

[11]Department of Biology, University of Pisa, CoNISMa, Pisa, Italy

[12]University of California San Diego, La Jolla, CA, USA

[13]UN Environment-World Conservation Monitoring Centre, Cambridge, UK

[14]Research and Development Center for Global Change (RCGC), JAMSTEC, Yokohama, Japan

[15]Tennenbaum Marine Observatories Network, Smithsonian Institution, Edgewater, MD, USA

[16]Marine Geospatial Ecology Lab, Nicholas School of the Environment, Duke University, Beaufort, NC, USA

[17]Intergovermental Oceanographic Commission IOC/UNESCO, Paris, France

[18]Ocean Sciences Department, University of California Santa Cruz, Santa Cruz, CA, USA

[19]Institut de Recherche pour le Développement (IRD), UMR MARBEC 248, Université Montpellier, Montpellier, France

[20]Department of Oceanography, University of Cape Town, Rondebosch, South Africa

[21]Institute for Marine Remote Sensing/IMaRS, College of Marine Science, University of South Florida, St. Petersburg, FL, USA

[22]CORDIO East Africa, Mombasa, Kenya

[23]Department of Biological Sciences, Ma-Re Institute, University of Cape Town, Rondebosch, South Africa

Correspondence
Patricia Miloslavich, University of Tasmania, Institute for Marine and Antarctic Studies, Hobart, Tas, Australia.
Email: pmilos@usb.ve

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Abstract

Sustained observations of marine biodiversity and ecosystems focused on specific conservation and management problems are needed around the world to effectively mitigate or manage changes resulting from anthropogenic pressures. These observations, while complex and expensive, are required by the international scientific,

governance and policy communities to provide baselines against which the effects of human pressures and climate change may be measured and reported, and resources allocated to implement solutions. To identify biological and ecological essential ocean variables (EOVs) for implementation within a global ocean observing system that is relevant for science, informs society, and technologically feasible, we used a driver-pressure-state-impact-response (DPSIR) model. We (1) examined relevant international agreements to identify societal drivers and pressures on marine resources and ecosystems, (2) evaluated the temporal and spatial scales of variables measured by 100+ observing programs, and (3) analysed the impact and scalability of these variables and how they contribute to address societal and scientific issues. EOVs were related to the status of ecosystem components (phytoplankton and zooplankton biomass and diversity, and abundance and distribution of fish, marine turtles, birds and mammals), and to the extent and health of ecosystems (cover and composition of hard coral, seagrass, mangrove and macroalgal canopy). Benthic invertebrate abundance and distribution and microbe diversity and biomass were identified as emerging EOVs to be developed based on emerging requirements and new technologies. The temporal scale at which any shifts in biological systems will be detected will vary across the EOVs, the properties being monitored and the length of the existing time-series. Global implementation to deliver useful products will require collaboration of the scientific and policy sectors and a significant commitment to improve human and infrastructure capacity across the globe, including the development of new, more automated observing technologies, and encouraging the application of international standards and best practices.

1 | INTRODUCTION

Climate change and our increasing use of the ocean are affecting important marine resources and ecosystems at local, regional and global scales and threaten the well-being of human kind. Economic activity associated with growing use of ocean resources needs to be balanced with the capacity of ocean ecosystems to sustain these activities. This requires up-to-date knowledge of resource status and trends (EIU, 2015). Agencies that look after marine resources need timely information of relevant ocean changes to improve forecasting capabilities (Gattuso et al., 2015; ITF, 2015), respond with adaptive and more rapid mitigating measures (Dunn, Maxwell, Boustany, & Halpin, 2016; Maxwell et al., 2015) and sustain blue economies (Golden et al., 2017). Because the ocean covers over 70% of the surface of the Earth and is on average 4 km deep, developing this knowledge is a challenge for any country. To meet the need of delivering ocean data to support governance and management, a framework for ocean observing emerged from the OceanObs'09 conference. This framework proposes the coordination and integration of routine and sustained observations

of physical, biogeochemical, and biological essential ocean variables, or EOVs, which are fit for purpose and defined by specific requirements (Lindstrom, Gunn, Fischer, McCurdy, & Glover, 2012). Some of these requirements include international reporting (e.g., the United Nations Convention on Climate Change or UNFCCC, the UN Sustainable Development Goals or SDGs, the Convention on Biological Diversity or CBD Aichi Targets) and assessments (e.g., the UN World Ocean Assessment; the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services/IPBES) (CBD, 2014a,b; Gattuso et al., 2015; Lu, Nakicenovic, Visbeck, & Stevance, 2015; UN, 2016). These are aimed at driving policies to help prepare, adapt, manage and mitigate the effects of ocean global change and providing the opportunity for developing countries to identify their needs for global participation and support, overall improving the economies and well-being of societies worldwide. As an example, coral reef monitoring since the late 1970s and 1980s enabled detection of change (decrease in coral cover) and attribution to warming temperatures as early as the 1990s (Wilkinson, 1998; Wilkinson et al., 1999; Williams & Bunkley-Williams, 1990). Recognizing the high cultural and socio-economic value of coral

reefs for human populations, this initiated a movement towards the establishment of a series of high level policies for coral reef conservation and management across the globe, including for example Aichi Target 10 (minimize reef loss). It also triggered the establishment of several long-term and large-scale monitoring programs, and of the Global Coral Reef Monitoring Network (GCRMN), strongly linked to the United Nations Environment Program (UNEP) through the auspices of the International Coral Reef Initiative (ICRI).

The goal of this paper is to identify biological essential ocean variables that when implemented as a sustained global ocean observing system (GOOS) will provide key information on global changes in marine resources and ecosystems in response to society's internationally agreed needs.

For 25 years, the GOOS has been a critical driver for initiating, coordinating and globalizing ocean observations. GOOS provides advice on physics, climate and biogeochemistry observations to governments around the world (Lindstrom et al., 2012). GOOS physical and biogeochemical EOVs are frequently supported as essential climate variables (ECVs) being based on specific scientific and societal requirements driven mostly by the need to measure climate change and for weather forecasts (Bauer, Thorpe, & Brunet, 2015; O'Brien, Lorenzoni, Isensee, & Valdés, 2017). To help understand and forecast better the responses of marine life and ecosystems to a changing ocean and expand the coverage of ECVs, there is a pressing and growing need to identify and implement biological and ecological EOVs into an integrated and multidisciplinary observing system (Miloslavich et al., 2015). Many of the biological ocean observations were initiated in search for answers to scientific questions on short-term monitoring (e.g., Jossi, 2010; Suthers & Rissik, 2009; and many others), and to detect change over longer terms, such as those associated with human and climate change signals at global (Henson, Beaulieu, & Lampitt, 2016; Henson et al., 2010) or regional scales (Taylor et al., 2012). Biological observations are increasingly also driven by their technical and scientific feasibility and for solving specific societal problems including in the economic and policy sectors (Allison & Bassett, 2015; Lindstrom et al., 2012). Lately, the proliferation of possible monitoring frameworks and "essential variables" under different names (see Table S1 for a list of frameworks and their variables) has created confusion and is delaying agreement on a coherent, coordinated and integrated global system that would make meaningful contributions similar to those now achieved by the global climate observing system (GCOS), which meets the needs of the UNFCCC (Bojinski et al., 2014; Houghton et al., 2012; WMO, 2016).

Biodiversity is varied and complex in detail and outcome. Biological EOVs therefore need to be carefully chosen to address a broad number of stakeholders with a consistent nomenclature and clearly defined standards. They should address fundamental characteristics of the biological components of marine ecosystems that can be combined into indicators to (1) represent the complexity of real-world natural systems, (2) track temporal and spatial changes in the state of the environment, (3) evaluate management performance, (4) deliver information and products to scientific and policy audiences (Hayes et al., 2015) and (5) assess progress towards international goals and

targets (Halpern et al., 2017; Tittensor et al., 2014; Walpole et al., 2009). With these criteria, GOOS defines biological/ecological EOVs *as those sustained measurements that are necessary to assess the state and change of marine ecosystems, address scientific and societal questions and needs, and positively impact society by providing data that will help mitigate pressures on ecosystems at local, regional and global scales.*

In this paper, we explain how we used the DPSIR (driver-pressure-state-impact-response) model, a well-known framework used to guide environmental assessment and reporting (Atkins, Burdon, Elliott, & Gregory, 2011; EEA, 1995; Hayes et al., 2015; Kelble et al., 2013; Maxim, Spangenberg, & O'Connor, 2009; Omann, Stocker, & Jäger, 2009) to prioritize types of observations and to build a suite of EOVs that will detect temporal and spatial changes in marine biodiversity and ecosystem state, thus supporting increasingly successful management of marine resources and ecosystems over the decades to come (Figure 1).

2 | MATERIALS AND METHODS

2.1 | Identifying the drivers and the pressures

To identify societal drivers and pressures, we reviewed the mission, mandates, reporting requirements and assessment processes of 24 international conventions or agreements pertinent to global change biology and ecology. Drivers were defined as the societal needs, and pressures were defined as the anthropogenic stressors on marine biodiversity and ecosystems. Conventions relevant to global change biology were selected from the University of Oregon's International Environmental Agreements Database Project (multilateral agreements related to coastal and marine habitats) (Mitchell, 2002–2016) and from the conventions compiled by Mahon et al. (2015). We included regional agreements related to the Arctic and the Southern Ocean and grouped Regional Fisheries Management Organizations and Authorities (RFMO/As) under the United Nations Convention on the Law of the Sea (UNCLOS) (Table S2). The process included an extensive review of climate change processes and expected impacts (IPCC, 2014). To cluster the drivers according to the conventions that address them, a dendrogram was produced using a complete clustering algorithm on a Jaccard distance coefficient matrix. The selection of the distance metrics was based on the binary characteristics of the data (presence/absence) and the relative efficiency of the coefficient (Finch, 2005). The complete clustering agglomeration was selected due to its higher cophenetic correlation value ($r = .929$) with the original data when compared to other methods (Borcard, Gillet, & Legendre, 2011). For each cluster of drivers, we calculated the percentage of conventions addressing each pressure.

2.2 | State of biological observations in the marine environment

We conducted an online survey to evaluate the current state, and technical and scientific capabilities of biological ocean observations within large geographical or long temporal scales and assessed their
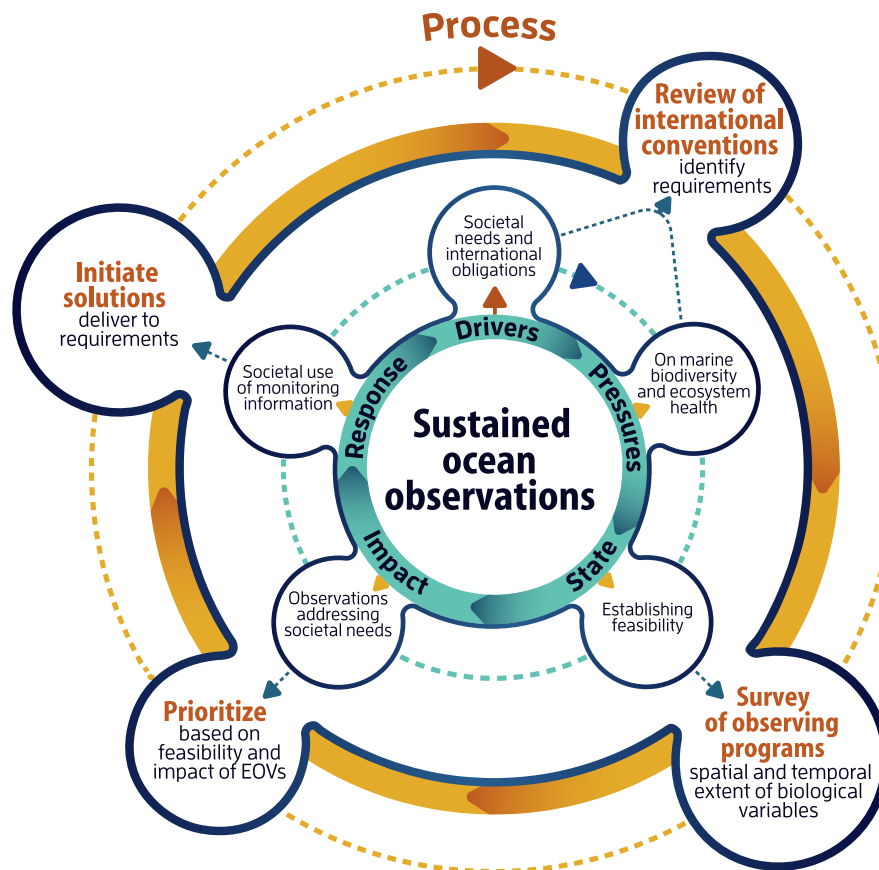
FIGURE 1 Process used to identify biology and ecosystems essential ocean variables (EOVs) (external circle). Each of the external bubbles describes steps in the process. The inner circle represents the DPSIR model (drivers-pressures-state-impact-response), with the bubbles providing the details on each of the five components [Colour figure can be viewed at wileyonlinelibrary.com]

potential scalability to expand to larger geographies. The survey included questions on the temporal and spatial scale and coverage of observations, target ecosystems, biological variables measured and data availability, among other queries (see Table S3 for the full survey questions). The survey was developed using the online Survey-Monkey platform and was open from January to July 2016. Invitations were distributed among large scientific and monitoring programs including the marine Long-Term Ecological Research Sites. It was also sent to the World Association of Marine Stations network, which could potentially have time-series data on marine biodiversity, distribution and abundance.

We considered as priority variables those that were measured by at least two thirds of the programs. For these priority variables, a standardized "Scalability Index" was created based on the temporal and spatial scales at which the programs operate to identify those variables with the highest feasibility for expansion to global coverage. The "Scalability Index" (SI) was calculated as the proportion of programs (Programs$_{prop}$) that address each of these priority variables weighted by their spatial cover (Spatial) and temporal extent (Temporal). Spatial cover and temporal extent were recorded on a 5-point scale: spatial (1 = 0–1 km, 2 = 1–10 km, 3 = 10–100 km, 4 = 100–1,000 km, 5 = >1,000 km) and temporal (1 = 1–5 years, 2 = 6–10 years, 3 = 11–20 years, 4 = 21–

50 years, 5 = >50 years). The Scalability Index SI was then calculated as:

$$ SI = \left[\frac{median(Spatial)}{max(Spatial)} + \frac{median(Temporal)}{max(Temporal)} \right] * Programs_{prop} $$

where Programs$_{prop}$ is the proportion of programs that measure the variable. Here, the maximum value for both the spatial and temporal scale is 5 for any variable. The index varied between 0 and 2. For example, the maximum value was 2 if all programs measured a particular variable at the maximal spatial and temporal scales. Therefore, those variables measured by programs with spatial extent >1,000 km and operative for more than 50 years were assumed to have the highest scalability for expansion into global coverage.

2.3 | Determining the impact of biological ocean variables

As a measure of how the variables address the societal needs identified by the international conventions, we used the SCOPUS abstract and citation database to search the peer-reviewed literature for how many publications referred to each driver, pressure or priority variable and how frequently these occurred together. The Relevance Index (RI) was calculated as:

$$RI_{drivers} = \frac{\# \text{ pubs } (D \& V)}{\# \text{ pubs } (D)} + \frac{\# \text{ pubs } (D \& V)}{\# \text{ pubs } (V)}$$

$$RI_{pressures} = \frac{\# \text{ pubs } (P \& V)}{\# \text{ pubs } (P)} + \frac{\# \text{ pubs } (P \& V)}{\# \text{ pubs } (V)}$$

where: #pubs (*D & V*) is the total number of publications addressing the driver and the variable together; #pubs (*D*) is the total number of publications addressing the driver alone; #pubs (*V*) is the total number of publications addressing the variable alone; #pubs (*P & V*) is the total number of publications addressing the pressure and the variable together; #pubs (*P*) is the total number of publications addressing the pressure alone.

The index varies between 0 and 2, the maximum value of the index would have been equal to 2 if 100% of the publications for a specific variable had addressed a specific driver or pressure.

3 | RESULTS

3.1 | Societal drivers and pressures

Nine societal drivers (Table S4) and ten anthropogenic pressures (Table S5) were identified from 24 international conventions and agreements. Drivers were grouped in four clusters based on the agreements that address them together (Jaccard similarity coefficient) as: (1) sustainable use of biodiversity, biodiversity conservation and biodiversity knowledge, (2) environmental quality and threat prevention and mitigation, (3) capacity building, sustainable economic growth and ecosystem-based management and (4) food security (Figure 2). As for pressures, 22 of the 24 conventions were concerned with loss of habitat and biodiversity resources, including losses through overfishing. Half of the conventions were concerned with climate change and explicitly included impacts on marine life. Other identified pressures on life in the ocean (for a much smaller number of the conventions) were pollution and eutrophication, coastal development, invasive species, solid wastes, ocean acidification, extreme weather events, noise and mining. Each of these drivers and pressures targets specific issues driving biological responses to a changing ocean including changes in biodiversity patterns, trends in primary productivity, zooplankton biomass, and fish abundance, incidence of harmful algal blooms and population size and trends of threatened species among many others (Tables S4 and S5).

3.2 | State of biological observations

The large majority of the 104 observing programs that responded the survey were guided by conservation and/or national policies, with fewer than half being scientifically driven (Table S6; http://goosocean.org/bioecosurvey). For most of the programs, quality-controlled data within international standards (e.g., DarwinCore, NetCDF, ISO19115, Ecological Metadata Language) are archived in a national data centre or other data repository, and available through a data portal interface, some with a few restrictions. Such restrictions vary, from data only being distributed upon request or conditional on funder acknowledgement, to more complex impediments such as not sharing sensitive data on fisheries or location of endangered species, moratoria after publication or within a specific time frame, or data policies still under discussion.

The earliest sustained biological observations began more than 100 years ago and represented national initiatives (e.g., the Western Channel Observatory in the UK), however most of the programs have operated for between 20 and 50 years, providing a strong baseline against which to measure current and future climate change impacts. The first large-scale program that is still sustained for some regions today is the Continuous Plankton Recorder (CPR) surveys, the first tow having taken place in 1931. A notable rise in the number of programs observing biological variables in the ocean began in the mid-70s, and the number is still increasing. Some of the more recently established programs are attempting to address larger geographic coverage (Figure 3). Of the 104 programs, only seven have either ceased or been reduced in sampling effort or observation sites. One of the major programs (CARIACO) with more than 20 years of operation ended since our survey was conducted due to lack of sustained funding and other support.

More than half of the programs operated at the largest spatial scale (>1,000 km), and sampling frequency was highly variable across programs, from daily to annually, depending on the variable (e.g., taxonomic group, habitat or ecosystem function). Observing methods and tools comprised a vast array of platforms, from satellite and remote sensing to visual observations, and from moorings, buoys and Autonomous Underwater Vehicles to water bottles. Plankton communities were the most observed followed by benthic invertebrates and nekton (bony fishes). The oceanic and neritic pelagic systems were the most observed, followed by seagrass ecosystems, rocky shores, soft sediments and coral reefs (Figure S1a,b). Phytoplankton and zooplankton were usually measured by the same programs; similarly, programs measuring seagrass and macroalgae frequently also measured associated benthic abundance, while coral reef focused programs typically also surveyed associated fish. In terms of temporal extent, the longest observations have been carried out on phytoplankton and zooplankton diversity and biomass or abundance, followed by observations on the distribution of large vertebrates such as sea turtles, seabirds and marine mammals as well as on diversity and abundance of some benthic invertebrates. Coral reefs (through coral cover) are the living benthic ecosystem with the longest history of observations (Figure 4).

Variables that were observed by at least two-thirds of the programs were (1) diversity, abundance and distribution of phytoplankton (and pigments), zooplankton, benthic invertebrates, bony fish, microbes, mammals and submerged vegetation, (2) diversity and abundance of birds, sharks, marine mammals, (3) cover of submerged vegetation, corals and benthic invertebrates, (4) distribution of microbes, invertebrate nekton, submerged vegetation and mammals, (5) behaviour and movement of bony fish and (6) microbial activity. For further analysis, these priority variables were simplified into the
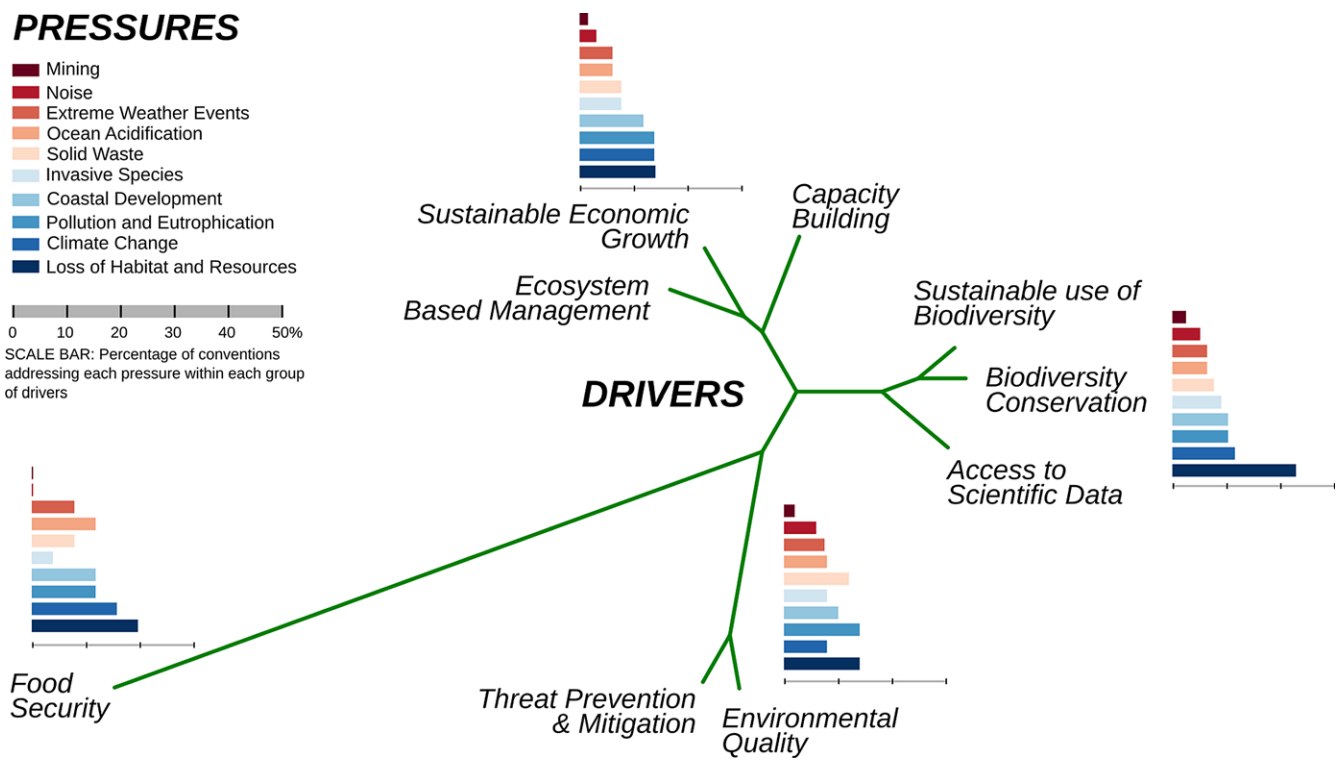
FIGURE 2 Societal needs as identified from the review of 24 international conventions or agreements relevant to global ocean biology. Drivers are clustered as addressed together by the conventions. Segments between drivers represent similarity, the shorter and closer, the more similar. Horizontal bars represent the pressures addressed concurrently with those drivers within the same conventions [Colour figure can be viewed at wileyonlinelibrary.com]
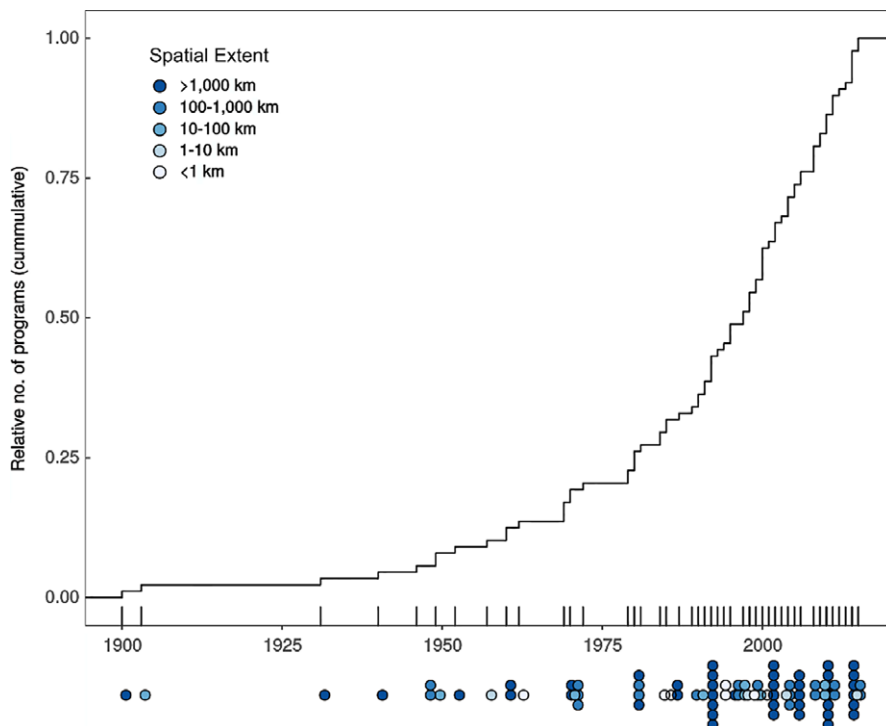
FIGURE 3 Timeline showing the cumulative number of biological ocean observing programs since the early 1900s (restricted to the 104 programs responding the survey). Internal tick-marks along the x-axis represent the years at which at least one new program started. External dots along the x-axis represent new programs throughout the timeline, the darker the dot, the larger the spatial scale at which each operates (as indicated in legend) [Colour figure can be viewed at wileyonlinelibrary.com]

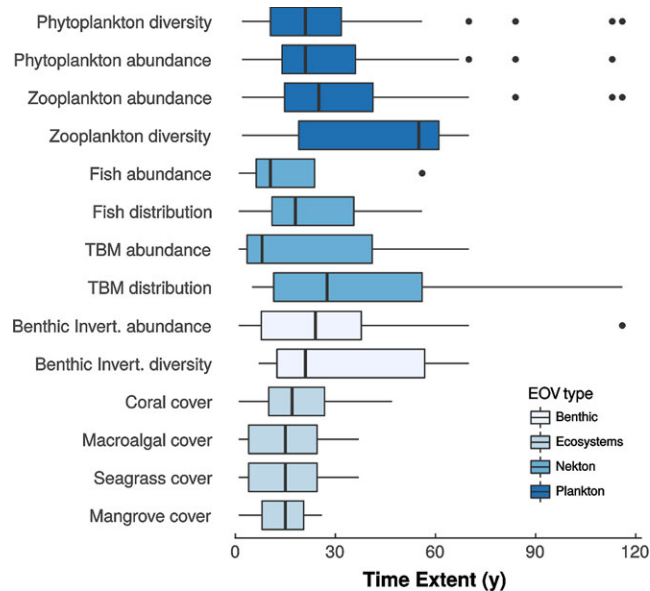**FIGURE 4** Time extent in years of the 104 observing programs measuring the different biological variables. The centre bar of the box plot represents the median, the box extremes the 1st and 3rd quartiles and the whiskers the 5th and 95th percentiles. Black dots represent values above the 95th percentile. TBM: sea turtles, sea birds and marine mammals. "Fish" includes sharks, rays and bony fish [Colour figure can be viewed at wileyonlinelibrary.com]

following categories: microbial diversity and abundance, microbial activity, phytoplankton diversity, phytoplankton abundance or biomass, zooplankton diversity, zooplankton abundance or biomass, benthic diversity, benthic abundance, fish distribution, fish abundance, turtle, bird and mammal distribution, turtle, bird and mammal abundance, coral cover, seagrass cover, macroalgal cover and mangrove cover. Overall, phytoplankton biomass, zooplankton abundance and biodiversity (including ichthyoplankton), and abundance of benthic organisms were the variables observed by the largest number of programs.

3.3 | Scientific relevance and societal impact of priority variables

The SCOPUS database contained a total of 12,240, 65,028 and 7,490 publications referring to the drivers, pressures and priority variables, respectively. Of these, there were 288 publications where drivers were mentioned with a variable (2.35% of all papers referring to the drivers) and 1,795 where pressures were mentioned with a variable (2.76% of all papers referring to the pressures). The variables that were connected the most to societal drivers and pressures within the literature were mangrove cover, followed by coral cover, macroalgal cover and fish abundance (Figure 5). The variables identified with the highest scalability were zooplankton abundance or biomass, phytoplankton diversity, abundance of benthic invertebrates, and phytoplankton abundance or biomass. The variables with the highest impact (using the "RI" for pressures only) were mangrove

cover and coral cover (Figure 6). The analysis yielded two groups of initial biological and ecosystem EOVs, one focused on ecosystem components and the other on habitat extent and ecosystem health. The ecosystem component EOVs are: (1) phytoplankton biomass and diversity, (2) zooplankton biomass and diversity, (3) fish abundance and distribution, (4) marine turtle, bird and mammal abundance and distribution. The EOVs focused on habitat extent and ecosystem health are (5) hard coral cover and composition, (6) seagrass cover and composition, (7) macroalgal canopy cover and composition and (8) mangrove cover and composition. As we learn more about the role of microbes in altered ecosystems and technologies become more feasible and affordable for global implementation, "microbial diversity and biomass" will emerge as another EOV.

The general scientific questions to be addressed by the implementing observing system are (1) what are the status and trends of these EOVs in the ocean and (2) have there been biogeographical or ecological shifts in their diversity, distribution and abundance in response to human alterations. The needed complementary variables to deliver these EOVs include taxonomic diversity, species distribution and population abundance among others, and many are framed within the context of essential biodiversity variables (EBVs) (Pereira et al., 2013). These EBVs will be integrated into the EOV framework by the Marine Biodiversity Observation Network (MBON) based on biodiversity observation requirements at different dimensions. Associated benthic invertebrate abundance will be measured as a complementary variable alongside the four benthic habitats (coral reefs, macroalgal, seagrass and mangrove communities). Information on specific scientific questions, the list of complementary variables, derived products and the societal drivers and pressures addressed by each EOV is detailed in Table S7. Specification sheets with technical information for each of the EOVs are available in the GOOS website (http://goosocean.org/eov).

4 | DISCUSSION

The diversity and distribution of marine species depends on physical and biological factors, including temperature and physiological adaptations, biological interactions, habitat area and food availability and quality. As oceans continue to warm and currents to change, we are observing new biogeography patterns and ecological interactions between species (Johnson et al., 2011; Last et al., 2011; Ling & Johnson, 2009; Pecl et al., 2017; Poloczanska et al., 2013; Wernberg et al., 2016) as has occurred in the geological past (Chaudhary, Saeedi, & Costello, 2016; Costello & Chaudhary, 2017; Harnik et al., 2012). Monitoring biodiversity and abundance of key groups and the extent of living habitats along with physical and biogeochemical EOVs, will assist scientists, managers and policy makers forecast and prepare for an expanding redistribution of species and its ecological, social and economic consequences (García Molinos et al., 2016). Our structured, quantitative approach to identify an initial set of biological and ecosystem EOVs provides a framework for monitoring these biological changes regionally and globally. The EOV framework (1)
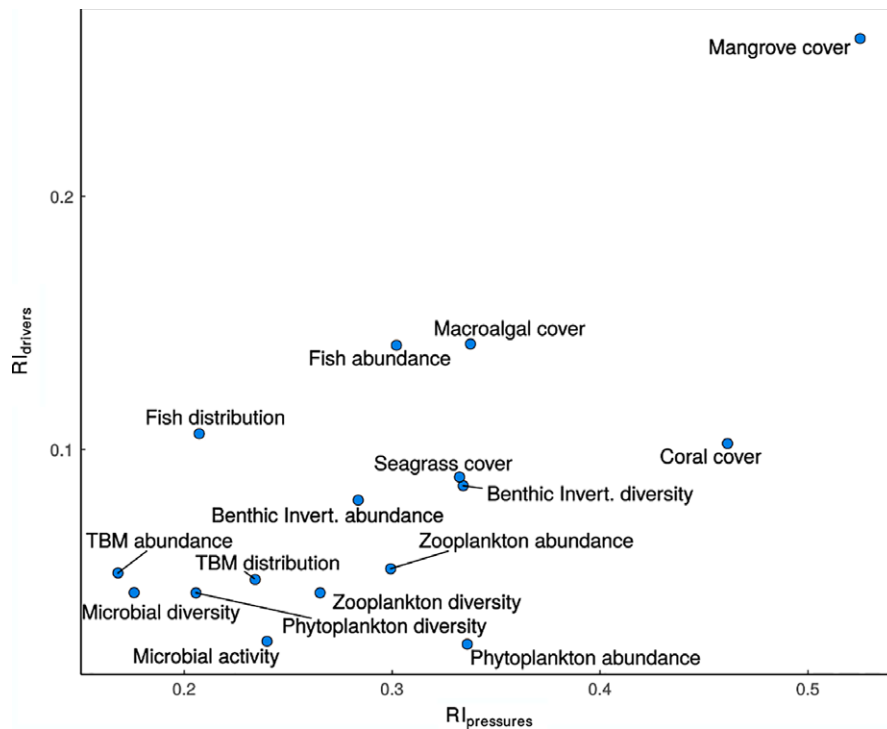
FIGURE 5 Relevance of the priority variables (i.e., measured by at least two thirds of the observing programs) to address societal drivers and pressures using the Relevance Index (RI). RI estimates how each of the variables addresses the convention's drivers and pressures based on the SCOPUS database. TBM: sea turtles, seabirds and marine mammals. "Fish" includes sharks, rays and bony fish [Colour figure can be viewed at wileyonlinelibrary.com]
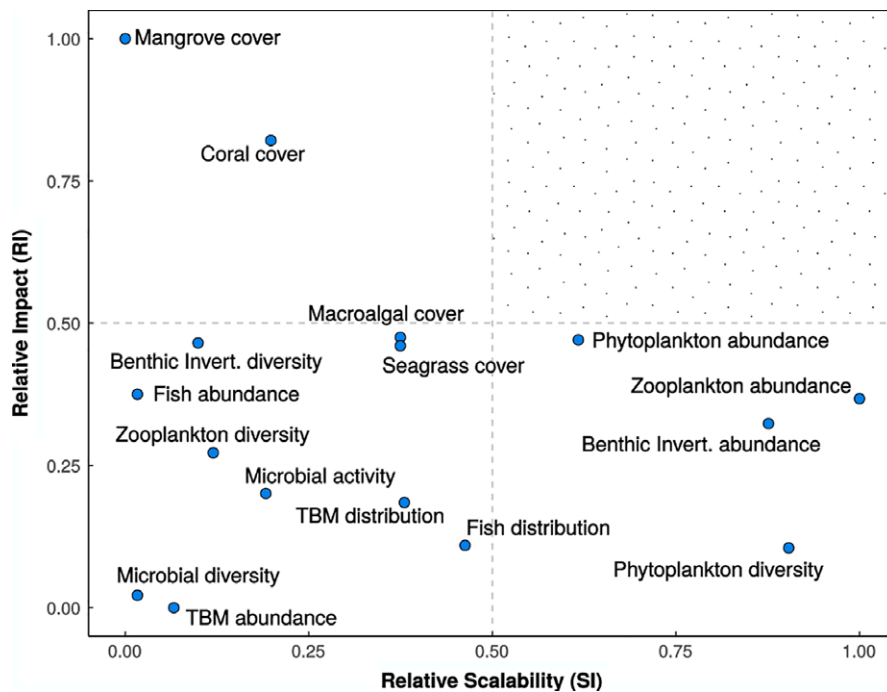
FIGURE 6 Relative impact vs. scalability graph for the priority variables (i.e., measured by at least two thirds of the observing programs). "Impact" based on Relevance Index for pressures and "Scalability" based on the Scalability Index (SI) considering spatial cover and temporal extent of observation of priority variables. Both axes were scaled to 0–1 using minimum and maximum values. The shaded grey area in the upper right quartile represents the target area for essential ocean variable investment according to the framework for ocean observing. TBM: sea turtles, seabirds and marine mammals. "Fish" includes sharks, rays and bony fish [Colour figure can be viewed at wileyonlinelibrary.com]

considers societal relevance to inform several international conventions and agreements (Figure S2), (2) builds on a century-long history of exploration and observing from an engaged scientific community and (3) builds on previously proposed technical and scientific frameworks (Constable et al., 2016; Duffy et al., 2013; IOOC BIO-TT, 2016; Lara-Lopez, Moltmann, & Proctor, 2016; Muller-Karger et al., 2014; Pereira et al., 2013; UNESCO-IOC, 2013, 2014; WMO, 2016; Table S1). The EOVs identified here simplify communication and we hope galvanize support for implementing a valuable and achievable global observing system.

Target investments should be made in strengthening the implementation of EOVs that meet both the criteria of high societal relevance and high technical feasibility at a global level, but that are also fit for purpose (Lindstrom et al., 2012). For the identified biological EOVs, societal impact will vary significantly across geographic areas, and will be influenced by specific local and regional needs. For example, a time-series of the more scalable variables (e.g., zooplankton abundance, phytoplankton abundance and diversity), will have significant relevance to understand long-term effects of the climate system at the global level, while a time-series of coral or of mangrove cover, two latitudinally restricted ecosystems which provide important ecosystem services, especially to more vulnerable societies, will have a disproportionate (and more immediate) social and economic impact in comparison to similar sized areas in the open ocean. Some of the EOVs with higher scalability (e.g., zooplankton abundance, phytoplankton diversity and abundance) are currently either measured primarily at higher latitudes by established research centres (Batten & Burkill, 2010; Edwards, Beaugrand, Hays, Koslow, & Richardson, 2010; Edwards et al., 2012; Koslow, Miller, & McGowan, 2015; McQuatters-Gollop et al., 2015) or can be partly assessed from satellites (e.g., net primary productivity or NPP; Siegel et al., 2016). As we move forward with implementation, there are existing approaches that can be used to improve both the global coverage and impact of these EOVs (e.g., assessments from remote sensing platforms; Muller-Karger et al., 2013), but these will need in situ verification at more local scales. It is essential that as a global system, observations should be accessible to all countries and capacity development and technology transfer will be indispensable elements of the implementation approach, both providing the global coverage and uptake. The cost of implementing a global system is another challenging factor to consider when developing each EOV. Within GOOS, the maturity of an EOV is gauged by considering the 'readiness' of the variable in terms of requirements, observations, and data and information (Lindstrom et al., 2012). For example, the live coral EOV is considered to be relatively mature as there are well-established programs that monitor the status of coral reefs on a regular basis (see Jackson, Donovan, Cramer, & Lam, 2014 for the Caribbean; Smith et al., 2016; for reefs in Hawaii and the central Pacific; De'ath, Fabricius, Sweatman, & Puotinen, 2012; GBRMPA, 2014 and Hughes et al., 2017 for the Australian Great Barrier Reef). Determining the cost of a global coral reef monitoring program, however, is complex because it depends on a variety of aspects that vary significantly depending on the reef location (remote vs. local),

labour costs, scientific capacity, operational capacity, scales, measured variables and protocol used, all of which are significantly sensitive to the living costs of each particular region (Table S8). While scientific knowledge and advances will underpin the GOOS, economics will determine its success.

4.1 | Applicability of the EOVs to globally assess marine life in a changing ocean

Given the complexity of marine ecosystems, some of the key issues to consider for the applicability of these EOVs are (1) what can these EOVs inform and in what time frame, and (2) will the EOVs be useful to detect nonlinear responses.

Measuring phytoplankton biodiversity, community composition and biomass on a sustained basis along with timely detecting global harmful algal blooms is the focus of several ongoing efforts (e.g., the Marine Biodiversity Observation Network or MBON and the IOC-UNESCO's Harmful Algal Bloom program) to make informed decisions (Duffy et al., 2013; Muller-Karger et al., 2014). Monitoring the phytoplankton EOV is a practical way to assess ocean ecosystem health and detect changes at multiple levels because many ocean ecosystem services, such as fishery catch potential (Cheung, Watson, & Pauly, 2013; Glantz, 2005; Platt, Fuentes-Yaco, & Frank, 2003), detection of harmful algal blooms (Paerl & Huisman, 2009), changes in food quality (Winder, Carstensen, Galloway, Jakobsen, & Cloern, 2017), and carbon sequestration and flux export to the deep sea (Siegel et al., 2014) depend on these microorganisms. Monitoring the phytoplankton community can also help understand top-down pressures (Casini et al., 2009; Frank, Petrie, Choi, & Leggett, 2005; Mozetič, Francé, Kogovšek, Talaber, & Malej, 2012; Prowe, Pahlow, Dutkiewicz, Follows, & Oschlies, 2012) and shifts that are occurring at higher trophic levels (Chavez, Ryan, Lluch-Cota, & Ñiquen, 2003; Frederiksen, Edwards, Richardson, Halliday, & Wanless, 2006; Hunt, 2007; Schwarz, Goebel, Costa, & Kilpatrick, 2013). Remote sensing is a sustainable means to monitor changes in the abundance of various functional groups of phytoplankton and can provide regional as well as three-dimensional insights into biological impacts from chemical and physical ocean changes when paired with in situ time-series (Boyd et al., 2016; Church, Lomas, & Muller-Karger, 2013; Kavanaugh et al., 2014, 2016; Rivero-Calle, Gnanadesikan, Del Castillo, Balch, & Guikema, 2015). Remote sensing data on ocean colour can estimate changes in chlorophyll and productivity over time scales from seasons to decades (e.g., Behrenfeld et al., 2006; Foster, Griffin, & Dunstan, 2014); however, similarly to physical EOVs, multi-decadal time-series (30–40 years or even more in the North Pacific) may be needed to finally distinguish between climate variability and climate change (Henson et al., 2010, 2016; Mantua & Hare, 2002; Minobe, 1997; NASEM, 2016). Regardless of the variable and duration, observing is necessary if and when attribution becomes possible, and for a host of other requirements. Fortunately, in many cases EOVs are building on existing long time-series, and existing collections like the CPR are being reanalysed with modern technologies, including genetics and electron microscopy to extend their value to

further biological groups. This means that the climate change signal can be detected in some areas or for some taxa while the global observing system is being built. Some scenarios suggest that the strongest signal of a warming ocean will be in large turnover of local community composition (Dutkiewicz, Scott, & Follows, 2013) and taxonomic time-series have the advantage of extending back a century or more (e.g., Last et al., 2011). The question of which kind of changes in community composition the phytoplankton EOV will have the power to detect will depend on the different organismal responses (Boyd et al., 2008). These may include adaptation (Irwin, Finkel, Müller-Karger, & Ghinaglia, 2015; Langer et al., 2006), geographic shifts of existing biomes (e.g., Rueda-Roa et al., 2017; Sarmiento et al., 2004) or the establishment of completely new communities (Boyd & Doney, 2003). Phytoplankton monitoring may detect climate-mediated shifts in biomes, especially in isolated areas or where boundaries are very strong (Boyd et al., 2008), however to detect adaptation, time-series of physiological manipulation experiments on natural populations will be required (Boyd et al., 2016).

Zooplankton monitoring results may be used in international initiatives, including reporting against SDG 14, to develop global indicators for the assessment of impacts of human activities, e.g., ocean acidification due to rising CO_2, plastic pollution, and marine ecosystem health. Zooplankton are distributed throughout the global ocean, and their diversity, even presence or absence of taxa, is sensitive to environmental stresses including warming which may result in regime shifts (Barange et al., 2010; Batten & Burkill, 2010; Beaugrand, Brander, Souissi, & Reid, 2003; Beaugrand et al., 2015; Beaugrand, Ibañez, Lindley, & Reid, 2002; Di Lorenzo et al., 2013; Edwards et al., 2010, 2012; Wooster & Zhang, 2004). Focusing on monitoring selected zooplankton species has been proposed as a means to maximize spatial coverage and detect changes in a timely manner (Wooster & Zhang, 2004). Changes in the zooplankton community will also influence higher trophic levels, including fish and large vertebrates (Beaugrand et al., 2003; Bi, Peterson, Lamb, & Casillas, 2011; Richardson, Bakun, Hays, & Gibbons, 2009).

Commercial fisheries data have been the most accessible and used to address temporal and spatial changes in fish communities and provide an assessment of the status of fish in the ocean under the impacts of fishing and climate change (FAO, 2016). Catch data, collected and made available by the UN Food and Agriculture Organization (FAO) since 1950, have been used in global studies as proxies for fish abundance and evaluation of fish stocks worldwide to compensate for the lack of direct fish abundance indices and stock assessments globally and for all stocks (Froese, Zeller, Kleisner, & Pauly, 2012; Halpern et al., 2012; Kleisner, Zeller, Froese, & Pauly, 2013). However, using catch data as indicator of fish abundance or fish spatial distribution can bias the evaluation of fishing impacts on fish resources (Pauly, Hilborn, & Branch, 2013; Shin et al., 2012) or of climate change on fish habitats (Reygondeau et al., 2012). On the other hand, fisheries-independent, large-scale studies are constrained by the availability of scientific survey data that provide direct estimates of fish abundance and presence, though see Koslow, Goericke, Lara-Lopez, and Watson (2011) for an excellent example

of a long time-series, with distributional changes linked to the changing ocean. Sharing of scientific data and metadata analyses have allowed evaluation of ecosystem and fish populations status under global change (e.g., Booth, Poloczanska, Donelson, Molinos, & Burrows, 2017; Bundy, Bohaboy, et al., 2012; Coll et al., 2016; Hutchings, Minto, Ricard, Baum, & Jensen, 2010; Kleisner et al., 2015; Poloczanska et al., 2013), shifts in fish spatial distribution (Last et al., 2011; Pinsky, Worm, Fogarty, Sarmiento, & Levin, 2013) and loss of marine biodiversity (McCauley et al., 2015). The response of fish population indicators to environmental changes may take generally less than 4 years (Bundy, Coll, Shannon, & Shin, 2012), but for more integrated fish community indicators, more than 10 years of data may be needed (Nicholson & Jennings, 2004). Survey data time-series, along with physical and plankton EOVs can help in refining our knowledge of fish spatial habitats (Druon, Fromentin, Aulanier, & Heikkonen, 2011; Jones, Dye, Pinnegar, Warren, & Cheung, 2012), pressures on fish communities (Fu et al., 2015; Link et al., 2009) and causes of interannual to decadal variability (Edwards et al., 2010; Frank, Petrie, Leggett, & Boyce, 2016).

Marine megafauna such as seabirds, sea turtles and marine mammals are ideal candidates for understanding and communicating the impacts of climate change on marine ecosystems (Durant et al., 2009; Hawkes, Broderick, Godfrey, & Godley, 2009; Lascelles et al., 2014; Moore, 2008; Moore & Huntington, 2008; Sydeman, Poloczanska, Reed, & Thompson, 2015; Sydeman, Thompson, & Kitaysky, 2012). Many populations appear to have consistent migration pathways (Horton et al., 2017), and may be having difficulty in adapting to shifts in environmental conditions (Ainley et al., 2005; Barbraud et al., 2011; Hazen et al., 2013; Jenouvrier et al., 2009; MacLeod, 2009; Soldatini, Albores-Barajas, Massa, & Gimenez, 2016; Sprogis, Christiansen, Wandres, & Bejder, 2018; Sydeman et al., 2012) and to bottom-up effects caused by changes in the distribution and abundance of prey species (Evans & Bjørge, 2013; Neeman, Robinson, Paladino, Spotila, & O'Connor, 2015; Sydeman et al., 2012). Resulting population declines worldwide may have dangerous top-down effects on the structure, function and stability of marine food webs (Estes et al., 2011; McCauley et al., 2015). At the same time, the recovery of many whale species has been one of marine conservation success stories although poorly recognized outside the science community (Bejder, Johnston, Smith, Friedlaender, & Bejder, 2016). Population trends result mostly from field or satellite observations of entire colonies and from animal telemetry (LaRue et al., 2014).

In addition to monitoring marine taxa, monitoring the health status and trends of foundation coastal ecosystems is also of societal relevance. Coral reefs have a long history of monitoring through the engagement of scientists, reef managers and other stakeholders (e.g., the GCRMN; Jackson et al., 2014; Obura et al., 2017; Wilkinson, 1998, 2008). Increasing awareness of the importance of coral reefs for biodiversity and ecosystem health indicators in policy circles (Convention for Biological Diversity, 2014; UNEA, 2016; World Heritage Convention, 2017) and the intensifying impacts of climate change (Heron et al., 2017; van Hooidonk et al., 2016; Wilkinson

et al., 2016) emphasize the need for increased global coordination, coverage and consistency. This will require formalizing societal requirements, strengthening and resourcing methods and reporting networks, and developing appropriate reports on coral cover as an indicator of reef health (Flower et al., 2017). Implementing capacity development and technology transfer to improve data series will be crucial, as most coral reefs (and certainly those supporting low-income communities) are in developing countries.

Marine vegetation ecosystems, including macroalgal assemblages, seagrass beds and mangrove forests harbour diversified assemblages of many species and contribute important functions and services to coastal ecosystems. These include high primary production, provision of nursery areas for commercially important species, protection from coastal erosion and carbon storage (Aburto-Oropeza et al., 2008; Donato et al., 2011; Ezcurra, Ezcurra, Garcillán, Costa, & Aburto-Oropeza, 2016; Hutchison et al., 2015; Krumhansl et al., 2016; Marbà, Díaz-Almela, & Duarte, 2014; Nagelkerken et al., 2008; Schiel & Foster, 2015). These ecosystems are vulnerable to global threats such as ocean warming, and to regional stressors resulting from intensifying human activities along the coast (Boström et al., 2014; Marba & Duarte, 2010; Marbà et al., 2014; Moore & Jarvis, 2008; Reusch, Ehlers, Hämmerli, & Worm, 2005; Waycott et al., 2009). Decades of observations and experiments on macroalgal communities, together with international collaborations, have provided a solid basis to understand their response to environmental change (Dayton, 1985) and show how highly context-dependent this response is (Krumhansl et al., 2016). In these communities, nearly instantaneous changes have been observed in response to heatwaves (Wernberg et al., 2016), whereas forest decline in relation to gradual warming has been observed on a decadal scale (Krumhansl et al., 2016). Such regime shifts from macroalgal forests to less productive and diversified alternative states dominated by turf-forming algae or barren habitat are increasingly documented worldwide (Filbee-Dexter & Scheibling, 2014; Ling, Johnson, Frusher, & Ridgway, 2009; Strain, Thomson, Micheli, Mancuso, & Airoldi, 2014; Wernberg et al., 2016). Similarly, seagrass cover is a sensitive indicator of global change because seagrass productivity and diversity are closely related to its areal coverage, density and biomass. These provide reliable proxies for other associated species and ecosystem processes of interest to conservation, management and fisheries. Field measurements of seagrass cover, density and biomass, are relatively straightforward (Short et al., 2006), but since some seagrass beds are also visible from various remote sensing platforms, methods are under active development to increase accuracy of seagrass measurement via satellites and drones (Hossain, Bujang, Zakaria, & Hashim, 2015). Lastly, mangroves are considered an important contributor to the blue economy (Aburto-Oropeza et al., 2008), but although historical estimates and an atlas of mangrove cover include local status and important species information (e.g., Friess & Webb, 2014; Spalding, 2010), they are snapshots using aggregated data from regional or national studies. More often, these studies lack the high spatial and temporal granularity or an agreed measurement method, limiting our understanding of biodiversity, functionality, carbon stocks and

conservation associated with mangroves. Remote sensing technology is helping to estimate mangrove cover at a worldwide scale; however, these can be limited without onground validation (McOwen et al., 2016) to clarify species composition and status, and even the value of good satellite coverage is limited if no one is paying attention (Duke et al., 2017).

Essential Ocean Variables are interdependent across trophic levels and ecosystems. These ecosystems are complex with nonlinear dynamics that can experience regime shifts (Fogarty, Gamble, & Perretti, 2016; Rocha, Yletyinen, Biggs, Blenckner, & Peterson, 2014), but there is already evidence that some of the proposed EOVs can capture these dynamics. For example, macroalgal canopy cover declines as a nonlinear function of grazing pressure and in response to multiple anthropogenic perturbations. Transitions from macroalgal forests to barren habitat or algal turfs are increasingly documented worldwide (Filbee-Dexter & Scheibling, 2014; Strain et al., 2014). Studies integrating observations, models and experiments have shown that macroalgal canopy cover can detect these catastrophic transitions and that early warning indicators can effectively anticipate the approaching tipping point (Benedetti-Cecchi, Tamburello, Maggi, & Bulleri, 2015; Ling et al., 2009; Rindi, Dal Bello, Dai, Gore, & Benedetti-Cecchi, 2017), therefore, using macroalgal canopy cover as an early warning system in marine coastal environments is a realistic prospect. The ability to detect nonlinear responses will also depend on sampling resolution in time and space, and improved methods of statistical analysis that can use data in an unaggregated form (Foster et al., 2014). Other factors to consider as well are the number of associated (and fit for purpose) physical and biogeochemical variables being sampled concomitantly, the strength of the signal and the complexity of the ecosystem (Metcalf, van Putten, Frusher, Tull, & Marshall, 2014), among others. These will vary considerably across EOVs.

We have discussed the scientific applications of the EOVs and how they are increasingly relevant for policy and to guide future management. Some of these EOVs, specifically plankton and those related to coastal habitats, are already being proposed as ECVs under the GCOS framework (WMO, 2016). In physical oceanography, essential variables (e.g., temperature) have been collected globally in a standardized manner providing valuable input to the IPCC. At present, there are no biological standards used globally even for well-known important ecosystems as coral reefs. One of the major roles of the global observing system will be to join forces with the observing networks (e.g., the GCRMN) to develop standard methods and to help raise their profile to support national and global reporting.

An emerging EOV is microbial diversity, function and biomass. While microbe-related variables ranked low on societal impact due to the comparatively small number of papers linking microbial science to societal drivers and pressures, ocean microbiome research has pointed towards their use as indicators of ecosystem stress (Sun, Dafforn, Brown, & Johnston, 2012). Significant progress has also been made in understanding their seasonality, habitat-consistency and role in biogeochemical processes in the ocean and as primary producers (Moran, 2015). The Census of Marine Life program made a major contribution to catalogue and quantify the diversity of

microbes in the ocean through the International Census of Marine Microbes (ICoMM) project (Amaral-Zetler et al., 2010). More recently, the Tara Oceans Expeditions have contributed significantly to the global knowledge of marine microbial communities by having created a dataset with more than 7,200 gigabytes of metagenomic data from a broad range of locations and depths across the global ocean (Sunagawa et al., 2015). At least 30% of the programs we surveyed carry out some type of microbial measurement, but few of them are currently prepared to do it at large scales (e.g., Tara Oceans, the Australian Integrated Marine Observing System—IMOS). A recent inventory indicated that there are more than 70 microbial or marine genomic observatories around the world and pointed out for the need of more coordinated efforts to maximize the collective efforts (Buttigieg et al., 2018). As "meta-omics" technologies are further refined and made more easily available globally and as automated energy-efficient samplers and processors can be added to existing sampling platforms, monitoring the ocean microbiome and its attributes will become a powerful tool to understand environmental effects on biodiversity (Bodrossy, 2015; Pomeroy et al., 2007).

4.2 | Challenges of global implementation of the EOVs

By focusing initial efforts on a small number of essential variables that are well specified, the GOOS EOVs provide a means to promote and facilitate networking, data standardization and consistent reporting, thereby raising their societal impact and relevance. As new technologies and new platforms are developed and more networks that build on existing national and regional observing programs are incorporated in the global observing system, EOVs will be revisited and their technical specifications will evolve. The emerging microbe EOV will be an example of this evolution. Implementing a global observing system of biological variables will face many logistical, technical and conceptual challenges. Some of these will be to: (1) achieve standardization of the measurements, or at least intercomparability of the data, (2) develop scientific and technical innovations that are balanced with long-term stability, (3) have the commitment from the international community to support the cost of the observing system and a clear strategy to develop capacity and transfer technology to where it is most needed, and (4) help to integrate experiments, observation and modelling into the observing system. The integration of models across the environmental, social and economic dimensions and strengthening the data capacity by improving data collection, storage and analysis technologies has been proposed to overcome some of these challenges (Addison et al., 2017). This will require standardizing methodologies for indicators and increasing data analysis and computing capacity (software, hardware and connectivity) in the developing world while encouraging international data publication standards and open data (Miloslavich et al., 2016). Integrating manipulative experiments with monitoring will provide additional insight on species-specific physiological adaptation mechanisms and suggest new hypothesis which, coupled with modelling, will result in better predictions of future shifts (Boyd et al., 2016).

The examples provided above illustrate the flexibility of EOVs to test theories and hypotheses relevant to ocean conservation through the integration of observations, models and experiments. While most of the proposed EOVs are part of ongoing monitoring programs to detect broad-scale trends, they are also suitable to experimental manipulation and more process-based studies to identify the underlying factors causing those trends. The distributed experimental approach, where local-scale experiments are embedded in large-scale sampling activities, is a strategy to integrate observational and experimental data (Hewitt, Thrush, Dayton, & Bonsdorff, 2007; Menge et al., 2002). In addition, emerging techniques such as Empirical Dynamic Modelling, offer new opportunities to integrate models with observations (Clark et al., 2015; Sugihara et al., 2012; Ye et al., 2015). These techniques improve our ability to detect causality in complex ecosystems and can be implemented with short, spatially replicated time-series, which are available and can be maintained for all the proposed EOVs.

International collaboration will be essential in integrating and coordinating these different scaled approaches (Duffy et al., 2013; Lu et al., 2015). A significant first step in this direction is the signed agreement between GOOS, the Ocean Biogeographic Information System (OBIS) and the MBON of GEOBON (http://www.iobis.org/documents/GOOS-BioEco-OBIS-GEOBON-MBON_collaboration_SIGNED.pdf). This collaboration is intended to build a unified, globally consistent and sustained observing system, committed to open access and data sharing, that will enhance current existing observation scopes and capacities; make use of the best available resources; implement best practices and international standards; and enhance global capacity. While this is a major step forward, it is still not enough. Establishing and/or strengthening collaborations with the proliferating number of ocean stewardship initiatives as well as ensuring the collaboration and commitment from governments and increasing public and policy awareness on the benefits of ocean observations will be the next required steps.

4.3 | Building an integrated, multidisciplinary GOOS

We have discussed the relevance of the EOVs to assess and detect spatial and temporal changes in marine biodiversity and ecosystems matched with societal needs. The next step will be their implementation. For implementation to succeed, this global observing system needs to: (1) be multidisciplinary and based on best practices, (2) build on existing observing platforms, and (3) strengthen and expand the current capacities. Measuring biological EOVs in conjunction with the other GOOS physical and biogeochemical EOVs will help characterize the interplay and dependence between the biological, chemical, physical and geological properties of the environment. This multidisciplinary approach is key to comprehensively understand the variety of effects of global change at different spatial and temporal scales across taxonomic groups and ecosystems (O'Brien et al., 2017). Many platforms that have traditionally focused on physical observations can be expanded to include biogeochemical and

biological observations. Likewise, many biological observations are accompanied by physical measurements that can also have use to the physical oceanographic community (e.g., animal telemetry; Hussey et al., 2015). An opportunity to strengthen the interaction between biological and physical and biogeochemical platforms could clearly be through the CPR program. The CPR time-series is unique not only for being one of the longest biological time-series in the ocean, but also because it was built using the same piece of sampler gear that is still considered technically excellent. At present, CPR deployment is being extended to further platforms, including some traditionally used only for physical sampling and discussions are underway to study the feasibility of installing biogeochemical sensors (e.g., for oxygen) to take measurements along with the CPR tows (Palacz et al., 2017).

Building and expanding on existing multiple observing programs and establishing alliances with global sampling platforms and/or long-term programs such as GO-SHIP (http://www.go-ship.org/), OceanSITES (http://www.oceansites.org/), GEOTRACES (http://www.geotraces.org/) and to emerging observing programs (e.g., the Deep Ocean Observing Strategy— http://www.deepoceanobserving.org/) among others, will be of utmost importance.

ORCID

Patricia Miloslavich http://orcid.org/0000-0001-5409-1401
Lisandro Benedetti-Cecchi http://orcid.org/0000-0001-5244-5202

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