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Introduction

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Author for correspondence:
Helmut Hillebrand
e-mail: helmut.hillebrand@uni-oldenburg.de

Integrative research perspectives on marine conservation

Helmut Hillebrand[1,2,3], Ute Jacob[2,3] and Heather M. Leslie[4]

[1]Institute for Chemistry and Biology of Marine Environments [ICBM], Carl-von-Ossietzky University Oldenburg, Schleusenstrasse 1, 26382 Wilhelmshaven, Germany
[2]Helmholtz-Institute for Functional Marine Biodiversity at the University of Oldenburg [HIFMB], Ammerländer Heerstrasse 231, 26129 Oldenbburg, Germany
[3]Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research, Am Handelshafen 12, 27570 Bremerhaven, Germany
[4]Darling Marine Center and School of Marine Sciences, University of Maine, 193 Clarks Cove Road, Walpole, ME 04573, USA

HH, 0000-0001-7449-1613

Whereas the conservation and management of biodiversity has become a key issue in environmental sciences and policy in general, the conservation of marine biodiversity faces additional challenges such as the challenges of accessing field sites (e.g. polar, deep sea), knowledge gaps regarding biodiversity trends, high mobility of many organisms in fluid environments, and ecosystem-specific obstacles to stakeholder engagement and governance. This issue comprises contributions from a diverse international group of scientists in a benchmarking volume for a common research agenda on marine conservation. We begin by addressing information gaps on marine biodiversity trends through novel approaches and technologies, then linking such information to ecosystem functioning through a focus on traits. We then leverage the knowledge of these relationships to inform theory aiming at predicting the future composition and functioning of marine communities. Finally, we elucidate the linkages between marine ecosystems and human societies by examining economic, management and governance approaches that contribute to effective marine conservation in practice.

This article is part of the theme issue 'Integrative research perspectives on marine conservation'.

1. Introduction

Biodiversity is changing rapidly across realms. The past year has seen the publication of the first global assessment of the status and trends of biodiversity by the Intergovernmental Platform for Biodiversity and Ecosystem Services (IPBES) [1], highlighting how critically biodiversity is affected by human actions on land and at sea, and how much this will affect human wellbeing. Also in 2019, unprecedented efforts in the quantitative synthesis of time series data provided a global picture on how much biodiversity is changing worldwide [2–4]. Land-use change [5] and climate change [6] have been identified as major drivers of past, current and future biodiversity change. Most scientists would agree that recent changes in biodiversity are occurring at much faster rates than in pre-human environments [7,8].

However, there is still debate on the net outcome of this turnover across scales [9,10], e.g. whether global species loss will lead to local species loss, or whether immigration will outpace extinction locally, leading to short- to mid-term increases in species richness. Biodiversity change has often been addressed by univariate measures (richness or indices or proportion of certain key species), which remain highly contingent on the temporal and spatial scales of assessments and are sensitive to statistical and ecological artefacts [11–13]. Therefore, it remains a challenge to capture the different aspects of changing biotic composition to reflect the multidimensional processes leading to biodiversity change. Recent debates about temporal changes in species richness [9,14,15] show that biodiversity change is the result of complex patterns of immigration and

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extinction dynamics [10,16], where the temporal turnover of composition reflects changes in the identity of species and their relative proportions. These temporal dynamics are strongly affected by spatial components of biodiversity [17], which themselves are altered by humans through spatial homogenization [18,19]. Finally, there is no simple linear relationship between the amount of compositional (i.e. taxonomical) biodiversity change and functional diversity changes [20,21], which may result in novel ecosystem processes and interaction networks [22,23].

These changes in biodiversity pose a challenge to local, regional and global conservation efforts. At the global level, the Aichi targets to halt biodiversity loss will not be achieved on schedule [24]. By contrast to the international agenda to address climate change, global biodiversity conservation does not have a single goal such as the less than 1.5°C warming target set in the Paris Agreement [25]. Turnover, extinction and immigration are natural processes, which make 'zero change' targets inappropriate. However, alternatives such as certain quota of areas protected from extractive uses often have been criticized for being arbitrary and misleading because the success of conservation is more related to quality and participation than the quantity of conservation measures [26,27]. The protection of strong interactors, including keystone species, has been used by many as a way to focus conservation action [28]. Yet we know that it is not only strongly interacting species that are vital to ecosystem functioning. Thus, knowledge of both species identity and assemblages is needed to design effective conservation measures [29,30].

Management strategies and targets for conservation are actively and widely debated, and have led to major shifts in how conservation has been envisioned and scientifically addressed—Georgina Mace wrote a brilliant essay on the history of conservation ecology a few years ago [31]. Most of these debates have a strong terrestrial focus, as marine conservation has, in comparison, a much shorter scientific track record. Additionally, marine conservation has some extra layers of complexity that need to be considered, a few of which we highlight here.

(a) Types and rates of change

The pressure on marine ecosystems is comparable to the anthropogenic changes on land, and only a small percentage of the seas can be considered 'pristine' [32,33]. However, two major differences exist regarding the type and rate of change: first, whereas the human impact on land can often be related to the amount of land conversion to range- or cropland, the human impact on marine ecosystems is often less area-based. Fisheries, eutrophication by river inflows and non-point pollution, deoxygenation, acidification and warming are not restricted to certain areas. Area-based changes often prevail only in coastal areas, exemplified through the expansion of coastal cities or conversion of mangroves to shrimp farms. Second, marine life has been shown to be more sensitive to changes in temperature [34], and at the same time species turnover is faster [2]. The former is thought to reflect lower thermal tolerances in marine biota given less variable temperature regimes, the latter the high connectivity and low dispersal barriers in open marine ecosystems [2,34,35].

(b) Area-based conservation

The main approach to marine conservation has been through marine protected areas (MPAs). Multiple benefits from MPAs, particularly fully protected marine reserves [36], have been documented, including higher fish biomass (and sometimes biodiversity) [26], the spillover of this increased biomass sustaining neighbouring fisheries [37] and increasing ecological resilience to change [38,39]. However, it has also been shown that without enforcement, MPA effects can be neutral or even negative [26] and different syntheses regarding MPAs arrive at different conclusions [40]. Some MPAs attract higher fishing pressure than non-protected areas [41], many are not adequately equipped with staff and budget [42] and the species that are meant to be protected are threatened by climate warming [43]. Moreover, many MPAs are isolated, reducing the anticipated spillover effects [44]. Debates regarding the effectiveness and strategies for the siting of MPAs might stem partially from expectations created by transferring this concept from terrestrial ecosystem management [45]. By contrast to land, the demarcation of a seascape as protected often reduces only one (mainly harvesting) of the multiple human pressures, but not others (nutrient input, deoxygenization). Therefore, expecting MPAs to operate as terrestrial protected areas may be unrealistic given the open, fluid and three-dimensional nature of the ocean.

(c) Complexity of marine governance

The vast, open, connected and three-dimensional characteristics of the ocean provide a physical challenge to marine conservation. Additionally, much of the world's ocean is outside of exclusive economic zones and thus national jurisdiction and governance regimes [46]. While a legal framework for the international sea exists through the United Nations Convention on the Law of the Sea (UNCLOS), managing areas beyond national jurisdictions is complex, multilayered and slow. The rate of progress of marine conservation of the high seas, even in laudable cases such as Antarctica [47], might be outpaced by the rate of biodiversity change.

2. Contributions to this issue

In this issue, we assemble a unique set of expert perspectives in the marine natural, social and transdisciplinary sciences to provide a forward-looking perspective on marine conservation. Marine environmental research and policymaking hinge upon understanding the consequences of human actions on ocean sustainability owing to multidimensional interactions among environmental responses, biodiversity changes and nature's contributions to people. Traditionally, marine natural and social sciences have addressed single aspects of human impacts on oceans, often focusing on direct links among specific drivers and responses [48]. However, both biodiversity [10] and nature's contributions to people [49] are multifaceted emergent properties of marine ecosystems that require agile, adaptive and adjustable management options to foster effective marine conservation. As guest editors, we thus aimed to recruit a diverse group of contributors representing different disciplines and approaches. We are happy to provide the views from more than 60 authors working in 12 countries, which we have organized into four sections that reflect areas of future scientific development (figure 1).

The first section, entitled 'From data to information', comprises four papers on novel approaches to assess marine biodiversity trends. Our knowledge on biodiversity trends in the ocean often derives from near shore ocean time series,

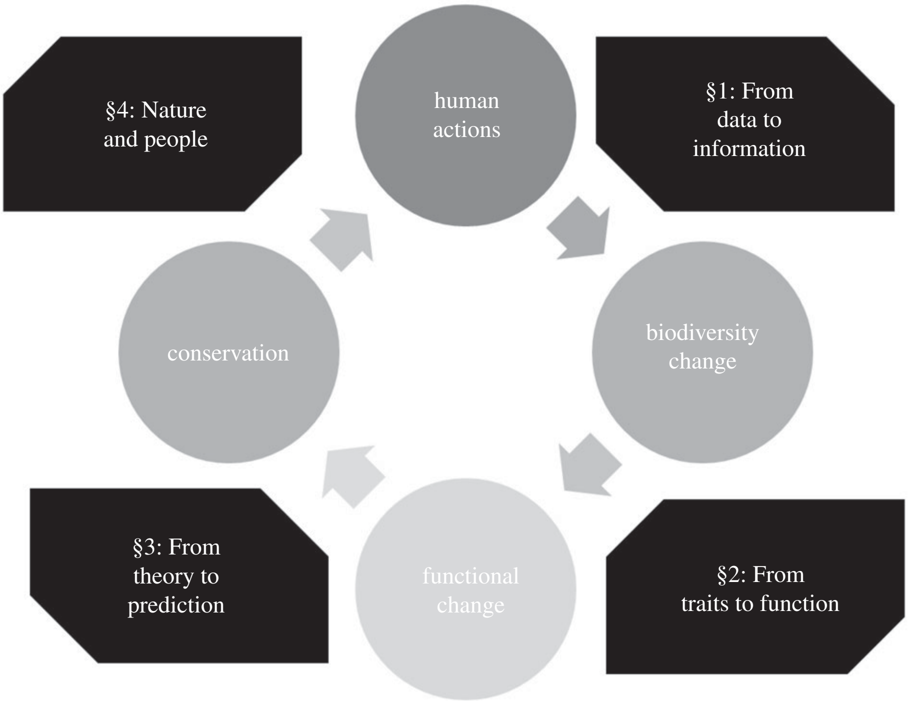

Figure 1. Logical flow of papers in this theme issue.

and for many parts of the ocean we have little knowledge of how much diversity actually changes. This is owing to the challenges of accessing many marine areas (deep sea, polar regions) and our lack of remote sensing tools to uncover marine biodiversity. In the first paper of this section, Webb & Vanhoorne [50] analyse the state of our knowledge on macroecological patterns in marine life. They find that for 44% of the more than 200 000 marine species in data repositories, only their taxonomic information is available, whereas other species are richer in data on biogeography, genetics, conservation status, etc. Making different data sources interoperable is a clear recommendation from this study. Rishworth *et al.* [51] use monitoring data from two coastal regions, Germany and South Africa, to show the extent of temporal variation in species composition. While species richness across organism groups and sites rarely showed significant monotonic trends, species turnover between adjacent years was massive (up to 30% p.a.), and even larger when dominance shifts were taken into account as well. Thus, marine conservation has to take this huge potential for dynamics into account. The next two papers of this section pinpoint to the data revolution ongoing in the environmental sciences, focusing on the assessment of marine biodiversity based on molecular or acoustic analyses. Laakmann *et al.* [52] show how biodiversity assessments have been shifted from classical morphotaxonomic analyses to the use of molecular tools, especially the analyses of organism-independent environmental DNA. Using copepods as a functionally important and well-investigated case, they focus on the advantages and pitfalls of respective methods. Then, Pieretti & Danovaro [53] review recent advances in using marine acoustics to monitor biodiversity in time and space. By contrast to common belief, the ocean is not a silent environment, as many taxa use acoustic communication and habitat exploration, while at the same time the marine soundscapes are altered by anthropogenic noise. But how are these ‘big data’ useful for marine conservation? To explore this question, the section closes with an article by Popa *et al.* [54] on deriving information from sequences, where they show pathways to link molecular information to functional changes in the ecosystem. They advocate including this information into the analyses of temporal trends, and combining such monitoring with modelling and targeted experiments to develop a mechanistic understanding of processes.

Given these advances in understanding and quantifying biodiversity patterns and their temporal and spatial change, the following section ‘From traits to function’ asks how such changes affect the processes characterizing marine ecosystems. Gårdmark & Huss [55] start at the individual level, where responses to warming can alter individual performance, population size structure and finally food web dynamics. They stress that intraspecific variation in responses to temperature and body size need to be embedded in devising and managing conservation efforts. Marshall & Alvarez-Noriega [56] extend on this theme, and focus on dispersal as a key life-history component. They use existing knowledge on two key aspects of life history, dispersal mode (non-feeding pelagic larvae, feeding pelagic larvae, no pelagic larvae) and development duration, to project dispersal strategies into the future. They predict higher dominance of species with feeding larvae and shorter developmental pelagic phases, especially in tropical regions. He *et al.* [57] then use a meta-analysis of 125 studies in coastal wetlands to show how much ecosystem functioning (as carbon cycling) depends on the biotic composition of the consumer guild. They find that the absence or presence of consumer guilds altered the carbon cycle by e.g. halving plant carbon stocks and increasing litter decomposition by more than 30%.

The theoretical underpinning of these ideas is at the core of §3 ‘From theory to prediction,’ where we feature different types of models. Dee *et al.* [58] model temperature-dependent predator–prey dynamics and find that including temperature variability (compared to constant or constantly warming temperatures) alters interacting multispecies assemblages with a multitude of potential outcomes, from predator collapse to stable coexistence. More generally, Bernhardt *et al.* [59] conceptualize the ability of organisms to cope with such variability, and complement the feedback strategies, where organisms respond to changes in conditions by feed-forward mechanisms, where they adjust to anticipated future changes in conditions via sensing the environment. Klausmeier *et al.* [60] then ask how evolutionary adaptation to changing conditions can occur and whether it can be fast enough to prevent extinction. They review different approaches to modelling evolutionary rescue, and finally propose a new approach that explicitly includes bounded environmental changes and limits to adaptation. Gross *et al.* [61] open the door to address spatially connected food webs, reviewing recent developments in metacommunity theory to analyse the structure and functioning of meta-foodwebs.

In the final section (§4 'Nature and people'), we approach marine conservation as a socio-ecological management issue. Kelly *et al.* [62] provide a thorough review on how marine citizen science informs the current understanding of marine biodiversity and supports the development and implementation of marine conservation initiatives. The connection between management of land and consequences at sea is at the core of the analysis of the stormwater impact on coastal ecoregions along the US west coast (Levin *et al.* 2020 [63]). Given the increasing coastal urbanization, stormwater runoff results in massive pollution by a complex chemical cocktail, which only can be mitigated by land management—and in fact it could be managed by treating a small fraction of the terrestrial surface. Jacob *et al.* [64] introduce a multi-layered network approach for a better understanding of how ecosystem services emerging from the diversity of traits embedded in biodiversity drive the total service provision and where conservation efforts must be placed. In a remarkable closing article, Peters [65] addresses marine governance and biodiversity protection as—at least from a theory perspective—uncharted territory. She argues that in order to understand our successes and failures in marine biodiversity conservation, we need more critical discussions about ontologies and geo-philosophies in our current understanding of ocean governance. Here a suggestion to de-territorialize governance to make it more dynamic and flexible elegantly loops back to the first papers of this issue on the dynamic nature of biodiversity change.

In summary, this issue provides an unprecedented effort to address marine biodiversity management by considering the entire chain of information needed, from basic data on the environment to human societal considerations. It would be impossible for an issue like this to provide complete coverage of this topic, but each contribution represents a unique view on the challenges faced in marine conservation. Concern over marine biodiversity loss is becoming increasingly central and important to the global debate, including through links to other key agendas such as the United Nations sustainable development goals (SDGs; see https://sdgs.un.org/goals) and the drive to address climate change and its impacts. Marine biodiversity and the benefits it provides to people is fundamental for achieving the SDGs, as is the need to address the goals synergistically through transformative change of societies and institutions at multiple scales. There is an urgent need to 'bend the curve' of marine biodiversity loss in a manner that simultaneously addresses the full suite of SDGs, and especially climate change, food security, nutrition and health, recognizing and responding to interconnections.

Data accessibility. No data are included in this paper.

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