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SPECIALTY GRAND CHALLENGE
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Past and Future Grand Challenges in Marine Ecosystem Ecology

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INITIAL GRAND CHALLENGES

Frontiers in Marine Science launched the Marine Ecosystems Ecology (FMARS-MEE) section in 2014, with a paper that identified eight grand challenges for the discipline (Borja, 2014). Since then, this section has published a total of 370 papers, including 336 addressing aspects of those challenges. As editors of the journal, with a wide range of marine ecology expertise, we felt it was timely to evaluate research advances related to those challenges; and to update the scope of the section to reflect the grand challenges we envision for the next 10 years. This output will match with the United Nations (UN) Decade on Oceans Science for Sustainable Development (DOSSD; Claudet et al., 2020), UN Decade of Ecosystems Restoration (DER; Young and Schwartz, 2019), and the UN Sustainable Development Goals (SDGs; Visbeck et al., 2014).

First, we analyzed each published paper and assigned their topic to a maximum of two out of the eight challenges (all information available in **Supplementary Table 1**). We then extracted the 3–5 most cited papers within each challenge using two criteria: the total number of citations during this 6-year period, and the annual citation rate (i.e., the mean annual number of citations since publication). We then collated the topics covered by this reduced list of papers (**Table 1**) and summarized the outcomes for each topic.

Not surprisingly, 50.5% of the papers dealt broadly with the role of marine biodiversity in maintaining ecosystem function, since they are related to the core of the journal section. They are followed by papers addressing relationships between human pressures and marine ecosystems (19.5%), and ecosystem modeling (11.6%). Just fewer than 10% of the papers were unrelated to any of the challenges defined by Borja (2014) (**Table 1**). Papers related to the assessment of ocean health had the highest impact, with a relatively high number of citations, despite the low number of papers published on the topic (**Figure 1**). In fact, of the top papers assigned to each challenge, those assessing ocean health received the highest annual mean number of citations, followed by papers on understanding relationships between human pressures and ecosystems, and those dealing with understanding the role of biodiversity in maintaining ecosystems functionality (**Table 1**).

The topics of the publications spanned all ecosystem components, from microbes to mammals; habitats from pelagic to benthic; many individual and multiple human pressures and natural stressors affecting species, their populations, communities and habitats; methodologies for monitoring, modeling, and assessment; conservation, protection, restoration, and recovery of marine ecosystems; global change effects; and different management issues (**Table 1**). Some of the papers that did not focus on the grand challenges dealt with a special Research Topic, for example, ocean literacy (Borja et al., 2020a).

GRAND CHALLENGES FOR COMING DECADE

Although publications in FMARS-MEE have focused on many of the challenges stated in 2014, critical gaps remain which will require considerable research effort to be bridged (**Table 1**). Furthermore, the analysis of the papers published from 2014 to 2019 in FMARS-MEE, and the discussion held by the editorial board when preparing this paper, points to some new or updated grand challenges, as core of our journal section. Other secondary challenges alongside governance, social, and methodological priorities, were identified as important and we also propose them for consideration into the next decade (**Table 2**). Addressing these challenges, which are deeply related to each-other (**Table 2**), would help increase our knowledge of the global ocean, raise awareness on ocean status and identify nature-based solutions to mitigate the impacts of current pressures.

New and Updated Grand Challenges

Our revisited list of new (N) grand challenges (**Table 2**) includes:

(N1) Understanding of interaction among diversity and ecosystem processes, structure and function, which is still the core of FMARS-MEE. Expanding the scope and relevance of future studies will allow to better understand the complex biophysical relationships among biodiversity, food-web structure, ecological processes, and ecosystem functioning, and thus increase our predictive capacity of the ecological consequences of shifts in biodiversity;

(N2) Measuring ecosystem shifts, biodiversity and habitat loss, clearly related to international commitments on sustaining biodiversity (O'Hara et al., 2019). Although ecologists recognize that Earth is now experiencing the sixth mass extinction, quantifying ecosystem shifts, and biodiversity loss remains challenging and often leads to scientific debates (e.g., Vellend et al., 2017);

(N3) Restoring degraded systems, in line with the UN DER. Marine and coastal ecosystems have suffered substantial degradation in the last century, with important loss in their capacity to deliver ecosystem services (Rocha et al., 2015). Ecological restoration efforts often have low success rates, indicating the need for new strategies, that better account for marine connectivity and interactions with adjacent ecosystems, as well as the physical environment (Gillis et al., 2017). To date, restoration efforts have focused on coastal ecosystems, but with increasing exploration for hydrocarbons and other resources offshore and in areas beyond national jurisdiction, approaches for deep-sea and open sea restoration should be explored and tested;

(N4) Moving from descriptive studies to those providing functional assessments, improving the understanding of marine ecosystems, supporting management and sustainability strategies for human activities in the ocean, in line with the UN DOSSD;

(N5) Understanding the cause-effect pathways and the response of ecosystems to increasing cumulative human impacts and climate change (Ortiz et al., 2018), as drivers of shifts in most marine ecosystems, altering species distributions and threatening biodiversity (Halpern et al., 2019). Such cause-effect pathways are inherently non-linear and include direct and indirect feedbacks (Fu et al., 2018). Consequently, this challenge is complex and requires novel methods of assessment and models spanning across disciplines (Crain et al., 2008; Phillips et al., 2019). The assessment of success rates for management under these often synergistic pressures (Audzijonyte et al., 2016); and

(N6) Supporting marine conservation actions and their efficiency under global change and shifting policies. Climate change and a developing policy landscape (e.g., Blue Growth, UN SDGs) present great challenges for marine conservation, requiring changes in human attitudes, and adaptive and creative approaches, such as adaptive conservation planning (including Marine Protected Areas (MPAs) design) that account for climate hotspots and refugia (Queirós et al., 2016), assisted evolution, and shifting focus from protecting species to protecting ecological functions (Rilov et al., 2020).

Secondary Challenges

In addition to the grand challenges, we have also identified some secondary (S) challenges (**Table 2**), including:

TABLE 1 | Grand Challenges in Marine Ecosystems Ecology, as defined by Borja (2014), number of papers published (and percentage) on each challenge in Frontiers in Marine Science (section Marine Ecosystems Ecology), topics covered by the most cited references for each challenge, considering mean annual citations per paper (excluding self-citations from all authors for the period 2014–2019) and/or total number of citations received (as in SCOPUS on 15th January 2020).

Grand challenge	Papers published (nr)	(%)	Most cited references	Topic covered	Top papers citations (annual mean | total)	Comments
1. Understanding the role of biodiversity in maintaining ecosystems functionality	187	50.5	Renaud et al., 2015	Macroalgal detritus and food-web subsidies in the Arctic	7.0 | 45	From the papers received in 2014–2019, this is the main core topic of the journal. This includes the multiple relationships and interactions between different ecosystem components, between them and the physico-chemical component of the system, including processes, structure and functionality. Likely this will also be the main topic in the future
			Kristensen et al., 2014	Effects of shifts in benthos and functional traits to biogeochemical cycling	6.3 | 47	
			Heithaus et al., 2014	Relationships between seagrasses, turtles and sharks	5.8 | 47	
2. Understanding relationships between human pressures and ecosystems	72	19.5	Katsanevakis et al., 2014	Human activities and alien species mapping	10.7 | 76	With increasing maritime activities, the need of understanding these relationships will be maintained, and, as such, occupying a part of the papers in the journal. Especially, the effects of multiple pressures on marine ecosystems will receive increasing attention. Some specific pressures (e.g., invasive species) will need a new grand challenge (**Table 2**)
			Patrício et al., 2016	DPSIR framework review	7.3 | 38	
			Korpinen and Andersen, 2016	Review on marine cumulative impact assessments	5.8 | 24	
			Chartrand et al., 2016	Dredging activity pressures on seagrasses	3.5 | 27	
3. Understanding the impact of global change on marine ecosystems	36	9.7	Duarte and Krause-Jensen, 2017	Seagrass meadows contribution to carbon sequestration	9.3 | 38	This global problem will receive increasing attention in our journal in coming years, since it will be a transversal issue for multiple aspects of the marine systems, from natural communities, but also for resources, conservation and management
			Thomsen et al., 2019	Extinctions after heatwaves	8.0 | 13	
			Lindemann and St. John, 2014	Phytoplankton dynamics in a changing world	4.3 | 31	
4. Assessing marine ecosystems health in an integrative way	31	8.4	Borja et al., 2016	Review on integrative methods to assess ocean's health	14.5 | 95	The importance of this challenge is highlighted with the number of citations and the increasing need of assessing the marine systems to take informed management decisions
			Aylagas et al., 2016	Metabarcoding in assessing the status of benthos	11.5 | 57	
			Danovaro et al., 2016	Innovative monitoring tools for ecological status	6.0 | 44	
			Goodwin et al., 2017	DNA sequencing to monitor ecological status	6.0 | 22	
			Borja et al., 2014	Methods to aggregate indicators in assessing the status	5.5 | 57	
5. Delivering ecosystem services by conserving and protecting our seas	14	3.8	St. John et al., 2016	Services provided by mesopelagic fishes	9.3 | 41	The links between the oceans' health (through conservation and protection) and the ecosystem services delivered, as well as the benefits for human well-being, need increasing attention
			Galparsoro et al., 2014	Services provided by benthic habitats	4.3 | 34	
			Mačić et al., 2018	Conservation planning and biological invasions	3.5 | 12	
6. Recovering ecosystem structure and functioning through restoration	16	4.3	Duarte and Krause-Jensen, 2018	Recovery from coastal eutrophication	2.0 | 5	Although our journal has attracted little attention on this challenge, the recovery of marine systems after degradation should have an increasing attention
			Pérez-Ruzafa et al., 2019	Recovery of a lagoon from eutrophicatio	2.0 | 5	
			Rouse et al., 2019	Conservation features for subsea infrastructures	2.0 | 2	
			Gillis et al., 2017	Restoring tropical coastal ecosystems	0.3 | 2	

(Continued)

TABLE 1 | Continued

Grand challenge	Papers published (nr)	(%)	Most cited references	Topic covered	Top papers citations (annual mean | total)	Comments
7. Managing the seas using the ecosystem approach and spatial planning	8	2.2	Newton and Elliott, 2016	Stakeholder engagement in marine management	3.5 | 26	Effects of management of the seas, an ecosystem-based approach and maritime spatial planning on marine ecosystems should receive increasing attention, because of different legislations worldwide
			Smith et al., 2016	Conceptual models in marine management	2.3 | 21	
			Tam et al., 2017	Thresholds and reference points for ecosystem-based management	2.0 | 12	
8. Modeling ecosystems for better management	43	11.6	Faillettaz et al., 2018	Larvae dispersal and connectivity	4.0 | 8	The use of models for habitats and species distribution, connectivity, climate change scenarios, monitoring and assessment, ecological processes, management, etc., will increase
			Mayorga-Adame et al., 2017	Modeling larval connectivity of coral	3.3 | 11	
			Nanninga and Berumen, 2014	Role of individual in larval dispersion	2.5 | 17	
			Robinson et al., 2017	Review of species distribution models	3.3 | 12	
			Lynam et al., 2016	Innovative modeling tools for management	2.3 | 16	
None of the above	34	9.2	Borja, 2014	Challenges in marine ecosystems ecology	8.3 | 57	Social-ecological issues, socio-economic topics, ocean literacy, solutions for the problems of the oceans, human health and oceans, etc., will become more important
			Vázquez-Luis et al., 2017	Mass mortality of an endangered bivalve	4.3 | 22	
			Xavier et al., 2016	Research challenges in the Southern Ocean	2.8 | 21	

Percentages add up to more than 100% because papers were assigned to up to two challenges.

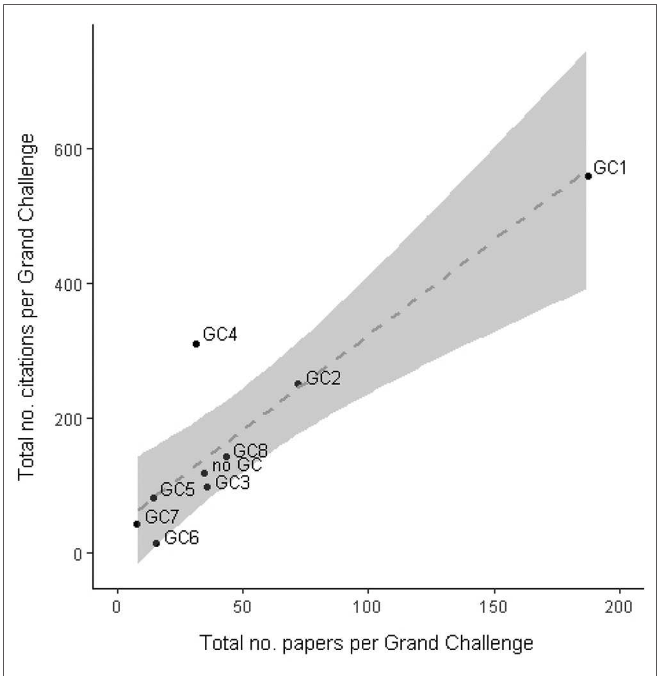

FIGURE 1 | Number of papers published in Frontiers in Marine Science, under the Marine Ecosystem Ecology topic, during the period 2014–2019. Papers are grouped per original Grand Challenge (GC1-8), as identified by Borja (2014), and plotted against the total number of citations received by all papers assigned to each Grand Challenge.

(S1) Linking ocean health with human health, as in the recent agenda proposed by Borja et al. (2020b)

(S2) Understanding the impacts of alien and neonative (Essl et al., 2019) species on ecosystems. Species modify their natural range and invade new regions either aided by human activities (alien species) or by natural means, tracking human-induced environmental change (neonative species). In both cases, they may substantially modify recipient communities, ecosystem functioning and services. Important knowledge gaps restrict our understanding of traits that facilitate invasions and the magnitude of their impacts, our capacity to predict future shifts in ecosystem processes and functioning due to invasive species, and our ability to propose adequate mitigation measures;

(S3) Assessing urban development and subsequent loss of natural coastlines and ecosystem services (Barragán and de Andrés, 2015)

(S4) Understanding the impacts of human activities as well as climate change in the deep ocean (Levin and Le Bris, 2015; Danovaro et al., 2017)

(S5) Considering the land-ocean continuum, with major terrestrial and riverine inputs to the ocean (Xenopoulos et al., 2017). Better understanding these processes would help resolve massive uncertainties in global ocean function, including nutrient cycling, and especially carbon cycling, tightly linked to climate regulation (Friedlingstein et al., 2019)

(S6) Reassessing and evaluating ecosystem processes under the marine "holobiont" paradigm (Margulis, 1991), meaning that any marine organism is a multispecies entity of host and associated microbes. The role of these microbes in organismal function, performance, interaction and ecological context is grossly underappreciated and hence poorly understood;

(S7) Assessing cumulative effects to guide management, since such assessments are increasingly used to inform environmental policy and guide ecosystem-based management but are inherently complex and seldom linked to management processes (Stelzenmüller et al., 2018). There is a need for developing best practices for the operationalization of cumulative effects assessments in a management context (Greenwood et al., 2019; Stelzenmüller et al., 2020); and

(S8) Investigating emerging pollutants (e.g., plastics and additives, pharmaceuticals), artificial light at night, noise and toxin effects on coastal and marine species, habitats and ecosystems (Chae and An, 2017; Rako-Gospić and Picciulin, 2019), including monitoring and assessment.

Governance and Social Priorities

We identified some major challenges related to governance (G) and social priorities (**Table 2**), including:

(G1) Using ecological knowledge, as well as traditional knowledge, to meet UN SDGs, and contributing to the UN DOSSD and DER;

(G2) Incorporating new methods into decision support tools for policy frameworks, promoting effective ecosystem-based management (Pinarbaşi et al., 2019);

(G3) Implementing climate-ready Marine Spatial Planning, including the role of MPAs in conserving the oceans, and creating climatic refugia (Queirós et al., 2016; Frazão Santos et al., 2019);

(G4) Developing transnational observation strategies, in the long-term (Moltmann et al., 2019);

(G5) Engaging society more effectively in ocean science, from ocean literacy, to citizen science and participation in supporting management decision making (Pocock et al., 2018; Borja et al., 2020a); and

(G6) Investigating the role of fake news and how we can use science and science communication to offset this (Scheufele and Krause, 2019). Understanding the impact of social media in positive (e.g., citizen science) and negative ways (e.g., dissemination of fake news).

Methodological Priorities

In this section, we identified some methodological (M) priorities, including:

(M1) Further developing and refining molecular tools for marine applications as decision support tools, particularly those related to the implementation of DNA/RNA-based approaches, e.g. metabarcoding (Pochon et al., 2017; Keeley et al., 2018). These are highly promising approaches, but often still have limited direct applications for monitoring and assessment. International standardization of protocols, Quality Assured/Certified laboratory workflows, and minimal reporting standards, which are critical for improved policy-level uptake, are needed (Leese et al., 2018; Pawlowski et al., 2018). Integration of multi-omics tools for understanding ecosystems functioning is also important;

(M2) Addressing problems multidimensionally, taking into account the whole Earth (e.g., planetary boundaries; Nash et al., 2017);

(M3) Achieving "Consilience," that is, a common path to knowledge by linking facts and fact-based theory across disciplines to create a common groundwork of explanation (Wilson, 1998); this will promote and embrace interdisciplinary and transdisciplinary studies, including e.g., marine ecologists, fisheries scientists, oceanographers, social scientists, economists;

(M4) Acknowledging cultural differences in conducting marine science. Much of the knowledge we produce today is an outcome of many ecologists who share their data and algorithms and release them open and free for access to other scientists and society. All this information can be used in big data and machine learning to tackle all the grand and secondary challenges outlined here (Ma et al., 2018)

(M5) Modeling the future states of marine ecosystems and their services in the face of scenario and process uncertainty (MacNeil et al., 2019). Real limitations still exist with our ability to project and simulate the ecology of a multiple stressors ocean, regime shifts, or extreme climate events (cold snaps, heatwaves); and

(M6) Developing thresholds/targets to assess current and future ecosystems health, especially under climate change (Borja et al., 2012; Queirós et al., 2018).

FINAL REMARK

To adequately address these revised grand challenges over the next 10 years, the FMARS-MEE editors recommend promoting open access to scientific data and publications in order to provide wider distribution of marine ecosystem science, ecological processes, and the complex relationships between biotic and abiotic components, at all levels of biological organization and scales of observation. Free and easy access to data and publications creates a system of information that is transparent, promoting confidence among stakeholders, marine users, policy-makers and the society at large, thus facilitating informed decisions to find solutions for global and ocean-based challenges, such as the UN SDGs, DOSSD and DER. These are core values of FMARS-MEE, enhancing collaborations across the global ocean (Borja et al., 2017; Duarte et al., 2018; Behrenfeld et al., 2019; Duffy et al., 2019; Moltmann et al., 2019).

TABLE 2 | Summary of the new (N) and updated Grand Challenges faced by marine ecosystems in the next decade, as identified by the editorial board of Frontiers in Marine Science (section Marine Ecosystems Ecology), which need to be addressed from science in different ways.

		New and Updated Grand Challenges					
		N1. Understanding of interaction among biodiversity and ecosystem processes	**N2. Measuring ecosystems shifts, biodiversity & habitat loss**	**N3. Restoring degraded systems**	**N4. Moving from descriptive studies to functional**	**N5. Understanding the response of ecosystems to increasing cumulative impacts**	**N6. Supporting marine conservation actions**
Secondary challenges	S1. Linking ocean health and human health						
	S2. Understanding the impacts of alien and neonative species						
	S3. Assessing urban development and impacts						
	S4. Understanding the impacts from human activities						
	S5. Considering land-ocean continuum						
	S6. Reassessing the marine holobiont concept						
	S7. Assessing cumulative effects to guide management						
	S8. Investigating emerging pollutants						
Governance and social priorities	G1. Using ecological knowledge to meet UN SDGs.						
	G2. Incorporating new methods into policy frameworks						
	G3. Implementing climate-ready Marine Spatial Planning						
	G4. Developing transnational observation strategies						
	G5. Engaging society more effectively in ocean science						
	G6. Investigating the role of fake news and how we can use science and social media						
Methodological priorities	M1. Developing and refining molecular tools						
	M2. Addressing problems multidimensionally						
	M3. Achieving 'Consilience'						
	M4. Acknowledging cultural differences in marine science, including open access and big data						
	M5. Modeling the future states of marine ecosystems						
	M6. Setting thresholds/targets to assess						

Also, we highlight other secondary (S) challenges, governance (G), social, and methodological (M) priorities, and the interactions with the Grand Challenges. UN, United Nations; SDG, Sustainable Development Goals; MPA, Marine Protected Areas. Note: for complete names of the challenges, consult the text.

AUTHOR CONTRIBUTIONS

AB developed the idea of the paper and wrote the first draft. Each author contributed with ideas for new challenges and contributed equally to the discussion and in writing the final manuscript.

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SUPPLEMENTARY MATERIAL

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