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100 Opportunities for More Inclusive Ocean Research: Cross-Disciplinary Research Questions for Sustainable Ocean Governance and Management

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In order to inform decision making and policy, research to address sustainability challenges requires cross-disciplinary approaches that are co-created with a wide and inclusive diversity of disciplines and stakeholders. As the UN Decade of Ocean Science for Sustainable Development approaches, it is therefore timely to take stock of the global range of cross-disciplinary questions to inform the development of policies to restore and sustain ocean health. We synthesized questions from major science and policy horizon scanning exercises, identifying 89 questions with relevance for ocean policy and governance. We then scanned the broad ocean science literature to examine issues potentially missed in the horizon scans and supplemented the horizon scan outcome with 11 additional questions. This resulted in an unprioritized list of 100 general questions that would require a cross-disciplinary approach to inform policy. The questions fell into broad categories including: coastal and marine environmental change, managing ocean activities, governance for sustainable oceans, ocean value, and technological and socio-economic innovation. Each question can be customized by ecosystem, region, scale, and socio-political context, and is intended to inspire discussions of salient cross-disciplinary research directions to direct scientific research that will inform policies. Governance and management responses to these questions will best be informed by drawing upon a diversity of natural and social sciences, local and traditional knowledge, and engagement of different sectors and stakeholders.

Keywords: ocean governance and management, interdisciplinary and transdisciplinary science, UN Decade of Ocean Science for Sustainable Development, inclusive research, Anthropocene Ocean, ecosystem services

INTRODUCTION

Creating and mobilizing new knowledge about the environmental and ecological status of the ocean, how the ocean is or could be used, and how it can be governed and managed is crucial, particularly given the important role that oceans play in supporting Earth's life support systems, 'blue growth' (European Commission, 2017), sustainable development, and the 2030 Agenda (United Nations, 2017; Singh et al., 2018). One response to our relatively limited knowledge of ocean status and stressors is the creation of the United Nations Decade of Ocean Science for Sustainable Development 2021–2030 (Ryabinin et al., 2019), hereafter the "Ocean Decade," with its dual goals of generating scientific knowledge and informing policies in support of the 2030 Agenda. One specific objective is to increase scientific knowledge to enhance uptake of ocean science knowledge at the science-policy interface, at global, regional and national levels (Claudet et al., 2019).

Increasing the uptake and use of scientific evidence in the public, private, and non-profit sectors requires credible and salient evidence-based research that is aligned with the needs of decision-makers (Hisschemöller and Hoppe, 1995; Cash et al., 2003; Sutherland et al., 2011). In the ocean science realm, examples of broad, policy-relevant questions that require scientific evidence might include: How do we as a society respond to sea level rise? How can we best address the individual and interactive effects of multiple ocean stressors (e.g., ocean acidification, marine heat waves, changes in circulation, pollution, harvesting)? How can we plan activities at sea to minimize their impacts on biodiversity and ecosystem services? The answers to such questions will of course be context-dependent. The science required to address them can require years of research, fit-for-purpose modeling tools and monitoring of social-ecological systems and processes over a wide range of temporal and spatial scales (Visbeck, 2018). Answering such complicated real-world challenges requires input from numerous branches of the natural and social sciences as well as insights from disciplines not usually considered in marine environmental science (e.g., law, public health, education, food security, systems analysis, communication, arts and humanities, etc.) in an inclusive, cross-disciplinary research approach (Lang et al., 2012; Parsons et al., 2014; Rudd et al., 2018b; Claudet et al., 2019). Cross-disciplinary research can be interdisciplinary or transdisciplinary. These approaches differ in the way collaborators integrate knowledge and methods to develop and meet shared research goals to achieve a real synthesis of approaches (Kelly et al., 2019). In interdisciplinary approaches, different academic research disciplines work together without non-academic collaborators, whereas in transdisciplinary approaches, different academic disciplines and non-academic collaborators work together (Kelly et al., 2019).

Scientists and policy-makers alike recognize the effort and resources required to gather appropriate data and develop capacity for delivering such evidence. However, due to the rapid pace of change in ocean environments as well as policy priorities, there is often a great pressure to address these questions within a very narrow timeframe and with a paucity of data. In anticipation of these requests and to help align scientific effort with policy needs, a number of scientific societies and research teams have performed foresight exercises (henceforth 'horizon scanning') to identify policy-salient research questions and develop insights about new issues on the horizon that may emerge and require attention from scientists and policy-makers.

Horizon scanning exercises have ranged in focus from issues of importance at local, national, sub-regional scales to those at international scales. Research identification and prioritization exercises have traditionally been 'top–down' affairs, with selected consultation from invited representatives from the scientific community (invited experts see e.g., Friedman et al., 2020) and private sector organizations (National Research Council et al., 2015; Holthus, 2018; Boero et al., 2019). However, the past decade has seen an increased use of 'bottom-up' horizon scanning approaches that draw on the collective expertise of thousands of scientists, policy-makers, and practitioners. Examples of bottom up approaches include those that are ocean-focused (e.g., Fissel et al., 2012; Rees et al., 2013; Parsons et al., 2014), deal with broader topics that have ocean-focused components (e.g., Fleishman et al., 2011; Ingram et al., 2013; Rudd et al., 2018b), or address terrestrial questions that also have, with some modification, applicability in the marine and coastal domain (e.g., Mihók et al., 2015).

Various horizon scanning exercises yield overlapping questions, though differences can naturally arise that have been attributed to region, scale, focal ecosystem, or scientific discipline. There can also be differences that may reflect the degree of involvement of various sectors, such as academia, industry, non-governmental organizations, and government (Rudd and Fleishman, 2014; Van den Brink et al., 2018).

As the Ocean Decade approaches, we find it timely to take a broad *global inventory* of the thousands of salient governance and management topics and questions that have emerged over recent years from the diversity of top–down and bottom–up sub-regional to international horizon scanning exercises. For this paper we identified policy-relevant and cross-disciplinary ocean science questions through a systematic screening of diverse horizon scanning exercises. To supplement the horizon scan review and ensure that no major themes were missed, we also examined 400,000 ocean science abstracts (1997–2017). Although many of the topics and questions identified by each horizon scanning exercise are specific to the context in which they were framed (thereby reflecting the habitats, ecosystems, threats and issues identified by the specific horizon scanning effort), many general themes are shared across different contexts.

To make the questions transferable to other contexts and to facilitate broader discussions, we consolidated and generalized the questions to reflect common themes. The result is an unprioritized list of generalized research questions that can be customized and be applied to specific scales, ecosystems, and socio-political contexts.

The horizon scanning exercises engaged thousands of scientists and academics, and representatives from non-governmental organizations, government agencies, and the private sector. In the cases we used, almost all represent the outputs from structured processes to consider emerging environmental challenges. Our endeavor synthesizes those immense efforts. Harvesting research questions and topics from a diversity of horizon scanning exercises and articles is an important first step in helping the scientific community to more quickly overview the emerging range of challenges across regions, ecosystems, and scales. The questions identified in our study will optimistically inspire discussion across sectors and further investigation within public and private research institutions, academic institutions, NGOs, and industry.

METHODS

We used a three-part strategy to identify important ocean policy research questions for inclusion in our synthesis. First we reviewed the horizon scanning literature to identify research questions and topics relevant for ocean governance and management. Second, to help ensure there were not any major gaps in the horizon scanning literature, we conducted a relatively simple text analysis of the recent (1997–2017) ocean science literature. Finally, we formulated the topics into general policy-salient research questions using a structured question syntax (described below).

Identifying Important Research Questions From the Horizon Scanning Literature (Part 1)

First, we identified important research questions from the horizon scanning literature. To identify important research questions we assembled a corpus of peer reviewed articles and reports from the gray literature that reported on science-to-policy question-generating exercises (e.g., 'big question' workshops, working group syntheses), and on topic-oriented horizon scans of emerging science-policy issues (**Table 1**). To ensure full coverage of potentially important research questions we also reviewed a small set of structured reviews and survey research that was based primarily on prior horizon scan research questions.

This is a relatively small literature, so a formal search strategy was not needed: we simply checked all citing articles for several key horizon scanning references (e.g., starting with e.g., Sutherland et al., 2009, 2011), examining each of those for content and any further horizon scanning literature they cited, and for our summary included studies that had identified research questions or topic with potential ocean relevance (even if they were terrestrially oriented studies but which covered general governance and management topic that would be equally applicable in the marine realm).

We coded and grouped questions from the question generating and horizon scanning exercises that addressed similar research topics. We then re-worded and re-combined questions so as to reflect common issues identified in these exercises. This resulted in 89 research questions that cut across a number of different themes.

TABLE 1 | Horizon scanning literature used to generate 89 of the science-policy questions presented in this paper (as described in part 1 of our Methods).

Science-to-policy question-generating exercises	Morton et al., 2009; Sutherland et al., 2009, 2011, 2012c, 2013b; Fleishman et al., 2011; Braunisch et al., 2012; Fissel et al., 2012; Lewison et al., 2012; Feary et al., 2013; Ingram et al., 2013; Kennicutt et al., 2014; Parsons et al., 2014, 2015; Seddon et al., 2014; Vugteveen et al., 2014; Jones et al., 2015; Mihók et al., 2015; Greggor et al., 2016; Kaiser et al., 2016; Kark et al., 2016; Levin et al., 2016; Nagulendran et al., 2016; Oldekop et al., 2016; Antwis et al., 2017; Armstrong et al., 2017; Green et al., 2017; Hernández-Morcillo et al., 2017; Sugiyama et al., 2017; Furley et al., 2018; Mardones et al., 2018; Rudd et al., 2018b; Weeks and Adams, 2018
Horizon scans of emerging science-policy issues	Sutherland et al., 2010, 2011, 2012a,b, 2013a, 2016, 2017, 2018; Rees et al., 2013; Parker et al., 2014; Jones et al., 2015; McWhinnie et al., 2017; Patiño et al., 2017; Ricciardi et al., 2017
Structured	Vegter et al., 2014; Partelow et al., 2018
reviews	Rudd and Lawton, 2013; Rudd, 2014;
Surveys	Rivero and Villasante, 2016

Identifying Research Topics That the Horizon Scans May Not Have Highlighted (Part 2)

Secondly, to supplement our review of the horizon scanning results and identify any potential gaps in important research topics that the horizon scans may have missed (or not prioritized sufficiently highly to include in their final question lists), we conducted our own expanded scan for research topics among the last 20-years of ocean and coastal article abstracts (n = 400,000) from ISI-listed journals. We downloaded to Endnote all abstracts for all articles returned in a search with keywords ocean*, coastal, or marine; while the search terms were excessively broad, we did not want to miss any potentially relevant literature by unduly constraining our initial search. We were therefore likely to capture, as a subset of our search, the ocean science and management literature included in the ISI core collection.

Once downloaded, we used the QDA Miner/Wordstat software package[1] to identify and group phrases of 2–5 words each that were potentially indicative of ocean science and management topics. Phrases were then aggregated (by MAR) into categories and themes, coarser groupings that served as potential research topics to be compared against research themes and topics identified in the horizon scanning study review. In total, we identified 138 categories of research over the past 20-years that could be relevant for policy-oriented research. These included 23 categories characterizing ocean systems, 77 characterizing threats to oceans, and 48 characterizing potential societal responses to threats.

Research topics identified in the abstract scan were then compared with those identified through the horizon scanning

[1] provalisresearch.com

exercises. This was necessarily a subjective exercise but in the end we decided to include 11 additional research topics in our final list (areas we thought may not have received sufficient attention in the horizon scans), bringing our question list to an even 100. Our final list comprised 100 non-prioritized cross-disciplinary research questions listed below.

Formulating Research Questions (Part 3)

All of the research topics that we identified from both the review of the horizon scanning exercises and the published ocean science literature were formulated into policy-salient research questions. In their original form, the syntax of each research question varied substantially. In an effort to reduce jargon and state questions in plain English and a consistent manner, we identified and removed the following components from each question:

- explicitly stated contextual qualifiers
- specifically identified decision-makers
- evaluative criteria and/or precise objectives.

Each of our 100 questions can be fine-tuned for practical use by readers by expanding them as follows:

> *Given the* ***perceived threat or opportunity*** *facing our* ***target human (or natural) constituency*** *[e.g., citizens, stakeholders, businesses, endangered species, habitat, etc...] in* ***our region*** *over the* ***relevant planning time horizon***, ***how can we*** *[e.g., consumers, citizens, households, firms, agencies, managers, etc...] as decision-makers* ***best*** *[e.g., effectively, efficiently, fairly, sustainably, minimize risks from, maximize benefits from, etc...]* ***intervene*** *[e.g., shape behavior, craft rules, mitigate impact, invest in human or technical capacity, fund science, etc...] so as to address our ocean challenge and achieve* ***our objectives*** *regarding quality of life [e.g., environment, people, communities, culture, technological development, wealth generation] and/or governance processes [e.g., transparency, participation, professionalism, equity, etc...]?*

For example, one question from the synthesis was *"How best can ocean de-oxygenation be addressed?"* For a specific context, it may be that the generic question could incorporate context-relevant details and be stated specifically as: *"Given ocean de-oxygenation may over the next decade stress and reduce fish populations in local coastal waters, and that those changes could adversely affect the livelihoods of local fishers, how can coastal planners effectively reduce the effects of other land-based stressors of coastal ecosystems so as to minimize the risk of damaging the coastal economy and the vitality of coastal communities?"*

By treating the questions in this way it should be possible for researchers or policy-makers working in specific contexts to translate generic questions of potential use in their situation into a very context-specific and policy-salient cross-disciplinary research question.

RESULTS

In this section we categorized the 100 non-prioritized questions into five broad themes: coastal and marine environmental change, managing ocean activities, governance for sustainable oceans, ocean value, and technological and socio-economic innovation.

Coastal and Marine Environmental Change

Coastal areas, which have attracted human development and settlement throughout history (Nielsen et al., 2017), are increasingly exposed to new combinations of pressures as human populations continue to grow and increase the use of coastal areas (Halpern et al., 2015; Jouffray et al., 2020). With increased and intensified use, marine environments are undergoing rapid change due to the combined effects of climate change (such as ocean warming, ocean acidification, sea level rise, and extreme events), land-based uses (such as pollution from effluence and agricultural runoff), extractive ocean uses (such as the harvest of living and non-living resources), transport (shipping, tourism, coastal runways), energy production, land reclamation, cabling for communications (Halpern et al., 2008b), and other human activities. These activities result in habitat degradation and loss, and rapid changes in environmental conditions. Managing these threats and impacts will require management and governance solutions from local to international scales (Bennett, 2018; Gissi et al., 2018; Pinsky et al., 2018).

Climate Change

Climate change due to increased greenhouse gas concentrations from anthropogenic sources is leading to increased ocean and atmospheric temperatures (Pachauri et al., 2014), ocean acidification (Doney et al., 2012), increased frequency and severity of extreme weather events (Stott, 2016), marine heat waves (Smale et al., 2019), sea level rise (Nicholls and Cazenave, 2010), and alterations to oceanic circulation (Caesar et al., 2018). Many ecosystems are unable to keep pace with the unprecedented speed of change (Doney et al., 2012). These impacts will influence food webs and the distribution and abundance of marine organisms (Poloczanska et al., 2016), will likely affect ecosystem structure and function, and the distribution of marine resources and habitats (Hoegh-Guldberg and Bruno, 2010; Cheung et al., 2013; Pecl et al., 2017), with profound implications for the societies that depend on them (Reid et al., 2014; Weatherdon et al., 2016).

Climate change questions resulting from our scan include:

(1) How can we best minimize the risks arising from ocean warming and marine heat waves in different ocean ecosystems?
(2) How can we best respond to sea-level rise?
(3) How can we respond to adverse effects of species on the move in response to climate change?
(4) How can we best address harmful biophysical, social and economic effects of ocean acidification?
(5) How can we best address the effects of climate change on primary production in the ocean?
(6) How can we identify and minimize the risks arising from disruption or collapse of thermohaline circulation patterns?

Terrestrial Drivers of Environmental Quality in the Ocean

Terrestrial activities such as land use and waste disposal practices have long been recognized as responsible for a diverse range of adverse effects in coastal and marine environments (Nixon, 1995; Rabalais, 2002; Howarth et al., 2011). Poorly managed agricultural, forestry, mining, and waste management practices release sediment (Syvitski et al., 2005), chemicals, and nutrients (Howarth et al., 2011), which can smother or poison coastal habitats and species (Shahidul Islam and Tanaka, 2004; Kroon et al., 2016). Plastic debris from land-based sources can be consumed by marine organisms causing injury and/or death (Kershaw and Rochman, 2015; Li et al., 2016; Kershaw et al., 2017;) and potentially facilitate the transport of toxins to organisms (Anbumani and Kakkar, 2018). Pollution from land-based sources can lead to various impacts on the marine environment ranging from habitat degradation, the alteration of primary productivity and food web structure, changes to ocean chemistry (such as anoxia), as well as affecting biodiversity which is vital to ecosystem structure and function (Shahidul Islam and Tanaka, 2004; Halpern et al., 2008b). This reduces the resilience of coastal ecosystems and undermines the long-term economic and food security of the people that depend on the affected areas (Worm et al., 2006; Halpern et al., 2009). Key questions include:

(7) How can we minimize adverse effects of nutrients and contaminants entering, or being remobilized in the marine environment?
(8) How best can ocean de-oxygenation be addressed?
(9) How can we minimize risks to human and environmental health arising from harmful algal blooms?
(10) How best can we identify and implement solutions to reduce plastics in the ocean?
(11) How can the effects arising from terrestrial environmental change be buffered so as to minimize their adverse marine impacts?
(12) How can we minimize adverse effects arising from human migration into or away from coastal areas?

Biodiversity Loss, Range Alteration

Ocean biodiversity supports many of the ocean industries, activities and services relied upon by society (Martin et al., 2015; Barbier, 2017; United Nations et al., 2017; Barbier et al., 2018) yet is vulnerable to global environmental change from large-scale impacts such as climate change and changes in ocean chemistry, as well as more localized changes such as habitat modification or disturbance (Worm et al., 2006; Bongaarts, 2019). Cumulatively, these changes reduce the resilience of ocean ecosystems and produce noticeable changes in species behavior (e.g., migration, reproduction) and habitat formation (Bongaarts, 2019). Indigenous and Traditional Peoples make up around 5% of the global population, yet are in charge of lands that account for over 40 percent of the world's biodiversity (Garnett et al., 2018), therefore Indigenous and Traditional Peoples' roles in conservation for biodiversity in the context of climate change will need to be a part of the solutions moving into the future.

Key questions include:

(13) How best can we facilitate migration and adaptation for biodiversity threatened by changing ocean conditions?
(14) How can we minimize adverse effects arising from the transfer and spread of marine invasive species?
(15) How, and when, can we best use triage approaches to manage marine species at risk?

Marine Hazards and Coastal Risks

Coastal areas attract human settlement and industries, and are experiencing rapid development (Barragán and de Andrés, 2015; Neumann et al., 2015). The development and intensification of human activities in coastal areas, such as land reclamation, and the conversion of habitats to support economic activities (e.g., aquaculture, port expansion, and human settlement) has resulted in the loss of buffering habitats that reduce wave action during storms, exposing coasts to increased risks of erosion and flooding (Neumann et al., 2015). Loss of habitats such as sand dunes, mangroves, seagrass beds, and coral reefs have been estimated to leave as many as 100–300 million people at increased risk of floods and hurricanes (Bridgewater et al., 2019). Populations living near coastal areas are projected to grow, which will expose increasing numbers to sea level rise and associated coastal risks (Neumann et al., 2015). There is increasing urgency to extend studies of human safety at sea and in the coastal zone, such as marine accident prevention, response, and occupational safety (Lubchenco et al., 2012; Luo and Shin, 2019; Watterson et al., 2020) as well as emergency management of coastal natural hazards (e.g., Jin and Lin, 2011).

Key questions include:

(16) How can we best prepare for changes in patterns of extreme weather events?
(17) How can we minimize the risks that marine hazards pose to coastal communities and economies?

Data and Monitoring

To inform sustainable management of the use of our oceans and coasts, vast amounts of ocean data are needed to understand and predict how marine ecosystems will respond to the rapid increase of global change (Pereira et al., 2010). Environmental and socio-economic data are needed for indicators, models, mapping efforts, and risk assessments that can inform decisions (Evans et al., 2019). Furthermore given the magnitude of existing and emerging data and 'Big Data,' new approaches for interpreting and synthesizing these data is critically lacking (Reichstein et al., 2019). International standards for long term monitoring programs, observing systems, data collection and quality, open access data repositories are needed (deYoung et al., 2019), with inclusion of data sovereignty requirements for Indigenous and Traditional Peoples (Sobrevila, 2008). Efforts have been in place to coordinate ocean observations within the framework of the Essential Ocean Variables (EOVs), a set of agreed minimum variables that need to be measured in a standardized fashion, so that data are comparable and easily delivered to end-users (Miloslavich et al., 2018). In addition, capacity-building and stakeholder engagement efforts, such as collaboration with communities, citizen scientists, and industrial sectors, governmental and international organizations will be needed to fill in data gaps (Kaiser et al., 2019). The connectivity and dynamics of ocean processes in space and time remain poorly understood, and typical data and/or capacity gaps can exist that challenge data collection, especially in areas that are remote, difficult to sample, and or face particularly rapid increase in human activities (e.g., coastal areas, the deep sea, and Arctic) (Halpern et al., 2015; Menegotto and Rangel, 2018). The benefits of policies and practices that incentivize and regulate the sharing and dissemination of data are receiving increased attention (Claudet et al., 2019; Evans et al., 2019; Weller et al., 2019). Environmental and socio-economic data are essential for decision making, and cross-disciplinary collaboration is required to design and prioritize data collection and monitoring (Claudet et al., 2019; deYoung et al., 2019; Evans et al., 2019; Kaiser et al., 2019).

Key questions include:

(18) How can we best ensure that core earth systems are maintained within acceptable boundaries?
(19) How can we best deliver comparable ocean data and data products for assessment of long-term, incremental, and cumulative effects of multiple stressors in the marine environment?
(20) How can we maximize the usefulness, value and accessibility of information provided by monitoring of key oceanographic, ecological, economic, and social variables?

Managing Ocean Activities

In addition to understanding and mitigating the drivers of ocean change, there is a need to balance negative effects arising from humans' use of the oceans with the benefits that humans derive from oceans (Gattuso et al., 2018). The questions in this section address sector-specific activities that extract or use coastal and marine natural resources. There are many considerations and the cumulative effects of current and potential multiple stressors is an important consideration (Clarke Murray et al., 2015). Processes such as marine spatial planning are key to coordinate existing and emerging ocean activities, since activities can have competing or complementary uses (Domínguez-Tejo et al., 2016).

Fisheries

Global wild fisheries catch was 79.3 million tons in 2016, and remains an essential source of animal protein for millions of people, especially in developing countries and small island developing states (Food and Agriculture Organization of the United Nations, 2020). Currently over 33% of fish stocks are considered full or over exploited (Food and Agriculture Organization of the United Nations, 2020) and over 55% of the ocean's area is fished (Kroodsma et al., 2018). Although the ecosystem impacts of fishing are scientifically well documented, fisheries management rarely use ecosystem descriptors to set fisheries management targets (Skern-Mauritzen et al., 2016). Hence, ecosystem-based approaches to management are not institutionalized in fisheries governance (Patrick and Link, 2015). Further a major challenge for managing fish stocks is illegal, unreported and unregulated - IUU fishing which is increasingly recognized and intensifying (Food and Agriculture Organization of the United Nations, 2020). Many IUU activities are extending further offshore to exploit deeper waters. Furthermore destructive fishing practices (e.g., bottom trawling, harvesting immature fish, discarding non-target species) continue to exacerbate increased fishing pressure on dwindling fish stocks in many parts of the World (Food and Agriculture Organization of the United Nations, 2020). Climate change is impacting on the distribution and dynamics of fish populations at various life stages, such as impacts to important life stage habitats such as nursery and spawning areas. Information on the locations and impacts of human activities including climate change on these habitats are lacking, leaving ecosystems that support fisheries vulnerable to habitat loss and blue growth activities (Sundblad et al., 2014; Pecl et al., 2017). Implementation of science based management plans as well as the end of subsidies that contribute to overcapacity and overfishing are essential (UN Economic and Social Council [ECOSOC], 2019). Finally, complex regulatory regimes and social norms will continue to be important considerations in controlling fisheries pressure in some areas (Gutiérrez et al., 2011), especially where they present challenges to the implementation of scientific advice.

Key questions include:

(21) How can we sustainably manage fisheries to account for the ecosystem impacts of fishing, climate change and the connectivity of life stages of targeted and non-targeted species, and the dynamics of changing habitats and marine ecosystems?
(22) How can IUU fishing be reduced or eliminated?
(23) How can we best eliminate harmful subsidies in fisheries?
(24) How can rapid technological advance in fishing be effectively governed and managed?

Aquaculture

With the decline in wild fish stocks, and the increasing demand for animal protein to feed the growing global population, the world aquaculture production has overtaken wild capture fish stocks, and in 2016 accounted for 53 percent of the 171 million tons of fish production (Food and Agriculture Organization of the United Nations, 2020). The top producing aquacultural countries are among some of the largest and/or poorest, highlighting the importance of aquaculture for global food security (Duarte et al., 2009; Food and Agriculture Organization of the United Nations, 2020). Environmental challenges of aquaculture range from impacts to water quality, introduction of non-native fish and pathogens from facilities, interactions with predators, habitat destruction or loss to provide space for aquaculture, introduction of contaminants (e.g., antifoulants, copper, antibiotics) and increased nutrient loads (Holmer et al., 2007; Diana, 2009). The scale of the impacts is expected to expand with the emergence of larger facilities being built offshore and as the number of inshore coastal facilities increase and interact with other pressures from ocean use (Gentry et al., 2017). Thus, a challenge for aquaculture will be to develop environmentally sustainable operations that are also economically viable (Gentry et al., 2017) such as the research regarding the integrated multi trophic aquaculture (Troell et al., 2009).

Key questions include:

(25) How can adverse environmental effects from intensive aquaculture best be alleviated?
(26) How best can aquaculture be used as a tool to improve marine environmental quality?
(27) How best can aquaculture help address the food needs of rapidly growing populations?
(28) How best can we develop and capture multiple benefits from aquaculture for new 'crops' (e.g., diatoms, nutraceuticals)?

Marine Tourism

Marine tourism is a rapidly expanding sector, and the long-term sustainability of this industry depends on the management of its impact, and the conservation and societal benefits of tourism activities. Environmental impacts may include (but are not limited to) those arising from tourism's carbon emissions (Lenzen et al., 2018), wildlife behavioral changes caused by attracting wildlife for viewing through, e.g., feeding or baiting (Burgin and Hardiman, 2015), the extraction of organisms (harvest, collection, fishing, etc.), the habitat conversion for the construction of resorts (Bishop et al., 2017), other effects such as direct damage (e.g., trampling marine vegetation or breaking of coral reefs) and pollution (Trave et al., 2017). The interdisciplinary question we identified that is relevant to this sub-topic was:

(29) How can we best manage marine and coastal tourism to capture economic benefits while ensuring environmental and social sustainability?

Offshore Mineral and Metal Extraction

Offshore seabeds are a source of mineral and metal deposits, such as those found at deep sea vents, and technological developments and interest in the extraction of these resources is increasing (Van Dover, 2011). Deep sea mining can introduce a large number of environmental risks, especially as most sea beds are pristine habitats that are sensitive to disturbance (Van Dover, 2011; Thornborough et al., 2019; Washburn et al., 2019). Many of the areas of interest for extraction are beyond national jurisdiction, so special measures are needed to assure environmental sustainability (Van Dover, 2011; Mengerink et al., 2014) and sharing of benefits from global resources (Jaeckel et al., 2016).

Key questions include:

(30) How best can we make decisions about when, where, and how to find, extract, and transport offshore resources?
(31) How can we manage and mitigate adverse environmental effects of deep sea mining?
(32) How best can we ensure equitable benefit sharing from extractive industries operating in international waters?

Renewable Energy

Renewable energy technologies, coupled with enhanced energy efficiency, are an essential part of climate change mitigation efforts worldwide (Edenhofer et al., 2011; Sathaye et al., 2011). Since the ocean provides vast supplies of potential energy in the form of wind, waves, tides, and thermal gradients, marine renewables are increasingly being considered as an important way to expand alternative energy portfolios (Thresher and Musial, 2010). Yet, the potential ecological consequences of marine renewable energy installations can include impacts to the sensory ecology and physiology of marine animals from construction noise, collision risks for birds and bats, along with habitat loss (Pezy et al., 2018). The degree of sensitivity of some taxa may change over time (Best and Halpin, 2019). Some of the potential benefits of marine renewable energy installations include increasing biodiversity by acting as artificial reefs and fish aggregating devices (Bishop et al., 2017). Though the literature is emerging, there remains an urgent need for studies addressing the environmental effects of marine renewable technologies (Boehlert and Gill, 2010; Adams et al., 2014; Bailey et al., 2014; Russell et al., 2014).

A key question includes:

(33) How can we best develop and deliver ocean-based renewable energy to society with minimal harm to the ocean environment?

Shipping

The global shipping network transports 90% of global trade, and contributes to roughly 3 percent of greenhouse gas emissions (approximately that of Germany) (Olmer et al., 2017). The shipping sector is undergoing rapid expansion and change due to its importance in international trade and in part due to the opening of new high latitude shipping routes with climate change (Ng et al., 2018). This expansion is promoting an increase in the size and number of ports, shipping lanes, and vessels (Tournadre, 2014). The construction and expansion of new ports and associated infrastructure is associated with habitat loss in coastal areas (Dafforn et al., 2015). The increased traffic, new routes and new ports increases the risk of spread of invasive species and pathogens via ballast water and through biofouling (Seebens et al., 2016). The expansion of the shipping sector (and maritime transport and tourism such as that involving cruise ships, Ytreberg et al., 2020) has likewise exacerbated the risk for the release of pollutants (e.g., sulfates, nitrates, and anti-fouling paints), black carbon, and nutrients from gray water and sewage (Jägerbrand et al., 2019). The increased number, size, and speed of ships raises the risk for e.g., collisions with marine mammals (Cates et al., 2017), underwater noise (Putland et al., 2018), oil spills (Chang et al., 2014), and anchor scouring (Davis et al., 2016). Ship breaking and recycling can release high local levels of pollutants such asbestos, heavy metals, polychlorinated biphenyls (PCBs), polyaromatic hydrocarbons (PAHs) and plastics (Barua et al., 2018) in the local environment.

Key questions include:

(34) How best can we reduce the exposure of aquatic species to the diversity of threats from the expanding shipping sector?
(35) How can new technologies help to decrease greenhouse gas and other emissions in the shipping sector?

Cumulative Impacts

The oceans are experiencing unprecedented growth in the number and intensity of stressors (Halpern et al., 2008b) from climate change and human activities, any of which can interact antagonistically or synergistically (Crain et al., 2008; Halpern et al., 2008a; Giakoumi et al., 2015; Alava et al., 2017). There is deep uncertainty about the impacts of these cumulative, interacting stressors, and also the unprecedented speed in which they appear and combine (Halpern et al., 2015). Understanding potential impacts of these interactions across all components of the ecosystem in a state of rapid change requires detailed monitoring, modeling and prediction of the marine environments in order to inform how ecosystem based management of biodiversity and resources may be affected. EIA tools and area based management instruments (e.g., zoning) and the regulation of human activities in time and space will be more effective if they can address the management of the growing number of cumulative effects (Clarke Murray et al., 2015).

Key questions include:

(36) How can we best address the individual and interactive effects of multiple ocean stressors?
(37) In the face of multiple ocean and upland stressors, how can we best ensure the long-term sustainability of marine habitats and the ecosystem services they provide?

Governance for Sustainable Oceans

Oceans governance arrangements and processes are the means through which societies align the interests of citizens and organizations with the goals and objectives of society as a whole (Campbell et al., 2016) and through which decisions about oceans and marine resources uses are made, risks are addressed, and benefits, costs and trade-offs are negotiated (Patterson et al., 2017). We define governance as the network of enduring institutional rules, practices, norms and relationships that connect the range of actors that influence and have a stake in the shared activity (Rhodes, 2007) – in this case the use of the oceans. Oceans pose special governance challenges because of (1) the difficulties in observing and inventorying the ocean environment and resources (Kaiser et al., 2019), (2) the mobility of many important ocean resources (Pinsky et al., 2018), (3) incomplete or uncertain institutional arrangements for ocean governance (Rudd, 2015), and (4) the long lag periods between the introduction of some pressures (e.g., current carbon emissions, increased anthropogenic nutrient loads to the sea, etc.), and their ultimate impact on ocean conditions (Schleussner et al., 2016). In the context of ocean sustainability, the research questions from our synthesis deal with the types of tools that can be used to effectively manage ocean use as well as broader questions relating to the appropriate role of, and strategies for, ocean governance.

Management Tools and Strategies

At the operational level, management tools and strategies are used to help achieve governance objectives. In the coastal and ocean context, there is a diversity of management options to consider. These include, for example, direct investment options, incentives, formal regulations, and ways to help shape the preferences and norms of individuals and businesses, and it is important to consider the full range of potential intervention options (Pretty, 2003; Link et al., 2018; United Nations Environment Programme, 2019). Despite the widespread scientific research highlighting the advantages of integrated and ecosystem based approaches to management (EBM) (Link and Browman, 2017), there is a general lack of political will (Link et al., 2018) and institutional barriers to implementing EBM in most jurisdictions remain (Rudd et al., 2018a). Only a limited number of governance entities, countries and organizations have committed to implementing EBM, and many questions remain on how to accelerate and implement EBM approaches (Rudd et al., 2018a). Modeling approaches, such as Integrative Ecosystem Assessment (Levin et al., 2009) and risk assessments (Haasnoot et al., 2013), can play a role in assessing tradeoffs and potential outcomes of policy decisions that aim to address the diversity and dynamics of interacting ecosystem components and pressures within and across jurisdictions.

Key questions include:

(38) What are the advantages and disadvantages of spatial intensification of coastal industries?
(39) How can insights and prescriptions from different management paradigms (e.g., MSY, blue growth, ecosystem-based, etc.) be used synergistically to improve ocean sustainability?
(40) What are the economic costs and benefits of adopting an ecosystem approach to ocean management?
(41) What policy, legal, or institutional arrangements can best facilitate integrated management of coastal and ocean environments from land to sea?

Governance Strategies

How governance entities negotiate and implement the rules that govern ocean use have important implications for sustainability both nationally and internationally. Governance approaches depend on constitutional arrangements, cultural contexts, and governments' discourses and political preferences for the types of management approaches and tools they use (Tompkins et al., 2008; Lotze et al., 2018). How governments choose governance strategies and specific ways in which policy instruments are advocated and selected is poorly understood and under-researched (Gluckman, 2016; Hutchings and Stenseth, 2016) and, in the context of ocean governance largely remains a black box. The interconnectedness of oceans and marine resources means that national and sectoral approaches must give way to integrated approaches and the interlinkages between managing jurisdictional waters and global oceans impacts required further research (Vogler, 2012). In addition, in many contexts, civil society opinions, stakeholder advocacy, and the need to address multiple use conflicts are giving rise to participatory mechanisms to govern marine spaces equitably (Lotze et al., 2018; Reynolds et al., 2020). Given the uncertainty of changes to oceans and marine ecosystems, governance arrangements must incorporate adaptive capacity to enable societies to prepare, respond and adapt to changing oceans ecosystem services (Folke et al., 2005). While general strategies for good governance are known (Ostrom, 2012), differences in governance style within agencies and between jurisdictions means that coordination and cooperation can be extremely challenging. Furthermore, current political trends toward increased nationalism and isolation may further hinder efforts to cooperate at the scale needed for effective ocean governance (Link et al., 2018; Rudd et al., 2018a).

Key questions include:

(42) How can we manage the environmental, social, and cultural risks of climate change and the impacts of human activities on the oceans and coasts?
(43) How best can a shift in governance focus from national sovereignty to global ocean governance maximize social, political, and economic returns?
(44) What are the relative advantages and disadvantages of top–down, bottom–up, property rights, and market-oriented strategies for ocean governance?
(45) How best can societies come to agreement and take actions when there are differences in opinions regarding the salience of threats to ocean sustainability?
(46) How do governance systems with different values, institutions, and capacities choose and implement measures that contribute to ocean sustainability?
(47) How can governments best decide how to prioritize trade-offs between environmental, social, and economic effects of ocean use?

Decision Support

Evidence from natural and social sciences is complex and must be distilled to highlight core insights so that it can be used by decision-makers, and to improve transparency and accountability in decision making (Fulton et al., 2011). Decision support tools involve combinations of models and assessment methods, and can be used to estimate the potential outcomes of management options based on available data and scenarios (Guisan et al., 2013). Such tools can help decision makers to envision alternative futures for oceans (Pinsky et al., 2018). They can provide insight about the capacity of particular types of management interventions to achieve particular governance objectives, and to assess the degree of relative risk a management option may entail (Guerry et al., 2012; Österblom et al., 2013). They play a crucial role in identifying pathways to ocean sustainability and for monitoring progress along those pathways. To reduce uncertainty, scenarios should be developed through the inclusion of a diversity of stakeholders including, for example, natural and social scientists, planners, industry, governance actors (Groves et al., 2019). By ensuring that consequences of decisions for their interests are addressed in the scenario design, the more easily tools will be called upon to inform policy (Österblom et al., 2013). Scenarios should reflect potential changes to ecosystem stressors (e.g., warming Arctic), and potential societal response (e.g., relocation of infrastructure to support fisheries, shipping lanes, settlements, offshore energy platforms, continued fishing moratoria, etc.) to those changes (Levin et al., 2009). In order to inform decisions that will lead to more resilient communities in the face of global changes, decision support tools should include worst case scenarios including low-probability, high-consequence events such as regime shifts, accidents, disasters, and unknown-unknowns (Groves et al., 2019). Moreover lessons learned from cases where the science uptake to decision-making has helped to navigate environmental challenges (so-called "bright spots"), should help to build mutual confidence and trust between science and policy makers, and encourage a participatory process (Cvitanovic and Hobday, 2018).

Key questions include:

(48) How can we ensure that ocean assessments and road map exercises include a spectrum of scenarios that adequately reflect feasible intervention options, relationships, and outcomes?
(49) How can we effectively account for low-probability but high-consequence events, and unknown unknowns in ocean decision support systems?
(50) How can we best catalyze, impede or buffer change when signals point to an impending tipping point in ocean systems?

Policy Coherence

Ocean governance often occurs in environments and at scales where environmental and political boundaries are incongruent (Maxwell et al., 2015; Skern-Mauritzen et al., 2016; Song et al., 2017; Pinsky et al., 2018; Kaiser et al., 2019). Addressing cross-boundary ocean governance challenges requires coordination, both at a sub-national level within countries and at a regional level for the ABNJ (Pinsky et al., 2018). Policy coherence – the degree to which policies in different sectors or jurisdictions align in their objectives – is needed, but challenges remain in its achievement (Cavallo et al., 2016; Jay et al., 2016; Gelcich et al., 2018). Too often the mandates and operations of one government agency are directly at odds with others, hindering cooperation and communication necessary for implementing sound management strategies that help ensure government agencies are working in ways that mutually contribute to sustainable ocean governance. Whenever policy coherence is not manageable, there is still room for scientific international cooperation to act as a soft power through the means of science diplomacy, in which a knowledge-based international partnership is built to address common challenges and their results may point to a need in better policy coordination, even between conflicting nations (Koppelman et al., 2010).

Key questions include:

(51) How can we best align policies and legislation across levels of government and international organizations to facilitate integrated ocean governance?
(52) How can governments align strategies and investments to create synergistic 'win-win' solutions and maximize

the environmental, social, and economic benefits from ocean use?

Nature and Use of Evidence in Decision-Making: From Knowledge to Action

In recent decades, the demand for evidence-based decision-making has increased dramatically in policy topics related to conservation and sustainability (Persson et al., 2018). Diverse evidence based predictive systems contribute to the generation of knowledge for sustainable development, and can include information from numerous disciplines, such as the natural and social sciences, as well as stakeholders, along with other traditional knowledge systems (Tengö et al., 2014; Hazard et al., 2019). In order for traditional knowledge to be effectively a part of the decision-making system proper respect and recognition of the differing epistemologies is essential (Foley, 2003; Buys et al., 2004; Mokuku and Mokuku, 2004). In order for sustainability efforts to be successful, the exchange of knowledge between knowledge generators, such as scientists or public, and the end-users, such as decision and policy makers, must support learning and effectively foster evidence-based decision making (Cvitanovic et al., 2016) and enable transitions in governance arrangements through emerging forms of public participation (Wyborn et al., 2019). Consequently, the knowledge to action framework requires that diverse stakeholders, including the knowledge producers and consumers, be included in the co-production of knowledge to increase the usability of science for society (Bednarek et al., 2018; Djenontin and Meadow, 2018).

Key questions include:

(53) How can we best arrive at an agreement as to what constitutes credible evidence for knowledge users?
(54) How can we help policy- and decision-makers understand and respond to scientific uncertainties and expert disagreements?
(55) How can local and traditional knowledge best be respected and used alongside western scientific knowledge to inform ocean science management and governance?
(56) How do different political cultures and institutions acquire and use scientific evidence for ocean governance and management?
(57) How can we best develop governance frameworks and evidence that highlight and overcome the problem of shifting baselines?

Addressing New/Emerging Governance Challenges

New technologies are opening up possibilities for ocean use, including for-profit extraction of novel ocean resources [e.g., mesopelagic fish (John et al., 2016), seafloor minerals (Hoagland et al., 2010), genetic resources (Harden-Davies, 2017)], and geoengineering interventions to help mitigate damage posed due to global carbon emission (Boyd and Vivian, 2019). The emerging technologies do, however, have unknown indirect effects on the ocean environment and the ecosystem services that oceans provide (Hoagland et al., 2010; John et al., 2016; Boyd and Vivian, 2019). New types and levels of risk need to be assessed and governance choices need to be made in a context of deep uncertainty (Schindler and Hilborn, 2015). How we use new technologies, and how we allocate the full costs and benefits that may arise from technological innovation will remain a challenge as the speed of technological innovation continues to accelerate.

Key questions include:

(58) How can geo-engineering of the ocean be governed?
(59) How can we best manage diseases that have the potential to move among wild and domestic marine species, and directly or indirectly affect human health?
(60) How can intellectual property rights and other emerging ocean ecosystem goods and services best be governed so as to ensure sustainable use and fair distribution of benefits from marine products, and to minimize impact on other ecosystems?
(61) How can mesopelagic fisheries be governed so as to balance the potential economic benefits of ecosystem services they provide, e.g., fishery production, biodiversity, and carbon storage?
(62) How do we govern human activities at sea in a manner that accounts for the rapid changes of the ecosystems due to climate change, connectivity and linkages of ocean processes in time and space?

Environmental Justice

Governance is not just about setting directions based on the objectives of a societal majority but also on ensuring rights for minorities, or disadvantaged segments of society (Bennett, 2018). Research over the past two decades in the terrestrial realm has demonstrated how many economically or politically marginalized segments of society are exposed to relatively more environmental degradation where they live compared to segments that are not marginalized (Whitmee et al., 2015). Residents in less wealthy countries and regions are often exposed to high levels of pollution and contaminants, and derive health risks from these (Hernández-Delgado, 2015). Moreover, many developing countries due to exposure to coastal flooding, growing population pressure, and weak governance, are among those at greatest risk to the impacts of climate change and fisheries challenges (Hernández-Delgado, 2015; Golden et al., 2016; Blasiak et al., 2017). Whilst degraded land and seascapes have been linked with negative health impacts of Indigenous and Traditional Peoples (Garnett et al., 2009; Durkalec et al., 2015), there is also a strong link between healthy environments and traditional land and sea management (Yibarbuk et al., 2001; Schmidt and Peterson, 2009; Ens et al., 2016; Renwick et al., 2017; Garnett et al., 2018). Recognition of the positive environmental outcomes in habitats that are occupied by Indigenous and Traditional Peoples needs to be recognized for the coastal and marine space, as it has in the terrestrial environment, as alternate solutions for improved environmental fairness (Aziz et al., 2013). Moreover, although global health has generally improved in recent decades, these improvements have often been "mortgaged against the health of future generations to realize economic and development gains in the present" (Whitmee et al., 2015). Mechanisms for recognizing and considering the voice of youth and children in ocean governance are thus also needed.

Key questions include:

(63) How can ocean resources be best used to positively impact human health and livelihoods of contemporary and future generations globally, and likewise contribute positively to traditional cultures, and the identities of Indigenous and Traditional Peoples?
(64) How can resilience and increased capacity to deal with ocean and coastal change best be enhanced among the people, communities, and societies most adversely affected?
(65) How can better understanding worldviews of people and cultures help inform sustainable ocean solutions?

Ocean Value

The ocean provides humans with benefits on multiple dimensions, such as food and nutrition, financial benefits for individuals and firms harvesting ocean resources, protection in the form of coastal defenses, employment and livelihoods to families living in coastal communities, climate and atmospheric regulation services, and beyond (Worm et al., 2006; Beaumont et al., 2007; Levin et al., 2009; Barbier et al., 2011; Barbier, 2017). In a broad context, 'value' reflects moral and ethical positions, so care must be exercised when considering what value represents to various people and communities (Costanza et al., 1997; Hein et al., 2006; Johnston and Russell, 2011; Bidwell, 2017). In economics, values are a reflection of the trade-offs people are willing to make between goods and services that are consumed or used, and economic value depends on personal preferences (de Groot et al., 2002; Hein et al., 2006; Boyd and Banzhaf, 2007; Barbier et al., 2011). One further complication arises because often the term 'ocean value' is used in relation to the 'blue economy' and economic development of the ocean: the term value in that context can be interpreted as the contribution of ocean goods and services to national GDP or other measures of economic activity.

Food Production Systems

Oceans have been a food source throughout human history and provide humans with multiple nutritional benefits. Health outcomes, especially for children, can be improved through diets that supply proteins, fatty acids, and micro-nutrients from seafoods (Golden et al., 2016; Willett et al., 2019). However the growing diversity of pressures on the marine environment, including climate change, jeopardize the security of these food production systems, and least developed countries and small island developing states that are most dependent on fisheries to deliver the majority of their animal protein are among the most vulnerable (Barange et al., 2014). Aquaculture has grown rapidly in recent years, and has overtaken the commercial production of wild caught fisheries (Food and Agriculture Organization of the United Nations, 2020). Aquaculture still carries a wide range of impacts on the marine environment, and the demand for fishmeal to feed aquaculture continues to place a pressure on wild fish stocks (Food and Agriculture Organization of the United Nations, 2020).

Key questions include:

(66) How can positive nutritional benefits from seafood be enhanced and promoted?
(67) How can the trade of marine food products be better monitored and managed to ensure human health?
(68) How can sustainable seafood production best help to achieve global food security?

Poverty Alleviation

Many of the world's poorest families, communities, and countries rely heavily on seafood harvesting and other ocean resources for income (Béné et al., 2016; Golden et al., 2016). Resources from the sea play a major role in alleviating poverty (Walmsley et al., 2006; Sowman et al., 2014), a major focus of the SDGs. To increase the contributions of ocean resources to poverty alleviation requires more information about the nature of markets for ocean resources and how different development strategies help or hinder poverty alleviation (Béné et al., 2016; Campbell et al., 2016; Nilsson et al., 2016).

Key questions include:

(69) How can we best manage any adverse effects arising from increased consumption of ocean resources arising as poverty is alleviated?
(70) How best can small-scale fisheries be used to increase food security while contributing to poverty alleviation?
(71) How can we sustain small-scale fisheries in globalized economies?
(72) How can we best protect those living in poverty from market price effects arising from the trade or regulation of ocean resources?

Valuation of Coasts and Oceans

Ecosystem goods consist of physical products that are taken from nature for human use. Ecosystem services encompass the processes that natural and biological systems sustain human systems (de Groot et al., 2002). Nearshore and coastal marine systems provide essential ecosystem goods and services to people, and consequently serve as a fundamental link between people and the environment (Barbier, 2017). Many of the types of ecosystem and environmental services that the marine environment provides, ranging from food from fisheries to coastal protection to education opportunities, is now well understood (Fisher et al., 2009). The market value of ecosystem goods and services represent the price or value of the goods or services traded in the market. Conversely, the provisioning of non-market goods includes things such as biodiversity or wetland ecosystems, along with the satisfaction that people derive from knowing a habitat or ecosystem exists. These non-market values represent the hidden social costs and benefits of ecosystem goods and services and are much more challenging to measure than market values since their value is external to the market (Howarth and Farber, 2002).

Consequently, if all values obtained from ecosystem goods and services are not accounted for in the valuation process, they are likely to be underemphasized or ignored in policy decisions. This is especially relevant to ecosystem goods and services that are not traded in the marketplace. Therefore, it is essential to consider the total economic value of marine ecosystem goods and services (i.e., including the full range of non-market benefits) to ensure that any impacts on the ocean environment or to communities dependent on marine habitats and resources are adequately reflected in economic-based policy decisions (Fisher et al., 2009).

Key questions include:

(73) How can we best assess the relative contribution of marine biodiversity to benefits humans derive from the ocean?
(74) How best can we assess the economic value of the ocean?
(75) What are the effects of commodifying nature on ocean sustainability and human well-being?
(76) What is the societal value of sub-surface carbon sequestration, e.g., from the mesopelagic?

Technological and Socio-Economic Innovation

Innovation will also need to be central if ocean sustainability is to be attained. Investments in a variety of societal assets will be needed, ranging from technological innovation for monitoring and modeling (Moltmann et al., 2019; Danovaro et al., 2020), to new types of financing arrangements, e.g. (Bos et al., 2015; Thiele and Gerber, 2017), and to new ways to directly conserve and enhance natural capital (Ouyang et al., 2016; Leach et al., 2019).

Enhancement and Restoration of Ecosystem Goods and Services

Ecosystem goods and services can be enhanced by traditional restoration efforts and management systems and through recent developments that draw on technological advances and an improved understanding of ecology (Morris et al., 2018). Natural ecosystems such as seagrass beds, mangroves and coral reefs provide added resilience against impacts of climate change by stabilizing coast lines, and protecting coastal areas from storm surges and wave action (Narayan et al., 2016). They can provide important structural habitats and nutrient sources that support biodiversity and nursery areas for fisheries (Whitfield, 2017), and an important role in sequestering carbon (Macreadie et al., 2017). Restoration of particular ecosystem goods and services also provides opportunities for some communities to enter the market system for the service they provide in maintaining and restoring ecosystems (e.g., such as mangroves, see Vierros, 2017).

Key questions include:

(77) How can we best enhance natural climate change mitigation mechanisms in the ocean?
(78) How and when can we restore depleted marine species that are commercially important?
(79) How do we best ensure that we derive environmental, social and economic advantages from marine protected areas?
(80) How can we best restore, rehabilitate, or compensate for habitat loss?

Technological Innovation

Technology is developing rapidly on virtually all fronts, and offers new possibilities to understand ocean dynamics and contribute to ocean sustainability (Bean et al., 2017). New types of sensors and data collection platforms (e.g., gliders, drones), environmental genomics, sonar have emerged and expanded the reach, resolution, diversity and depths of ocean information available (Moltmann et al., 2019). Efforts to disseminate and harmonize information across a wide diversity of users will need to keep pace with the data as it emerges (Muller-Karger et al., 2018). New technologies also pose governance challenges (e.g., deep sea mining, geoengineering) because they are developing quickly and there may be limited opportunities to field test them and ascertain short- and long-term consequences of their deployment (McGee et al., 2018; Boyd and Vivian, 2019).

Key questions include:

(81) How can we develop advanced forensics for tracing and managing the sources of existing and emerging contaminants in the ocean?
(82) How can we best minimize waste and capture the full value of marine resources?
(83) How can advances in vessel monitoring technology best be developed and deployed to monitor and detect illegal behavior in the oceans?
(84) How can advances in technology and data processing best be utilized to increase the likelihood of compliance with regulations governing marine resource use?
(85) How can we best design and implement complex, large-scale coastal infrastructure projects?
(86) How can advances in genetics best be used to identify and develop new opportunities for sustainable ocean use?
(87) How can we develop and govern rapidly evolving new technologies that potentially affect both ocean health and the well-being of people and industries that rely on the ocean?
(88) How can government policy and investment decisions best facilitate rapid technological advances that foster more sustainable use of the oceans?

People and Communities

Innovation for ocean sustainability is not limited to enhancing the natural environment or fostering technological innovation, but also includes innovations in the way people are educated and trained (International Union for Conservation of Nature and Natural Resources. Commission on Education and Communication, 2002), and innovations in the way that organizations and communities organize ocean activities and management (Addison et al., 2018). Innovations that increase levels of human and social capital can be just as, or more, effective in supporting ocean sustainability as are investments in ecological enhancement and technological development (Šlaus and Jacobs, 2011). Some efforts include citizen and participatory science efforts, training and education programs, and science communication (Fritz et al., 2019; Schrögel and Kolleck, 2019). As environmental systems are complex, capacity development and education must support skills rooted in systems thinking, engagement in diverse collaborations and partnerships, and leadership and management expertise (Bodin, 2017). For example, investments in the leadership capacity of individuals from fishing communities can help alleviate overfishing (Sutton and Rudd, 2015).

Key questions include:

(89) How can we rapidly increase the skills of workforces and bureaucracies to support the global transition to an environmentally, socially and economically sustainable blue economy?
(90) How can we create capacity for systems thinking and promote cross-disciplinary collaborations for solving complex ocean challenges?
(91) How can we best use innovations in citizen science to foster ocean health and human well-being?
(92) How can we best build management and leadership capacity among citizens and communities engaging in coastal and ocean governance and management?

Incentivizing Sustainable Business Practices

Global supply chains that link the producers of ocean resources to the consumers and firms that use off those resources can be exceedingly complex, weakening the links between producers and consumers (Crona et al., 2016). Moving toward more sustainable oceans will require change in both production practices and consumer behavior. To be most effective, there needs to be clear signals from one end of the supply chain to another and mechanisms that encourage sustainable business practices and household consumption choices. On the production side, firms extracting or using ocean ecosystem services or the ocean environment (e.g., to produce renewable energy) have potential to improve their production practices, reducing adverse environmental and social impact (Kaldellis et al., 2016). Profitability will always be the driver for private sector firms, so measures that increase firm revenues and/or decrease costs influence their behavior. Governments have traditional regulatory and fiscal (e.g., tax) tools – the 'sticks' – at their disposal for activities within national jurisdiction but there are also opportunities for various types of incentives – the 'carrots' – to encourage more sustainable firm behavior. There are also other options to increase profitability by opening markets for byproducts, including incentivizing waste reduction and valorization (e.g., Geissdoerfer et al., 2018). Further, along the many different points along the supply chain that brings ocean resources into the marketplace, there may, for instance, be further measures to increase the efficacy of the supply chain, reducing food waste, and increasing transparency. For industries that use ocean resources, there are also options to use regulatory or non-regulatory measures that are aimed at increasing production efficiency, getting more out of every unit of resource extracted from the ocean.

Key questions include:

(93) How can international trade systems be incentivized so as to retain stable and affordable local food systems?
(94) How can we encourage private sector investment for sustainable marine products supply and value chains?
(95) How can we best ensure that the costs of ocean degradation and benefits of ocean stewardship are properly attributed to responsible parties?
(96) How can socially responsible business practices in the ocean sector best be rewarded so that both environmental sustainability and long-term business resilience are enhanced?
(97) How can environmental sustainability create economic value for ocean industries?
(98) How can innovations in financing be used to accelerate ocean stewardship and sustainability?

Incentivizing Sustainable Consumer Behavior

Consumer choices are highly dependent on product prices but consumers are also motivated by other factors, including perceived environmental threats, the availability of information about the environmental consequences of their consumption choices, and prevailing social norms (Stern et al., 1999). In general, options for nudging consumption choices in a way that support ocean sustainability include measures that impact consumer prices for ocean products or their substitutes, help consumers make informed purchase decisions that take account of the personal or environmental health impacts of their personal consumption choice, and that encourage social norms more conducive for supporting ocean sustainability. Challenges for those wanting to make sustainable seafood consumption choices include widespread mis-labeling of products in the marketplace (Jacquet and Pauly, 2008) and potential confusion over competing labeling standards (Parkes et al., 2010). Premium prices for sustainable seafood are not always passed back to ocean resource producers, so they may not receive any 'market signal' about consumer demand for sustainable production (Blomquist et al., 2015). New technologies such as DNA barcoding (Galimberti et al., 2013), blockchain (Cook and Zealand, 2018), and evolving consumer apps have the potential to encourage sustainable purchasing behavior and dramatically improve traceability along the seafood supply chain.

Key questions include:

(99) How best can we influence consumer choices so as to sustainably increase benefits derived from oceans?
(100) What is the most beneficial information for consumers wishing to make informed decisions about the environmental and social impacts of their personal ocean-relevant consumption choices?

DISCUSSION

Transformational change of governance and management, supported by the co-creation of transdisciplinary knowledge, is essential to achieve SDGs (Singh et al., 2018). In order to supply relevant evidence to inform policy, sustainability research must address cross-disciplinary questions using inclusive research approaches. We have used scientists' written outputs to identify and track important and emerging ocean sustainability issues. We have drawn attention to the interconnections among these questions which underlines the interdisciplinary and transdisciplinary nature of the issues we are facing. In the transdisciplinary context, knowledge is co-created with an inclusive diversity of disciplines (including the natural, social sciences, technology, public health, engineering, law, economics, educators, anthropology, psychology etc.) and through the interaction with stakeholders and publics/citizens (Wyborn et al., 2019). Additional research within any of these disciplines is necessary, but alone is insufficient to achieve ocean sustainability. There is likewise a need to build upon existing research, as well as the design and use of new transdisciplinary knowledge to support transformations/transitions to ocean sustainability.

Making Cross-Disciplinary Approaches the Norm

Participatory governance processes will be at the front and center going forward. Scientists and governance researchers will need to co-create the answers to societal questions to support SDGs, and resources will therefore need to be allocated for both science and governance research, and increasing the uptake of science to policy. One important implication is, further, that crafting and answering contextually sophisticated research questions necessarily needs input from across academic disciplines and from different types of actors. Cross-disciplinary approaches to sustainability research should be considered the norm for real problem solving (Brandt et al., 2013). Issues surrounding whose values are recognized and which types of interventions are considered feasible will virtually always be present when considering management and governance options for supporting ocean sustainability.

Natural science questions cannot be totally isolated from the broader management, governance, and human concerns

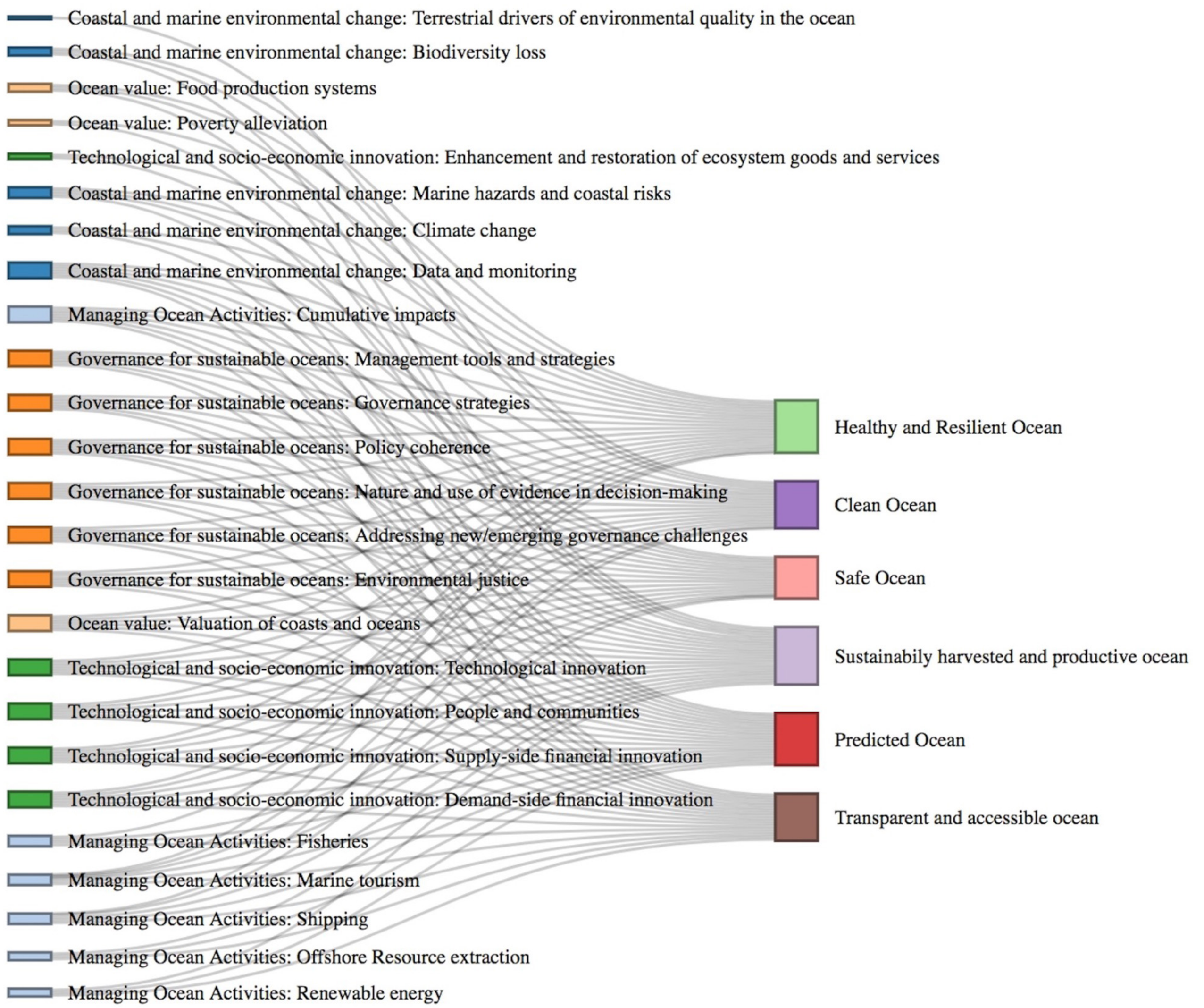

FIGURE 1 | Sankey diagram detailing the connectivity between the broad themes and sub-headings (broad theme: sub-heading) related to the cross-disciplinary research questions outlined in this paper to the UN Decade of Ocean Science for Sustainable Development outcomes (Ryabinin et al., 2019). Size of the colored boxes associated with each theme or outcome is related to the number of connections.

(Bodin, 2017). Our list of 100 questions is broad and thematic. The issues they address are complex, and would require refinement to be addressed. It would be possible to expand on the rationale for each question and each question could be the focus of a research program. The priority each of these questions receive will necessarily vary across regions and jurisdictions. We provided an example of how our list of 100 questions could be refined to form more specific questions. Our list of 100 questions could likewise be customized by region for research students, departments, and national and international research initiatives for any scale, ecosystem, or socio-political context. While these research questions cover the great majority of issues covered in the recent literature on ocean research and governance the list of 100 should be interpreted as '100 important questions' not the '100 *most* important questions,' since the final choice of topics to include was to some degree a subjective perspective.

Aligning These 100 Ocean Governance Research Questions With the UN Decade of Ocean Science and the 2030 Agenda for Sustainable Development

The UN Decade of Ocean Science for Sustainable Development (The Decade) was adopted to foster significant development in knowledge supporting the management of the ocean and has two major goals, "to generate the scientific knowledge and underpinning infrastructure and partnerships needed for sustainable development of the ocean and to provide ocean science, data and information to inform policies for a well-functioning ocean in support of all Sustainable Development Goals of the 2030 Agenda" (Ryabinin et al., 2019). The Decade has six guiding societal outcome areas: A clean ocean, a healthy and resilient ocean, a predicted ocean, a safe ocean, a sustainably harvested and productive ocean, and a transparent and accessible ocean. The strategic approach of The Decade includes a reciprocal interaction between research and knowledge generation and practical applications and policy initiatives, and this will require transdisciplinary and cross sectoral exchange of ideas, based on effective communication tools (Bucchi and Trench, 2016).

We propose that our list of 100 important questions could serve as an independent starting point to stimulate discussion related to key emerging research needs for management- and governance-oriented research questions for the 2020s. Many of the questions that emerged from the horizon scanning exercise are important themes underpinning the societal outcome areas for The Decade (**Figure 1**). For example, better understanding marine hazards and coastal risks is foundational to moving toward a safe ocean and information on climate change, cumulative impacts, and the enhancement and restoration of ecosystem goods and services is central to a healthy and resilient ocean. The research needs concerning novel governance challenges were related to emerging industries (e.g., Climate-geoengineering, Offshore resource extraction- deep sea mining, Fisheries- mesopelagic fisheries). Our questions represent some of the "known unknowns" that transdisciplinary science could address to inform ocean policy. As our Anthropocene ecosystems continue to reorganize and reshuffle in response to the diverse dynamics of global change, we can expect that critical unforeseen questions are likely to arise over time (currently "unknown unknowns"). Our capacity to contribute scientifically to understanding these dynamics and developing solutions to challenge may improve by embracing other forms of knowledge via more and broader social participation in knowledge production. We may also gain new insights and discoveries that highlight where we understood less than we thought. The questions will therefore evolve over time.

CONCLUSION

There is urgency for cross-disciplinary research, and also opportunity. The UN Decade of Ocean Science is a once in a lifetime opportunity to do things differently. The range of topics covered in this list questions necessitates an inclusive view of ocean science. Ocean science should include knowledge generation from many different disciplines, sectors, and from a diversity of stakeholder perspectives. Sustainable development relies on understanding the interplay between human and natural systems and the fair operation of society within planetary boundaries (Steffen et al., 2015). This means that governance and management are front and center with essential input from nature and social science, law, public health, and policy researchers, industry, educators, civil society, traditional peoples, and across generations.

Going forward, basic monitoring and assessment of the social-ecological system will continue to be needed, in addition to cross-disciplinary theorization and methodologies (Gurney et al., 2019; Kelly et al., 2019). Scientific and technological advances are necessary, but alone are insufficient to achieve better outcomes/impacts, and advancing technology can by no means be used to abdicate responsibility for ocean sustainability. We live in an age in which uncertainties need to be addressed, evaluated and communicated to inform better decision making, with a broader social participation so sustainability can actually be reached. Research on the processes of governance and management, and governing across jurisdictions is also needed to identify interventions that are effective (Bennett and Dearden, 2014; Bodin, 2017). It is expected that we will need to accomplish as much as possible with the scarce resources that are expected to be allotted for ocean sustainability, as SDG14 is currently considered the lowest priority SDG of all for most countries (Custer et al., 2018).

The political changes we are seeing in our world are likely to make transformative/transitional changes to participatory ocean governance challenging to achieve. Nevertheless, scientists cannot expect that scientific evidence will be used unless there is advocacy for the use of credible information in the political process. Mechanisms for such advocacy are needed. The spread of misinformation and disinformation campaigns, and other weaknesses in communication (van der Linden and Löfstedt, 2019), means it may be more important than ever for scientists to be engaged in the political process in one way or another (e.g., public commentaries, participation in scientific societies such as AAAS, AGU, BES, etc.). At the very least, scientists should actively advocate the use of credible information and evidence based approaches to decision making, and dissuade the use of information that is not supported scientifically. The coming few years will be critical.

We hope that this paper will help students, professional organizations, industry members, and policy actors that are engaged in ocean problem solving to consider the breadth of ocean challenges, and seek opportunities to address them through inclusive research going forward. We also hope that it may act as a tool that helps ensure that a broad range of governance- and management-oriented challenges are considered. Sustainability research in an SDG context addresses societal challenges, and requires the co-creation of research that includes diverse branches of inquiry ranging from e.g., natural science, social science, traditional knowledge, philosophy, policy and governance research, law, human behavioral sciences, education science, and other disciplines. Further work can be done to identify the organizations and scientists who currently work on these topics, identify potential partnerships, and to build our capacities for cross-disciplinary research to address the challenges and opportunities ahead.

AUTHOR CONTRIBUTIONS

MR designed the study and carried out the analyses. ES produced the **Figure 1**. MW led the writing and wrote the paper with input from all authors. All authors contributed to the article and approved the submitted version.

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