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Scientists' perspectives on global ocean research priorities

Murray A. Rudd *

Environment Department, University of York, York, UK

Edited by:
Julian Clifton, University of Western Australia, Australia

Reviewed by:
Ben Milligan, University College London, UK
Marcus Geoffrey Haward, University of Tasmania, Australia
Todd C. Stevenson, University of Washington, USA

****Correspondence:***
Murray A. Rudd, Environment Department, University of York, Heslington, York YO10 5DD, UK
e-mail: murray.rudd@york.ac.uk

Diverse natural and social science research is needed to support policies to recover and sustain healthy oceans. While a wide variety of expert-led prioritization initiatives have identified research themes and priorities at national and regional scale, over the past several years there has also been a surge in the number of scanning exercises that have identified important environmental research questions and issues "from the bottom-up." From those questions, winnowed from thousands of contributions by scientists and policy-makers around the world who participated in terrestrial, aquatic and domain-specific horizon scanning and big question exercises, I identified 657 research questions potentially important for informing decisions regarding ocean governance and sustainability. These were distilled to a short list of 67 distinctive research questions that, in an internet survey, were ranked by 2179 scientists from 94 countries. Five of the top 10 research priorities were shared by respondents globally. Despite significant differences between physical and ecological scientists' priorities regarding specific research questions, they shared seven common priorities among their top 10. Social scientists' priorities were, however, much different, highlighting their research focus on managerial solutions to ocean challenges and questions regarding the role of human behavior and values in attaining ocean sustainability. The results from this survey provide a comprehensive and timely assessment of current ocean research priorities among research-active scientists but highlight potential challenges in stimulating crossdisciplinary research. As ocean and coastal research necessarily becomes more transdisciplinary to address complex ocean challenges, it will be critical for scientists and research funders to understand how scientists from different disciplines and regions might collaborate and strengthen the overall evidence base for ocean governance.

Keywords: research priorities, oceans research, marine research, crossdisciplinarity, transdisciplinarity, horizon scanning, big questions, best-worst scaling

INTRODUCTION

Oceans provide critical, multi-dimensional support for life on earth (Costello et al., 2010; Halpern et al., 2012) and, given their role in Earth sustainability (Rockström et al., 2009; Griggs et al., 2013), will play a central role in society's shift toward a more sustainable future. Oceans, however, face serious threats on multiple fronts due to over-exploitation of marine life (Jackson et al., 2001; Lewison et al., 2014), changes in upland land use, hydrological cycles and pollution (Derraik, 2002; Small and Nicholls, 2003; Crossland et al., 2005; Camargo and Alonso, 2006; Lotze et al., 2006; Dahms, 2014), climate change and its associated effects on sea level rise, ocean temperature redistribution and acidification (Hoegh-Guldberg, 1999; Caldeira and Wickett, 2003; Church and White, 2006; Heip et al., 2011; Doney et al., 2012; Balmaseda et al., 2013; Kroeze et al., 2013; Achterberg, 2014; Hollowed and Sundby, 2014), and other emerging challenges (Keeling et al., 2010; Cole et al., 2011; Ramirez-Llodra et al., 2011; Gramling, 2014). Further, ocean governance has special challenges associated with political and legal arrangements within and beyond areas of national jurisdiction (Berkes et al., 2006; Warner, 2014), monitoring marine environmental and ecological conditions (Katsanevakis et al., 2012), limited knowledge regarding the links between ocean environmental conditions and ecological structure, function and services (Balvanera et al., 2006; Heip et al., 2009; Armstrong et al., 2012; Liquete et al., 2013), and understanding how various governance interventions affect goods and services that oceans provide humans (Rudd, 2004; Schlüter et al., 2013). These issues may strongly impact food security and livelihood viability for hundreds of millions of people who depend on ocean resources (Allison et al., 2009; Garcia and Rosenberg, 2010; Johnson et al., 2013).

There is a crucial need for targeted natural and social science research that builds our understanding of earth processes, helps identify possible solutions to critical challenges, and provides the knowledge needed to catalyze transformational changes in human behavior (Hackmann and St. Clair, 2012; Pahl-Wostl et al., 2013). A variety of efforts to identify ocean research priorities have been undertaken in the past at national and regional levels, often through agency-led approaches that draw on eminent scientists for advice (e.g., International Ocean Discovery Program, 2011; European Marine Board, 2013; Expert Panel on Canadian Ocean Science, 2013; National Oceanic and Atmospheric Administration, 2013). In recent years, an increasing number of bottom-up, participatory horizon scanning and "big question" exercises have also taken place. Those efforts, while usually not ocean-specific (but see Fissel et al., 2012; Feary et al., 2013; Rees et al., 2013; Parsons et al., 2014), represent the collective insights of thousands of scientists and have identified many important ocean- and coastal-oriented research questions (Sutherland et al., 2006, 2009, 2013b; Pretty et al., 2010; Fleishman et al., 2011; Rudd et al., 2011; Boxall et al., 2012; Ingram et al., 2013). With ongoing international efforts to set ocean research direction for the coming decades (e.g., the USA Decadal Survey of Ocean Sciences 2015 [nas-sites.org/dsos2015/] and Future Earth [www.futureearth.info/]) it is timely to take stock of the opinions of scientists and policy-makers who participated in the numerous bottom-up horizon scanning and big question exercises. This could help ensure that the full spectrum of ocean research needs have been considered during the formulation of the high-level directives that will shape global ocean research funding over the next decade or more.

Understanding differences in research priorities among scientists from different disciplines (Rudd and Lawton, 2013) and regions (Cooke et al., 2010) is particularly important given the need to provide balanced science advice to policy-makers and to bring crossdisciplinary research insights specifically to bear on cross-cutting ocean challenges. The need for crossdisciplinary collaboration between scientists from different disciplines and between scientists, policy-makers, and members of society is widely recognized in earth systems sustainability research (Hackmann and St. Clair, 2012; Mooney et al., 2013; Pahl-Wostl et al., 2013). The growing move toward transdisciplinary research (Thompson Klein, 2004; Spruijt et al., 2014) is well-recognized in the environmental field (Pohl, 2005; Hirsch Hadorn et al., 2006; Jolibert and Wesselink, 2012; Sutherland et al., 2012b; Bremer and Glavovic, 2013; Lawton and Rudd, 2013; Pennington et al., 2013) and will likely become increasingly important as scientists are called on to provide various types of science advice (Singh et al., 2014; Spruijt et al., 2014) that help address society's most pressing and complex problems (Lubchenco, 1998; Defries et al., 2012).

In this synthesis, I identified 657 important research questions from prior big question and horizon scanning research identification exercises (henceforth simply scanning exercises—see Sutherland et al. (2011b), for a methodological summary) and distilled those to a set of 67 core questions. Those questions, drawn from across the physical, ecological and social sciences, relate to challenges ranging from basic environmental science needs to society's relationship with a changing ocean. I then used those questions in an internet survey of international scientists who have recently worked on ocean-related issues, assessed their research priorities, and tested how their disciplinary background and other potentially salient demographic and professional characteristics were associated with those priorities. This paper emphasizes the methodological approach used for the study and its key findings; in-depth analysis of particular research priorities, scientists views on their role at the science-policy interface, and opinions about potential solutions to pressing ocean challenges are left to future analyses.

METHODS

RESEARCH QUESTION IDENTIFICATION

I examined 28 different reports and articles that over the last 8 years identified research questions or issues with potential salience to ocean sustainability. Those included: 13 general (i.e., non-marine) big question exercises (Sutherland et al., 2006, 2009, 2012b, 2013b; Morton et al., 2009; Brown et al., 2010; Pretty et al., 2010; Fleishman et al., 2011; Kark et al., 2011; Rudd et al., 2011; Boxall et al., 2012; Braunisch et al., 2012; Ingram et al., 2013) and five specific to coastal and marine issues (Fissel et al., 2012; Feary et al., 2013; Rees et al., 2013; Parsons et al., 2014; Vugteveen et al., 2014); six annual horizon scanning exercises (Sutherland et al., 2008, 2010, 2011a, 2012a, 2013a, 2014); and four ocean-specific reports that identified important research questions and that were based on expert opinions (Heip et al., 2011; Heip and McDonough, 2012; Snelgrove et al., 2012; Borja et al., 2013).

In aggregate, the research scanning exercises solicited at least 10,409 candidate questions from over 5700 contributors globally (see Data Sheet 2 in the Supplementary Material for a summary of all 28 exercises). Candidate questions were accepted from individuals and organizations in open and inclusive solicitation processes (Sutherland et al., 2011b), with much effort expended by research teams to draw candidate questions from as wide a range of sources as possible. Of the 10,409 candidate questions, there were a total of 1961 marine-oriented questions submitted by at least 461 contributors. Typically in these exercises the candidate questions were winnowed initially by the core research team for each exercise, with a focus on reducing question redundancy and eliminating questions outside the scope of the exercise. A reduced pool of candidate questions would then undergo further editing, combining or revision at an in-person workshop where experts (typically between 15 and 50 individuals) winnowed candidate questions to a final list of priority research questions (typically between 40 and 100) or horizon scanning issue (between 15 and 25). In total, the 28 exercises I examined resulted in final selection of 1020 questions and issues from non-marine scanning exercises, and 202 from the oceans-focused scanning exercises. These were complemented by another 125 questions and issues identified in the four expert opinion-based reports.

The non-marine scanning exercises were authored by 605 individuals, of whom 46 appeared to have primary expertise in coastal and marine research. Of those 46, 30 had natural science backgrounds, 13 were from social sciences, and three from other disciplines; 28 worked in academia and 18 had other professional affiliations. Of 330 research questions or issues identified in these articles that were potentially relevant for oceans, 50 were retained and incorporated into the final questions used in this survey.

In the five marine-oriented scanning exercises, 107 co-authors contributed to the final publications. Of those, 98 appeared to be coastal and marine research specialists; 80 were from the natural sciences, 10 from the social sciences, and 8 from other fields. A total of 83 were from academia and 15 had other affiliations; the average h-index of marine co-authors on these publications ranged from 7 to 26 (based on Google Scholar and calculated with Publish or Perish, www.harzing.com/pop.htm).

Of 202 research questions or issues identified in those five articles, 20 were retained as final questions for this survey.

The expert opinion-based articles were co-authored by 42 scientists; 41 of those authors were from academia and were individuals whose primary expertise was in coastal and marine research in the natural sciences. The average h-index for authors in those reports ranged from 21 to 26. Of 125 research questions or issue identified in these articles, 13 were retained as final questions in this survey.

In summary, from 22 of 28 of these publications I identified 657 research questions or issues of potential relevance for this survey (research questions from 6 of the exercises were redundant or regional in nature). These were collated, coded qualitatively according to pre-defined and emergent themes, and distilled into 67 research questions (**Table 1**) that were relatively evenly distributed across major disciplines (i.e., the physical, ecological, and social sciences) and were used as the basis for this international survey of scientists working on coastal and ocean issues.

SURVEY DESIGN

The objective of the internet survey was to collect information necessary to fully rank the 67 research questions for each individual scientist, thus allowing subsequent comparisons of respondents' priorities according to demographic or professional factors. Practically, the only way to rank this many items is with Best-Worst Scaling (BWS) (Finn and Louviere, 1992), an approach that has been used in other research prioritization ranking studies (Rudd and Lawton, 2013; Rudd and Fleishman, 2014; Rudd et al., 2014). In order to ensure that all respondents saw each of the 67 questions at least twice, 36 BWS ranking tasks were needed. Sawtooth Software's (2009) experimental design generator was used to create 300 survey versions to which respondents were randomly assigned. That combination of 300 survey versions was, in combination, the most efficient of 1000 randomly generated design combinations that were tested.

Respondents were asked in the sequence of 36 BWS ranking tasks to choose, in their opinion, the most and least important from among subsets of only 4 of the 67 research questions at a time. At the end of the 36 BWS ranking tasks, respondents were shown a list of the 10 questions that, based on their own answers to the BWS tasks, they ranked as most important and the 10 they ranked as least important. Each respondent was asked how well those ranking results from the BWS exercise corresponded to their actual priorities (excellent, good, fair, poor). Each respondent's three top-ranked research questions were used to further query individuals on the reasons they ranked those questions highly and what single advance could best help answer the question (for brevity, not reported here). Additional information was collected on demographic and professional characteristics of respondents. An experimental series of ratings regarding respondents' attitudes toward knowledge production and cooperation between scientists and policy-makers (Lawton and Rudd, 2014) was also collected but again, for brevity, is not reported here. The survey (Data Sheet 1 in the Supplementary Material) was approved in February 2014 by the Environment Department's Research Ethics Committee at University of York.

SAMPLE

The sample frame for the survey was research-active scientists with expertise in coastal and ocean science relevant to the sustainable management of oceans. I used an ISI Web of Science search to construct a sample by identifying authors of articles from appropriate journals and for whom email contact information was available. The Web of Science search was restricted to journals with a 2012 impact factor of greater than 0.5 and targeted journals for which the primary focus was marine-oriented and potentially relevant to ocean sustainability. Only research articles published between 2011 and late-2013 were used.

In the initial screening, I found 17,127 articles (from 64 journals) with author contact information. I screened out irrelevant articles based on titles, but comprehensive abstract evaluation was not possible, so some engineers, naval architects, mathematicians and freshwater specialists were retained in the sample (they could self-screen in the survey itself). After the removal of duplicate emails, 16,402 unique individuals with email contact information remained. Invitations with one-click survey hyperlinks were emailed to potential respondents. Following standard survey protocol (Dillman et al., 2009), five contact points were used to distribute the internet-based survey; these included a pre-survey notice (without a survey link), first survey distribution and, for respondents who had not yet completed the survey at time milestones, a short reminder, second survey distribution, and final notice. The survey opened on 15 February 2014 and closed 19 March 2014.

DATA ANALYSIS

With Hierarchical Bayesian (HB) analysis (Sawtooth Software, 2009), ranking scores, measured as the likelihood of being chosen the most important among all 67 research questions, were calculated for all 67 questions for each individual that completed the survey. Essentially, the HB process borrows information about how an individual's research priorities differ from the sample mean to adjust the mix of individual preferences and sample average in the next model iteration. I used standard Sawtooth HB options, setting prior variance for each parameter to 2 (with 5 degrees of freedom) and ran 20,000 iterations for burn-in and a further 10,000 iterations for coefficient calculation.

The ranking scores represent the likelihood of a research question being chosen as most important and sum to 100. A question with mean ranking score of 2.0 can be interpreted as being twice as important to a survey respondent as an item with mean of 1.0. When 67 research questions are ranked randomly, the mean likelihood of any question being chosen most important is 1.493 (= 100/67).

Fitness scores (root likelihood * 1000) are a measure of a single respondent's ranking consistency across BWS ranking tasks (Sawtooth Software, 2009) and were calculated for each respondent who completed the survey. Based on a model using this study's experimental design and with $n = 2100+$ simulated respondents who answered all BWS ranking tasks randomly, a respondent's fitness score should be above 380 if, in this four-option 36-task BWS design, that person is to be classified as non-random responder with 95% confidence.

Table 1 | Final list of [unranked] research questions synthesized from 22 research scanning exercises.

	Abbreviation	Full question text	Source(s)[a]
1	Seafood supply chains	How can the trade of marine species be better regulated, managed, and monitored to help achieve local and global food security while protecting ocean ecosystems?	Parsons et al., 2014, question 62/Fissel et al., 2012, question 40
2	Ocean deoxygenation	How can the spatial and temporal dynamics of de-oxygenation in ocean and coastal environments be assessed and managed?	Heip et al., 2011, theme 33[b]
3	Temperature redistribution	How are global temperature increases being distributed among ecosystems, including the deep ocean?	Sutherland et al., 2014, issue 05[c]
4	Local ecological knowledge	How can local and traditional knowledge be most effectively communicated and synthesized with scientific knowledge to inform ocean science management and governance?	Rudd et al., 2011, question 33
5	Science communication	What forms of scientific evidence, risk assessment, and knowledge transfer most effectively increase the probability of achieving marine ecosystem-management objectives?	Rudd et al., 2011, question 34
6	Effects of MPAs on humans	What are the human well-being costs and benefits of marine protected areas, how are these distributed, and how do they vary with governance, resource tenure arrangements, and site characteristics?	Sutherland et al., 2009, question 29
7	Effects of economic subsidization	What are the effects of direct and indirect economic subsidization on marine ecosystem function and services at local, regional, and international levels?	Sutherland et al., 2009, question 79
8	Ecosystem service valuation implications	How can marine goods and services be valued, and how will the adoption of monetary value by ocean managers affect the conservation of marine resources?	Borja et al., 2013, issue 07, Sutherland et al., 2008, issue 24
9	Global economic value of the ocean	What is the global economic and non-monetary value of various seascapes and habitats from the intertidal to the deep sea and to what extent does this value depend on biological diversity?	Snelgrove et al., 2012, question 19[d]
10	Effects of worldviews on conservation	How have humankind's various worldviews shaped perceptions, relationships, and narratives related to the marine environment, and how do these influence marine conservation?	Parsons et al., 2014, question 64
11	Human dissociation from nature	What are the effects of increasing human dissociation from nature on the conservation of marine biological diversity?	Sutherland et al., 2009, question 83
12	Ocean literacy messages	What are the most critical messages and concepts that should be communicated to citizens to change their beliefs and attitudes regarding ocean health and management, and will those messages change behavior?	Sutherland et al., 2009, question 82/Parsons et al., 2014, question 49
13	Property rights and conservation	How do resource tenure systems shape conservation outcomes in different social and ecological contexts?	Sutherland et al., 2009, question 77
14	Risk assessment for governance	How should uncertainty, risk, and precaution be incorporated into effective ocean governance and policy-making?	Parsons et al., 2014, question 60
15	Transaction costs of ocean management	What are the relative ecological, social, and economic costs and benefits of stewardship, regulatory, and market mechanisms for ocean management?	Rudd et al., 2011, question 28/Rees et al., 2013, question 28
16	Policy coherence across domains	What are the benefits and costs of horizontally and vertically integrating ocean policies and regulations within and across different policy domains such as environment, health, and trade?	Rudd et al., 2011, question 29
17	Political culture and the use of science	How do different political cultures and institutions affect the acquisition and treatment of scientific evidence in ocean policy formulation, implementation and evaluation?	Sutherland et al., 2012a, question 01
18	Information for sustainable food choices	What information is most useful to consumers wishing to make informed decisions about the environmental and social impacts of their seafood choices?	Pretty et al., 2010, question 96
19	Compliance with rules	What factors influence the likelihood of compliance with ocean legislation and regulations at local, national, and international levels?	Sutherland et al., 2009, question 88/Rudd et al., 2011, question 37
20	Management capacity of human communities	What are the effects of different strategies for building community capacity on levels of citizen engagement in coastal and ocean stewardship, restoration, and conservation?	Rudd et al., 2011, question 32
21	Job creation	What types and numbers of jobs can be created by ocean research?	Borja et al., 2013, issue 03
22	Restoration effectiveness	To what extent can coastal and ocean habitat restoration or rehabilitation compensate for loss of quantity or quality of existing species' habitat?	Rudd et al., 2011, question 07

(Continued)

Table 1 | Continued

	Abbreviation	Full question text	Source(s)[a]
23	Deep water resource exploitation	What are the effects of marine exploration and exploitation of living and mineral resources on benthic ecosystems and seafloor conditions, especially in deep water?	Fissel et al., 2012, question 28
24	Aquaculture effects	How can aquaculture and open water farming be developed so that impacts on wild fish stocks and coastal and marine habitats are minimized?	Pretty et al., 2010, question 04
25	Triage for species at risk	How do we better identify species at risk of extinction in marine ecosystems, and when should the triage approach to conservation of critically endangered species be applied to marine systems?	Parsons et al., 2014, question 44
26	Coral reef management strategies	Which management actions are most effective for ensuring the long-term survival of coral reefs in response to the combined impacts of climate change and other existing stressors?	Sutherland et al., 2009, question 48
27	Integrated upland-coastal management	How do policy, legal, or institutional arrangements shape the effectiveness of integrated management for terrestrial watersheds and adjacent coastal environments?	Rudd et al., 2011, question 38
28	High seas governance	What are the unique challenges of high seas management and what are the best methods for ensuring effective and credible high seas governance and conservation outside the legal jurisdiction of any single country?	Parsons et al., 2014, question 52/Sutherland et al., 2009, question 53
29	Polar colonization by warmer-climate species	What are the effects of climate-driven species dispersal and colonization on ecosystem function and services in polar oceans?	Sutherland et al., 2010, issue 12/Sutherland et al., 2012a, issue 01
30	Ocean productivity	What will be the impacts of global change on phytoplankton and oceanic productivity, and what will be the feedbacks of these impacts on the climate?	Sutherland et al., 2009, question 51
31	Effects of marine diseases on human health	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?	Sutherland et al., 2009, question 66/Rudd et al., 2011, question 30
32	Top predator decline	What are the effects of world-wide declines of top predators on ecological function and ecosystem services?	Sutherland et al., 2013b, question 88
33	Cumulative stressors	How will the individual and interactive effects of multiple stressors (e.g., ocean acidification, anoxia, warming, fishing, pollution) affect the capacity of marine ecosystems and species to adapt to changing oceans?	Sutherland et al., 2009, question 52/Parsons et al., 2014, question 14
34	Upland hydrology effects on oceans	How will changing terrestrial hydrological regimes affect coastal and marine ecosystem structure, function, and services?	Brown et al., 2010, question 23
35	Sea level rise and vulnerable coasts	How can the relationships between coastal sea-level forcing mechanisms, regional variability in sea-level rise, and future storm tracks be modeled and used to identify and protect vulnerable coastlines?	Heip et al., 2011, theme 03/Heip et al., 2011, theme 06
36	Contaminants	What is the relative importance of various types of chemical (e.g., pharmaceuticals, pesticides, nanomaterials) and non-chemical stressors? n terms of their effects on coastal and marine ecosystem structure, function, and services?	Kark et al., 2011, question 20/Boxall et al., 2012, question 12
37	Ocean acidification	How will ocean acidification affect marine biological diversity, including non-calcifying organisms, and ecosystem function and processes such as nutrient speciation and availability, trophic interactions, reproduction, metabolism, and diseases?	Sutherland et al., 2009, question 46/Heip et al., 2011, theme 64
38	MPAs and resilience	To what degree can no-take or highly-protected MPAs provide resilience or a buffer against ecosystem disruption caused by climate change and ocean acidification?	Parsons et al., 2014, question 13
39	Greenhouse gas flux	How will climate change affect the magnitude and spatial patterns of atmosphere-ocean-sea-floor exchanges of important greenhouse gases (e.g., methane, carbon dioxide) and aerosols?	Fissel et al., 2012, question 08
40	Shifting ecological baselines	How can effective policy-making and evaluation of marine systems be proactively advanced in light of recognized shifting of historical baselines?	Parsons et al., 2014, question 53
41	Integrating oceans with climate models	How can surface sea temperature and sea-ice-related uncertainty be identified, reduced, and integrated in climate modeling systems?	Heip et al., 2011, theme 09
42	Extrapolating paleoecological shifts	To what extent can we extrapolate from paleoecological range shifts to understand twenty-first-century environmental change in the marine environment?	Sutherland et al., 2013b, question 84

(Continued)

Table 1 | Continued

	Abbreviation	Full question text	Source(s)[a]
43	Uncertainty in modeling	How can we efficiently and effectively plan adaptation measures to cope with extreme events given the uncertainty associated with model predictions?	Brown et al., 2010, question 06
44	Crossdisciplinary ocean science and management	What strategies can be used to promote long-term integrated cross-disciplinary collaborations in ocean science and management?	Parsons et al., 2014, question 71
45	Oceanographic data	What are the long-term trends in three dimensional distributions of key oceanographic variables (temperature, biomass, oxygen saturation, salinity, carbon system, sea-level change, currents, etc.) in the world's oceans?	Fissel et al., 2012, question 21
46	Energy development	What technologies and strategies are needed to develop and deliver ocean-based renewable and non-renewable energy and minerals to society with minimal harm to the ocean environment?	Fissel et al., 2012, question 39
47	Bycatch effects	How can the impacts of bycatch from legal and illegal, unreported, and unregulated fisheries be reduced to a level that will allow for reversal of declining trends of affected species?	Parsons et al., 2014, question 05
48	Seafood production strategies	How should the efficient capture and processing of seafood be maximized while harvesting resources within sustainable limits and maintaining good marine ecological function?	Ingram et al., 2013, question 07
49	Macroalgal culture	What are the economic opportunities for, and ecological consequence of, rapidly increasing macroalgal culture as a raw material for food and biofuel production?	Ingram et al., 2013, question 12/Sutherland et al., 2014, issue 04
50	Ecosystem management alternatives	What are the advantages and disadvantages, for ecosystems and managers, of adopting an ecosystem approach vs. surrogate organism (indicator or umbrella species) approach to conserving marine biological diversity?	Braunisch et al., 2012, question 25/Sutherland et al., 2009, question 63
51	Climate change mitigation and manipulation	What are the natural mechanisms through which the ocean and the seabed can mitigate climate change, and what are the risks of manipulating these mechanisms (e.g., changing the albedo, fertilizing the ocean in geoengineering initiatives)?	Fissel et al., 2012, question 09
52	Climate change-induced species dispersal	What determines the rate at which marine species distributions respond to climate change?	Sutherland et al., 2013b, question 83
53	Adaptive capacity of marine life	What demographic traits determine the resilience of natural populations to marine disturbance and perturbation?	Sutherland et al., 2013b, question 26
54	Invasive species effects	To what extent is biotic invasion and native species loss be creating marine ecosystems with altered properties?	Sutherland et al., 2013b, question 68
55	Tipping points	What attributes of marine ecosystems facilitate prediction of impending transitions among alternative states?	Fleishman et al., 2011, question 24
56	Evolutionary consequences of connectivity	What are the evolutionary consequences of marine species becoming less connected through fragmentation or more connected through globalization?	Sutherland et al., 2013b, question 01
57	Ecosystem structure to service linkages	To what extent can ecological function and the supply of ocean ecosystem services be predicted on the basis of marine ecosystem composition and structure?	Rudd et al., 2011, question 01
58	Global biodiversity and ecological function	How does the relationship between biological diversity and ecosystem functioning change across different marine habitats at a global scale?	Snelgrove et al., 2012, question 08
59	Biodiversity contributions to ecosystem function	What is the relative contribution of marine biological diversity at different levels of organization (genes, species richness, species identity, functional identity, functional diversity) to ocean ecosystem functioning?	Sutherland et al., 2013b, question 63
60	Monitoring cumulative effects	What monitoring technologies and methods can effectively and efficiently deliver comparable ocean data and data products for observation and assessment the long-term, incremental and cumulative effects of multiple stressors in the marine environment?	Kark et al., 2011, question 10/Rudd et al., 2011, question 35/Parsons et al., 2014, question 54/Fissel et al., 2012, question 23
61	Biological connectivity	How do the dispersal and movement of marine species, individuals, or genes connect populations and ocean locations?	Snelgrove et al., 2012, question 05
62	Coastal adaptation to sea level rise	What factors determine the rates at which coastal ecosystems can respond to sea-level rise, and which of these are amenable to management?	Sutherland et al., 2009, question 12

(Continued)

Table 1 | Continued

	Abbreviation	Full question text	Source(s)[a]
63	Melting ice effects	How will interactions between ice melting and oceanographic conditions affect marine biological diversity and ecosystem services?	Sutherland et al., 2009, question 09/Heip et al., 2011, theme 15
64	Coastal hazard management	How can the spatial extent, frequency, and risk of marine hazards affecting coastal waters (e.g., hydrate-triggered landslides, tsunamis, extreme storm events) be forecast and their effects minimized?	Fissel et al., 2012, question 05
65	Polar oil spills	What are the impacts of oil spills in cold and deep oceans and under sea ice, and what are the appropriate strategies and technologies for prevention and mitigation?	Fissel et al., 2012, question 27
66	Thermohaline circulation	What are the potential causes, risks, and consequences of thermohaline circulation changes and collapse?	Heip et al., 2011, themes 21–24
67	Benthopelagic coupling	What is the role of marine biota and benthopelagic coupling in ocean–atmosphere carbon cycling and primary production?	Sutherland et al., 2006, question 05

[a] When two or more references provided, the wording of the final question combines aspects from the questions in the original papers.

[b] Themes from Heip et al. (2011) are numbered in the order they appear in Executive Summary Box A (pp. 10–15).

[c] Issues identified in horizon scanning exercises were rephrased to pose them as a research question.

[d] Questions from Snelgrove et al. (2012) are numbered in order of appearance.

The final dataset for this analysis thus consisted of respondent-specific demographic and professional variables (age, articles published, career length, major discipline, level of education, gender, region of residence, sector of work, and, for government employees, whether they were scientists or non-scientists), survey-related variables (time to complete the survey, self-reported accordance of BWS ranking results with respondents' "true" priorities, and fitness score calculated based on respondents' consistency in answering BWS ranking tasks), and a vector of 67 ranking scores per respondent. Fitness score was also divided into deciles to permit testing of how relative fitness level was associated with specific levels of other covariates. No information gathered from partially completed survey responses was used in the analysis.

After the HB analysis, the 67 research questions were sorted by overall median rank order for the sample as a whole and differences in median ranking score for salient demographic, professional, and survey-specific variables were calculated. For each of the 67 research questions, I tested for differences in median ranking scores with a Kruskall–Wallis test (alpha level 0.01) and significant differences (alpha level 0.01) in median rank among factor levels with Tukey–Kramer *post-hoc* comparisons. Friedman tests were used to identify significant differences in median ranking scores for adjacent ranked research questions (alpha level 0.01). Differences in median fitness scores among disciplines and other factors were compared with Kruskall–Wallis tests (alpha level 0.01) and Tukey–Kramer *post-hoc* comparisons (alpha level 0.01). Pearson χ^2 tests were used to test for differences in fitness among different levels of demographic and professional factors.

RESULTS

SURVEY RESPONSE

After accounting for bounced emails, multiple email addresses for single authors, long-term leave and retirements, and respondent self-screening from the survey (i.e., respondents who lacked suitable experience), 14,309 surveys were distributed to scientists who were potentially members of the sample frame. A total of 2187 respondents (15.3%) completed the full survey; another 1425 (10.0%) partially completed the survey.

Survey completion time, from the time the survey was first accessed until the completed survey was submitted, ranged from 9 min to 30 days with a median completion time of 50.4 min. Only one factor, region of residence, exhibited significant differences among levels (Kruskall–Wallis $H = 53.6$, 6 d.f., $p < 0.01$): respondents from Africa and the Middle East (AME) took significantly longer ($p < 0.01$) to complete the survey than respondents from either Australia, New Zealand and South Pacific (ANZSP) or North America (NA).

SURVEY RESPONDENTS

Fitness scores were calculated for each survey respondent. Mean and median fitness for the sample was 521.3 and 522.5, respectively; the null hypothesis that fitness score was normally distributed was rejected (Shapiro–Wilk $W = 1.000$, $p < 0.01$). For the simulated survey ($n = 2139$ random responders), the mean ranking score was 1.493 and the hypothesis of a normal distribution could not be rejected at the 1% level (Shapiro–Wilk $W = 0.97$, $p = 0.0864$). Median fitness score for the simulated respondents was 321.4, with 95% of observations (i.e., 2.5 and 97.5% quantiles) lying between the range of 286.3 and 380.3. The medians of real (522.5) and simulated (321.4) samples were significantly different (Kruskal–Wallis $H = 3185.1$, 1 d.f., $p < 0.01$). Note that 55 respondents from the survey had fitness scores less than 380.3, the upper limit of the 95% confidence bound for random responders, so it is likely that some respondents taking this survey responded randomly during their BWS ranking tasks. **Table 2** provides a summary of key demographic, professional, and survey-specific variables for respondents who completed the survey ($n = 2187$).

FITNESS SCORES

Higher levels of median fitness score (i.e., higher levels of respondents' internal consistency in making BWS comparisons) were associated with higher levels of self-reported fit between the

Table 2 | Demographic characteristics of survey respondents ($n = 2187$).

Age	n	Gender	
<30 years	139	Female	843
30–39 years	798	Male	1344
40–49 years	592	Fit (self-reported)	
50–59 years	435	Poor	16
≥60 years	223	Fair	426
Articles published		Good	1392
≤2	158	Excellent	353
3–5	332	Region[a]	
6–10	394	AME	57
11–25	493	ANZSP	196
26–50	406	EA	128
51–100	266	EUR	873
>100	138	NA	736
Career length		SCAC	150
≤5 years	208	SSE	47
6–10 years	511	Sector—overall	
11–15 years	493	Academic—faculty	1489
16–20 years	286	Academic—students	125
31–30 years	406	Government	390
>30 years	283	Private sector	61
Discipline		NGOs	91
Physical sciences	604	Other	31
Ecological sciences	1429	Sector—government	
Social sciences	154	Not government	1797
Education		Government non-scientist	56
PhD	1874	Government scientist	334
Other	313		

[a]*AME, Africa and Middle East; ANZSP, Australia, New Zealand and South Pacific; EA, East Asia; EUR, Europe; NA, North America; SCAC, South and Central America, and Caribbean; SSE, South and Southeast Asia.*

survey's objective ranking of an individual's priorities and their subjective priorities. Other significant factors related to experience and expertise (articles published, career length, and, potentially, being a government scientist) and region of residence (**Table 3**). The developed-developing world divide was notable, with respondents from the AME, EA, and SSE regions having consistently lower fitness scores than respondents from NA, ANZSP, Europe (EUR), and South and Central America and Caribbean (SCAC) (**Figure 1**) (the boxplot shows median fitness, a box from the 1st to 3rd quartiles, whiskers with end caps extending to the 2.5 and 97.5% quantiles, and a notch on box denoting the 95% confidence interval for the median).

RESEARCH PRIORITIES

An exploratory latent class analysis suggested that three main factors influenced respondents' ranking of research questions: disciplinary background; region of residence; and survey fitness scores. The influence of those factors on overall priority rank was examined in more detail for individual research questions. For the top-ranked question (cumulative stressors, Q33), for example, discipline (**Figure 2**), region (**Figure 3**), and fitness level were all significantly associated with median ranking score (**Table 4**); increasing career length and female gender were also significantly associated with median ranking score. Similar findings for other potentially divisive questions (not reported here for brevity), suggest that maintaining a primary focus on respondents' disciplinary association, region of residence, and level of consistency in making BWS comparisons during the survey is appropriate.

Table 5 shows the full list of 67 research questions ordered by aggregate median ranking score for all 2187 survey respondents and broken down by respondents' major discipline. The median ranking scores for each pair of research questions adjacent in rank order (i.e., moving down column 1) were compared with Friedman tests. For example, the Friedman test statistic ($S = 126.3$) listed for the top-ranked cumulative stressor question indicates that the median ranking score for that question was significantly greater ($p < 0.01$) than the median for the second-ranked ocean productivity question. Ocean productivity, in turn, had a significantly higher median than ocean acidification ($S = 10.15$, $p < 0.01$). Other significant gaps in medians for adjacent questions occur between questions ranked 4 and 5, 6 and 7, 9 and 10 (**Figure 4** shows median scores for the top 20 questions), 42 and 43, 46 and 47, 56 and 57, and, near the bottom of the rankings, between 63 and 64, and 66 and 67.

Table 5 also shows results from the comparisons of median ranking across the three major disciplines. In the preliminary latent class analysis, I found that the research priorities of physical ($n = 508$) and applied scientists ($n = 96$), and ecological scientists ($n = 1422$) and respondents with "other" disciplinary affiliations ($n = 7$), were statistically indistinguishable, so I combined those groups and henceforth refer to them simply as physical ($n = 604$) and ecological scientists ($n = 1429$). Note that equality of median ranking scores for the three disciplines could not be rejected for only a single research question (coral reef management strategies, ranked 18). For the majority of research questions, Kruskall–Wallis statistics were highly significant and there were significant differences in median ranking scores among at least two of the disciplines (from Tukey–Kramer *post-hoc* comparisons).

The top 20 research questions for each major discipline are shown in **Table 6**. For physical and ecological scientists, seven of the top 10 research questions are shared between the disciplines; a higher proportion of more disciplinary-oriented questions appeared lower in rank, between 11 and 20. The research priorities for social scientist respondents are much different than for both groups of natural science respondents, with only one question (cumulative stressors) in the top 10 shared across all three groups.

The differences in research priorities were much less pronounced when respondents were grouped according to their region of residence. Five of the top 10 research questions were shared among all seven regions (**Table 7**) and even the regions with low numbers of respondents (i.e., AME, $n = 57$; East Asia [EA], $n = 71$; and South and Southeast Asia [SSE], $n = 19$) had similar patterns of research priorities compared to the larger groups. This highlights the relative importance of disciplinary background relative to area of residence in shaping scientists' research priorities.

Table 3 | Differences in median fitness score for respondents belonging to different demographic and professional categories.

Factor	Level 1	Level 2	Level 3	Level 4	Level 5	Level 6	Level 7	Kruskall–Wallis *H*
Age	<30 years	30–39 years	40–49 years	50–59 years	≥60 years			
n	139	798	592	435	223			1.97
Median	525.2	521.1	527.3	522.5	520.3			
Articles published	≤2	3–5	6–10	11–25	26–50	51–100	>100	22.52*
n	158	332	394	493	406	266	138	
Median	512.2[a]	516.5[b]	521.0	519.9	530.9	533.8[a,b]	523.4	
Career length	≤5 years	6–10 years	11–15 years	16–20 years	31–30 years	>30years		17.46*
n	208	511	493	286	406	283		
Median	513.4[a,b]	522.0	518.7	526.8	527.6[a]	530.5[b]		
Discipline	Physical sciences	Ecological sciences	Social sciences					0.36
n	604	1429	154					
Median	523.9	522.0	521.5					
Education	PhD	Other						4.05
n	1874	313						
Median	522.8	515.3						
Fit (self-reported)	Excellent	Good	Fair	Poor				67.52*
n	353	1392	426	16				
Median	540.3[a,b]	523.3[a,c]	505.5[b,c]	515.8				
Gender	Female	Male						0.12
n	843	1344						
Median	523.4	521.8						
Region	AME	ANZSP	EA	EUR	NA	SCAC	SSE	65.30*
n	57	196	128	873	736	150	47	
Median	496.4[a,b,c]	524.0[a,d,e]	496.7[f,g]	527.8[b,d,f,h,i]	528.1[c,g,j]	510.4[h,k]	479.5[e,i,j,k]	
Sector—government	Not government	Government non-scientist	Government scientist					9.47*
n	1797	56	334					
Median	521.7	508.2[a]	529.2[a]					
Sector—overall	Academic—faculty	Academic—students	Government	Private sector	NGOs	Other		8.75
n	1489	125	390	61	91	31		
Median	520.1	514.4	525.9	522.6	534.0	539.0		

**Denotes Kruskall–Wallis H statistic was significant at the 1% level; alphabetical superscripts indicate pairs of median fitness levels that were significantly different at the 1% level in Tukey–Kramer post-hoc comparisons.*

Region was closely associated with respondent fitness level. A contingency table shows Pearson chi-square test residuals of fitness deciles by region of residence (**Table 8**). The proportions of actual vs. expected respondents per cell is, in aggregate, significantly different ($\chi^2 = 132.69$, 54 d.f., $p < 0.01$), with disproportionately high levels (residual > 2) of respondents from AME, EA, SCAC, and SSE in the lowest decile of fitness. That is, respondents from developing regions had higher proportions of random respondents.

DISCUSSION

None of the 67 research questions distilled from the 28 publications I examined for this study are unimportant; the questions identified in the scanning exercises had been through an extensive, bottom-up process that involved widespread solicitation of research questions needed to inform environmental policy-making and systematic vetting of those submissions (Sutherland et al., 2011b). They were supplemented for this survey with important research questions identified by experts in ocean and coastal research, and published in other reports or articles. While the question "*To what extent can we extrapolate from paleoecological range shifts to understand 21st-century environmental change in the marine environment*?" was, for instance, ranked as 59th in overall priority by survey respondents, this question was deemed important enough to receive major focus of the International Ocean Discovery Program's (2011) science plan for 2013–2023. All 67 research questions are important precisely because of the level of vetting that they had already been through prior to being included in this survey. Clearly, however, some research questions rose to the top of the priorities list and were viewed by international scientists as topics worthy of great scrutiny and effort because of their potential importance for understanding and solving ocean sustainability challenges.

SURVEY RESPONDENTS

While 15.3% is a modest survey completion rate [e.g., in a 2011 coastal scientists' survey, Rudd and Lawton (2013) obtained a 35.2% response rate], completing 36 BWS tasks was arduous and

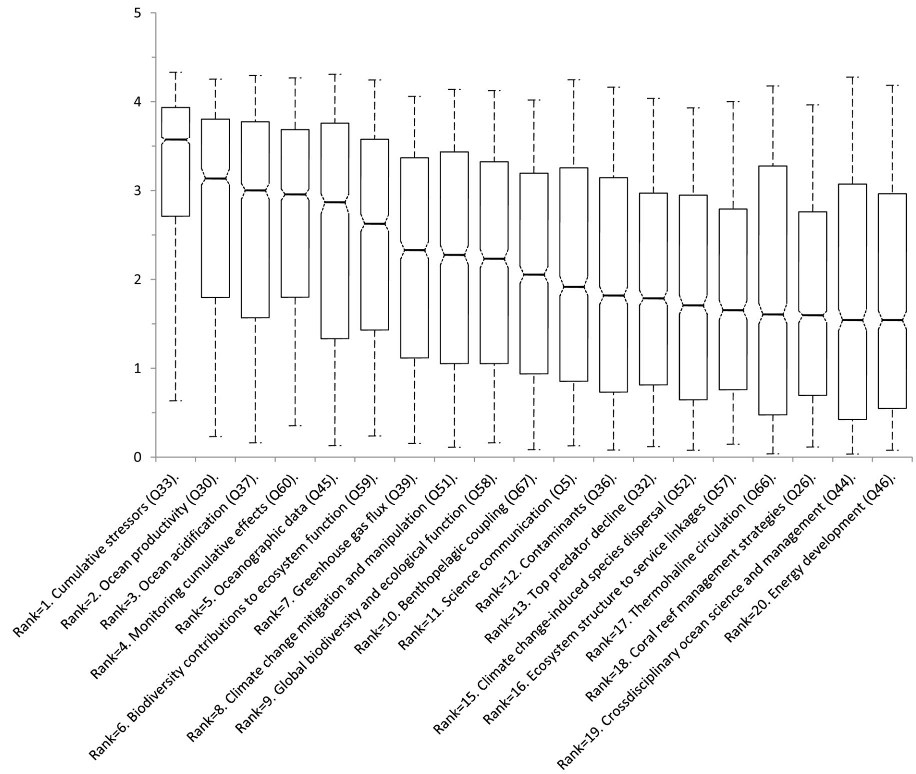

FIGURE 1 | Box plot of median ranking score for the 20 research questions ranked, in aggregate, as highest priority.

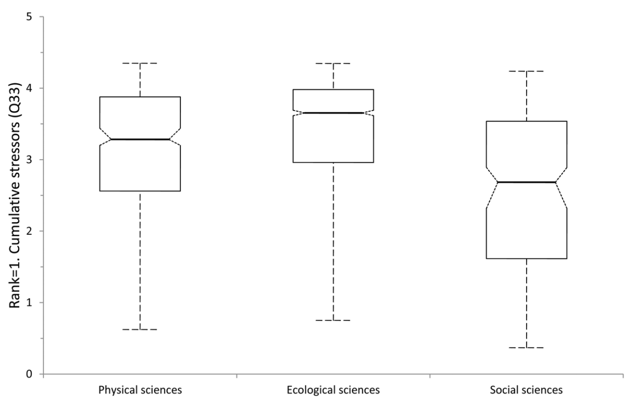

FIGURE 2 | Box plot of median ranking score for top-ranked question (cumulative stressors) for each of three disciplinary categories.

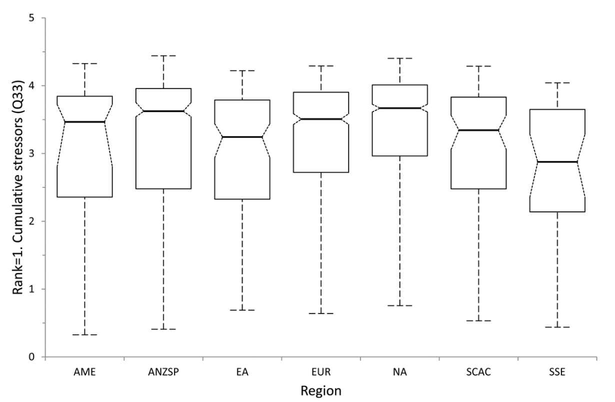

FIGURE 3 | Box plot of median ranking score for top-ranked question (cumulative stressors) for each of seven regions.

contributed to the relatively high proportion of incomplete surveys. In addition, the sample likely included authors without appropriate ocean-related expertise who simply ignored survey invitations. Given the breadth of expertise represented by the respondents who completed the survey (i.e., respondents represented approximately 36,000 person-years of ocean research experience and accounted for 68,000 ocean-relevant publications), the sample provided a rich source of information about research priorities. It was not, however, possible to test for self-selection bias because no general characterization of the sample frame as a whole was possible. The over-representation of developed country scientists in prior scanning exercises has been noted (Cooke et al., 2010; Boxall et al., 2012), but their concerns focused on the composition of workshop participants who finalized the lists of important questions. In this survey, the sample was based on an ISI Web of Science search; as such, the sample was dominated by developed country researchers who are the source of the majority of published articles in the higher-impact journals from which I

Table 4 | Median ranking score for research questions in aggregate rank order and with differences in rank by disciplinary category.

Factor	Level 1	Level 2	Level 3	Level 4	Level 5	Level 6	Level 7	Level 8	Level 9	Level 10	Kruskall–Wallis *H*
Age	<30 years	30–39 years	40–49 years	50–59 years	≥60 years						6.56
Median	3.60	3.55	3.60	3.49	3.62						
Articles published	≤2	3–5	6–10	11–25	26–50	51–100	>100				9.87
Median	3.42	3.47	3.57	3.52	3.61	3.65	3.61				
Career length	≤5 years	6–10 years	11–15 years	16–20 years	31–30 years	>30 years					17.28*
Median	3.35^{a}	3.53	3.60	3.62^{a}	3.49	3.68					
Discipline	Physical sciences	Ecological sciences	Social sciences								102.95*
Median	$3.28^{a,b}$	$3.65^{a,c}$	$2.68^{b,c}$								
Education	PhD	Other									2.72
Median	3.59	3.44									
Fit (self-reported)	Excellent	Good	Fair	Poor							7.35
Median	3.53	3.59	3.49	2.74							
Fitness score decile	1 lowest 10%	2	3	4	5	6	7	8	9	10 highest 10%	54.16*
Median	$2.96^{a,b,c,d,e,f,g}$	$3.30^{h,i,j,k}$	3.60^{a}	3.55^{b}	3.66^{c}	3.55	$3.69^{d,h}$	$3.64^{e,i}$	$3.62^{f,j}$	$3.62^{g,k}$	
Gender	Female	Male									23.88*
Median	3.65^{a}	3.48^{a}									
Region	AME	ANZSP	EA	EUR	NA	SCAC	SSE				52.17*
Median	3.47	3.62	3.24^{a}	3.51	$3.67^{a,b}$	3.34	2.88^{b}				
Sector—government	Not government	Government non-scientist	Government scientist								1.89
Median	3.56	3.61	3.61								
Sector—overall	Academic—faculty	Academic—students	Government	Private sector	NGOs	Other					3.89
Median	3.57	3.49	3.61	3.45	3.57	3.75					

Denotes Kruskall–Wallis H statistic was significant at the 1% level; alphabetical superscripts indicate pairs of median fitness levels that were significantly different at the 1% level in Tukey–Kramer post-hoc comparisons.

Table 5 | Differences in median ranking score for the top-ranked question (cumulative stressors) by respondents belonging to different demographic and professional categories.

	Questions in rank order	Median likelihood of being chosen most important research question				
		Overall ($n = 2187$)	Physical scientists ($n = 604$)	Ecological scientists ($n = 1429$)	Social scientists ($n = 154$)	Kruskall–Wallis H
1	Cumulative stressors (Q33) ($S = 126.03$)†	3.57	3.28[a,b]	3.65[a,c]	2.68[b,c]	102.95*
2	Ocean productivity (Q30) ($S = 10.15$)†	3.14	3.41[a,b]	3.13[a,c]	1.22[b,c]	151.80*
3	Ocean acidification (Q37) ($S = 0.93$)	3.00	3.20[a]	3.03[b]	1.44[a,b]	80.56*
4	Monitoring cumulative effects (Q60) ($S = 7.37$)†	2.96	3.07[a,b]	2.98[a,c]	2.17[b,c]	51.96*
5	Oceanographic data (Q45) ($S = 2.85$)	2.88	3.69[a,b]	2.56[a,c]	0.97[b,c]	297.54*
6	Biodiversity contributions to ecosystem function (Q59) ($S = 24.82$)†	2.63	1.92[a,b]	3.09[a,c]	1.39[b,c]	253.97*
7	Greenhouse gas flux (Q39) ($S = 1.19$)	2.33	3.28[a,b]	2.07[a,c]	0.98[b,c]	315.58*
8	Climate change mitigation and manipulation (Q51) ($S = 0.24$)	2.28	2.99[a,b]	2.12[a,c]	1.09[b,c]	125.60*
9	Global biodiversity and ecological function (Q58) ($S = 14.00$)†	2.23	1.73[a,b]	2.62[a,c]	1.13[b,c]	172.37*
10	Benthopelagic coupling (Q67) ($S = 1.10$)	2.05	2.62[a,b]	2.04[a,c]	0.53[b,c]	189.74*
11	Science communication (Q5) ($S = 0.70$)	1.92	1.77[a]	1.84[b]	3.22[a,b]	69.14*
12	Contaminants (Q36) ($S = 0.44$)	1.82	2.08[a]	1.84[b]	0.80[a,b]	75.24*
13	Top predator decline (Q32) ($S = 3.79$)	1.79	1.08[a]	2.20[a,b]	1.09[b]	230.51*
14	Temperature redistribution (Q3) ($S = 0.44$)	1.74	2.51[a,b]	1.56[a,c]	0.56[b,c]	188.51*
15	Climate change-induced species dispersal (Q52) ($S = 0.01$)	1.71	1.70[a]	1.88[b]	0.51[a,b]	112.38*
16	Ecosystem structure to service linkages (Q57) ($S = 3.00$)	1.65	1.14[a]	2.02[a,b]	1.33[b]	123.49*
17	Thermohaline circulation (Q66) ($S = 1.48$)	1.61	3.14[a,b]	1.40[a,c]	0.39[b,c]	246.89*
18	Coral reef management strategies (Q26) ($S = 0.17$)	1.59	1.55	1.64	1.20	6.85
19	Energy development (Q46) ($S = 1.70$)	1.54	2.08[a,b]	1.31[a]	1.39[b]	65.36*
20	Crossdisciplinary ocean science and management (Q44) ($S = 0.71$)	1.54	1.82[a,b]	1.30[a,c]	3.08[b,c]	68.98*
21	Ocean literacy messages (Q12) ($S = 0.08$)	1.51	1.08[a,b]	1.55[a,c]	3.03[b,c]	65.00*
22	Melting ice effects (Q63) ($S = 1.19$)	1.48	2.15[a,b]	1.37[a,c]	0.46[b,c]	170.84*
23	Aquaculture effects (Q24) ($S = 0.17$)	1.41	1.21[a]	1.49[a]	1.66	12.59*
24	Upland hydrology effects on oceans (Q34) ($S = 0.20$)	1.40	1.85[a,b]	1.27[a,c]	0.74[b,c]	125.25*
25	Bycatch effects (Q47) ($S = 1.01$)	1.39	0.81[a,b]	1.69[a]	1.84[b]	143.09*
26	Sea level rise and vulnerable coasts (Q35) ($S = 1.19$)	1.37	2.44[a,b]	1.10[a]	1.15[b]	258.65*
27	Seafood production strategies (Q48) ($S = 0.01$)	1.33	0.89[a,b]	1.53[a]	2.07[b]	69.23*
28	Biological connectivity (Q61) ($S = 0.00$)	1.29	0.92[a,b]	1.63[a,c]	0.49[b,c]	166.00*
29	Restoration effectiveness (Q22) ($S = 0.10$)	1.25	1.15[a]	1.34[a,b]	1.00[b]	18.97*
30	MPAs and resilience (Q38) ($S = 0.08$)	1.23	0.77[a,b]	1.49[a]	1.48[b]	111.27*
31	Adaptive capacity of marine life (Q53) ($S = 3.30$)	1.19	0.69[a]	1.62[a,b]	0.70[b]	197.31*
32	Triage for species at risk (Q25) ($S = 0.63$)	1.14	0.91[a]	1.28[a,b]	0.85[b]	65.83*
33	Deep water resource exploitation (Q23) ($S = 0.38$)	1.10	1.20[a]	1.16[b]	0.61[a,b]	46.89*
34	Risk assessment for governance (Q14) ($S = 1.10$)	1.08	1.00[a]	1.00[b]	3.17[a,b]	109.07*
35	Coastal hazard management (Q64) ($S = 0.00$)	1.07	1.94[a,b]	0.82[a]	0.86[b]	228.49*
36	Ocean deoxygenation (Q2) ($S = 0.38$)	1.07	1.77[a,b]	0.93[a,c]	0.38[b,c]	216.12*
37	Coastal adaptation to sea level rise (Q62) ($S = 0.02$)	1.06	2.02[a,b]	0.85[a]	0.79[b]	215.53*
38	Polar colonization by warmer-climate species (Q29) ($S = 0.50$)	1.05	1.36[a,b]	1.03[a,c]	0.45[b,c]	113.65*
39	Integrating oceans with climate models (Q41) ($S = 0.29$)	1.04	2.14[a,b]	0.87[a,c]	0.40[b,c]	320.60*
40	Ecosystem management alternatives (Q50) ($S = 0.24$)	1.02	0.67[a,b]	1.19[a]	1.04[b]	89.69*
41	Invasive species effects (Q54) ($S = 2.44$)	1.01	0.70[a]	1.32[a,b]	0.49[b]	178.57*
42	Uncertainty in modeling (Q43) ($S = 6.92$)†	0.96	1.66[a]	0.73[a,b]	1.62[b]	172.84*
43	Integrated upland-coastal management (Q27) ($S = 1.38$)	0.86	0.89[a]	0.77[b]	2.62[a,b]	117.11*
44	Polar oil spills (Q65) ($S = 0.06$)	0.84	1.28[a,b]	0.73[a]	0.46[b]	86.65*
45	Effects of MPAs on humans (Q6) ($S = 0.20$)	0.77	0.55[a,b]	0.80[a,c]	2.68[b,c]	143.60*
46	High seas governance (Q28) ($S = 7.61$)†	0.76	0.49[a,b]	0.81[a,c]	2.41[b,c]	121.45*
47	Seafood supply chains (Q1) ($S = 0.13$)	0.73	0.58[a,b]	0.74[a,c]	1.97[b,c]	92.33*

(Continued)

Table 5 | Continued

	Questions in rank order	Median likelihood of being chosen most important research question				
		Overall ($n = 2187$)	Physical scientists ($n = 604$)	Ecological scientists ($n = 1429$)	Social scientists ($n = 154$)	Kruskall–Wallis H
48	Global economic value of the ocean (Q9) ($S = 0.13$)	0.72	$0.47^{a,b}$	$0.80^{a,c}$	$1.23^{b,c}$	51.96*
49	Evolutionary consequences of connectivity (Q56) ($S = 0.77$)	0.69	0.42^{a}	$1.01^{a,b}$	0.29^{b}	189.97*
50	Tipping points (Q55) ($S = 0.04$)	0.66	0.57^{a}	$0.74^{a,b}$	0.39^{b}	27.67*
51	Policy coherence across domains (Q16) ($S = 2.71$)	0.64	0.52^{a}	0.60^{b}	$2.76^{a,b}$	154.30*
52	Shifting ecological baselines (Q40) ($S = 0.04$)	0.57	$0.37^{a,b}$	$0.64^{a,c}$	$1.08^{b,c}$	81.03*
53	Ecosystem service valuation implications (Q8) ($S = 3.30$)	0.54	$0.31^{a,b}$	$0.64^{a,c}$	$1.86^{b,c}$	136.57*
54	Local ecological knowledge (Q4) ($S = 0.13$)	0.52	0.50^{a}	0.46^{b}	$2.41^{a,b}$	104.95*
55	Effects of marine diseases on human health (Q31) ($S = 0.01$)	0.48	0.61	0.44	0.40	17.00*
56	Management capacity of human communities (Q20) ($S = 6.69$)†	0.47	$0.39^{a,b}$	$0.44^{a,c}$	$2.78^{b,c}$	154.57*
57	Transaction costs of ocean management (Q15) ($S = 2.05$)	0.43	$0.34^{a,b}$	$0.41^{a,c}$	$2.85^{b,c}$	216.88*
58	Compliance with rules (Q19) ($S = 4.30$)	0.42	$0.26^{a,b}$	$0.42^{a,c}$	$2.69^{b,c}$	202.95*
59	Extrapolating paleoecological shifts (Q42) ($S = 1.10$)	0.37	$0.80^{a,b}$	$0.31^{a,c}$	$0.08^{b,c}$	160.28*
60	Effects of economic subsidization (Q7) ($S = 3.15$)	0.30	$0.21^{a,b}$	$0.30^{a,c}$	$1.53^{b,c}$	172.36*
61	Political culture and the use of science (Q17) ($S = 1.81$)	0.29	$0.22^{a,b}$	$0.27^{a,c}$	$1.97^{b,c}$	162.87*
62	Information for sustainable food choices (Q18) ($S = 5.24$)	0.28	0.20^{a}	0.27^{b}	$0.80^{a,b}$	61.69*
63	Macroalgal culture (Q49) ($S = 0.56$)	0.23	0.32^{a}	0.20^{a}	0.16	33.52*
64	Human dissociation from nature (Q11) ($S = 84.15$)†	0.23	$0.16^{a,b}$	$0.24^{a,c}$	$0.69^{b,c}$	39.30*
65	Effects of worldviews on conservation (Q10) ($S = 0.77$)	0.15	0.13^{a}	0.13^{b}	$1.18^{a,b}$	133.09*
66	Property rights and conservation (Q13) ($S = 526.44$)†	0.15	$0.11^{a,b}$	$0.15^{a,c}$	$1.40^{b,c}$	184.92*
67	Job creation (Q21)	0.01	0.03^{a}	0.01^{a}	0.01	57.28*

*Friedman S is reported in parentheses: †denotes that aggregate median ranking score for that question was significantly higher (at 1% level) than the next research question ranked immediately below; *denotes that the Kruskall–Wallis H statistic was significant at the 1% level; superscripts a, b, c indicate pairs of median rankings that were significantly different at the 1% level in Tukey–Kramer post-hoc comparisons.*

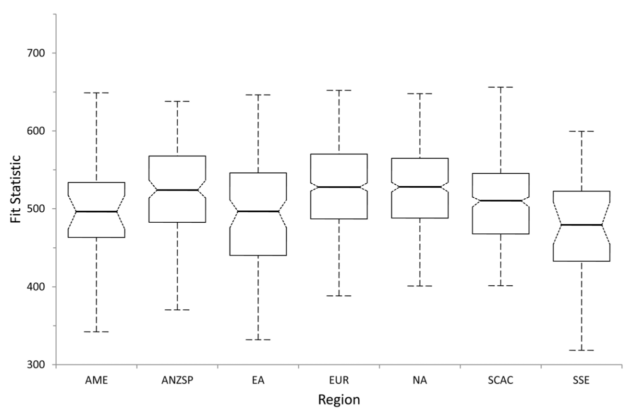

FIGURE 4 | Box plot of median fitness score for respondents from each of seven regions.

drew the sample. This reflects a broad trend, with great disparities in scientific publishing between scientists from developed and developing countries (King, 2004). While the developed country scientists were active and knowledgeable, there may be important research issues for which these rankings do not reflect the perspectives of scientists from developing countries.

There were certainly some random BWS responders in this survey but, based on fitness scores, it appears that most scientists who completed the survey took the ranking tasks seriously, were attentive, and answered questions with a relatively high level of consistency. Random responders were proportionally more likely to be from developing regions, with East Asian respondents being the relatively most likely to belong to the lowest fitness level. It may be that some of the respondents from developing regions were challenged interpreting technical English research questions from outside their own discipline.

RESEARCH PRIORITIES

Results from this survey highlight the degree to which research priorities vary among scientists, particularly along disciplinary divides between respondents from the natural and social sciences. Among the physical and ecological scientists, it is important to highlight that, despite clear disciplinary tendencies, seven of the top 10 priority questions were, in fact, shared by the two groups: cumulative stressors (ranked 1 overall), ocean productivity (ranked 2), ocean acidification (ranked 3), monitoring cumulative effects (ranked 4), oceanographic data (ranked 5), greenhouse gas flux (ranked 7), and climate change mitigation and manipulation (ranked 8).

Only the cumulative stressors question, top-ranked in aggregate, was among the top 10 priorities for social scientists; many

Table 6 | Comparison of 20 top ranked questions by disciplinary category.

Rank	Physical scientists (*n* = 604)	Ecological scientists (*n* = 1429)	Social scientists (*n* = 143)
1	*Rank = 5. Oceanographic data (Q45)*	**Rank = 1. Cumulative stressors (Q33)**	*Rank = 11. Science communication (Q5)*
2	*Rank = 2. Ocean productivity (Q30)*	*Rank = 2. Ocean productivity (Q30)*	Rank = 34. Risk assessment for governance (Q14)
3	**Rank = 1. Cumulative stressors (Q33)**	*Rank = 6. Biodiversity contributions to ecosystem function (Q59)*	*Rank = 20. Crossdisciplinary ocean science and management (Q44)*
4	*Rank = 7. Greenhouse gas flux (Q39)*	*Rank = 3. Ocean acidification (Q37)*	Rank = 21. Ocean literacy messages (Q12)
5	*Rank = 3. Ocean acidification (Q37)*	**Rank = 4. Monitoring cumulative effects (Q60)**	Rank = 57. Transaction costs of ocean management (Q15)
6	Rank = 17. Thermohaline circulation (Q66)	Rank = 9. Global biodiversity and ecological function (Q58)	Rank = 56. Management capacity of human communities (Q20)
7	**Rank = 4. Monitoring cumulative effects (Q60)**	*Rank = 5. Oceanographic data (Q45)*	Rank = 51. Policy coherence across domains (Q16)
8	*Rank = 8. Climate change mitigation and manipulation (Q51)*	Rank = 13. Top predator decline (Q32)	Rank = 58. Compliance with rules (Q19)
9	*Rank = 10. Benthopelagic coupling (Q67)*	*Rank = 8. Climate change mitigation and manipulation (Q51)*	**Rank = 1. Cumulative stressors (Q33)**
10	*Rank = 14. Temperature redistribution (Q3)*	*Rank = 7. Greenhouse gas flux (Q39)*	Rank = 45. Effects of MPAs on humans (Q6)
11	Rank = 26. Sea level rise and vulnerable coasts (Q35)	*Rank = 10. Benthopelagic coupling (Q67)*	Rank = 43. Integrated upland-coastal management (Q27)
12	Rank = 22. Melting ice effects (Q63)	Rank = 16. Ecosystem structure to service linkages (Q57)	Rank = 46. High seas governance (Q28)
13	Rank = 39. Integrating oceans with climate models (Q41)	Rank = 15. Climate change-induced species dispersal (Q52)	Rank = 54. Local ecological knowledge (Q4)
14	*Rank = 12. Contaminants (Q36)*	*Rank = 12. Contaminants (Q36)*	**Rank = 4. Monitoring cumulative effects (Q60)**
15	Rank = 19. Energy development (Q46)	*Rank = 11. Science communication (Q5)*	Rank = 27. Seafood production strategies (Q48)
16	Rank = 37. Coastal adaptation to sea level rise (Q62)	Rank = 25. Bycatch effects (Q47)	Rank = 61. Political culture and the use of science (Q17)
17	Rank = 35. Coastal hazard management (Q64)	Rank = 18. Coral reef management strategies (Q26)	Rank = 47. Seafood supply chains (Q1)
18	*Rank = 6. Biodiversity contributions to ecosystem function (Q59)*	Rank = 28. Biological connectivity (Q61)	Rank = 53. Ecosystem service valuation implications (Q8)
19	Rank = 24. Upland hydrology effects on oceans (Q34)	Rank = 31. Adaptive capacity of marine life (Q53)	Rank = 25. Bycatch effects (Q47)
20	*Rank = 20. Crossdisciplinary ocean science and management (Q44)*	*Rank = 14. Temperature redistribution (Q3)*	Rank = 23. Aquaculture effects (Q24)

Bold denote research question is the top 20 for all three disciplinary groups; italics denote it is in the top 20 for two of three disciplinary groups.

of the high priority questions for social scientists were low in the ranking order for natural scientists. Why should social scientists' priorities be so different? It is useful to bear in mind that the rationale behind the research scanning exercises is based on the premise that science can be aligned with policy-makers' needs (Rudd, 2011); if policy challenges can be clearly articulated, then aligned natural and social sciences can be brought to bear that builds understanding about natural systems and human behavior to help solve salient policy problems. At one level, social scientists work to understand human behavior and systems just as natural scientists focus on environmental and ecological systems; they are neutral information providers for policy-makers who need to make decisions on issues beyond the realm of science. This is a relatively traditional view among environmental scientists providing science advice to policy-makers (e.g., Rice, 2011). This perspective of social science is implicit, for example, in NOAA's current research plan, which emphasizes a major science challenge in acquiring and incorporating "knowledge of human behavior to enhance our understanding of the interaction between human activities and the Earth system" (National Oceanic and Atmospheric Administration, 2013, p. 19). In this survey, the question on the effects of MPAs on humans (rank 45 overall, rank 10 for social scientists) is an example where social scientists might conduct empirical research that directly complements natural science research and helps form a neutral, crossdisciplinary information package for decision-makers.

At a higher level, social scientists are also interested in the purposive aspects of environmental management (i.e., knowledge about better practices) and normative aspects of society's relationship with the environment (i.e., how transformational knowledge about learning processes and value changes can catalyze sustainable solutions) (Hirsch Hadorn et al., 2006). There

Table 7 | Comparison of 10 top ranked questions by respondents' region of residence.

Rank	AME (*n* = 57)	ANZSP (*n* = 141)	EA (*n* = 71)	EUR (*n* = 554)	NA (*n* = 474)	SCAC (*n* = 128)	SSEA (*n* = 19)
1	**Rank = 1. Cumulative stressors (Q33)**	**Rank = 1. Cumulative stressors (Q33)**	**Rank = 1. Cumulative stressors (Q33)**	**Rank = 1. Cumulative stressors (Q33)**	**Rank = 1. Cumulative stressors (Q33)**	**Rank = 6. Biodiversity contributions to ecosystem function (Q59)**	**Rank = 1. Cumulative stressors (Q33)**
2	**Rank = 5. Oceanographic data (Q45)**	**Rank = 4. Monitoring cumulative effects (Q60)**	**Rank = 6. Biodiversity contributions to ecosystem function (Q59)**	**Rank = 6. Biodiversity contributions to ecosystem function (Q59)**	*Rank = 3. Ocean acidification (Q37)*	**Rank = 1. Cumulative stressors (Q33)**	Rank = 20. Crossdisciplinary ocean science and management (Q44)
3	*Rank = 3. Ocean acidification (Q37)*	**Rank = 2. Ocean productivity (Q30)**	**Rank = 2. Ocean productivity (Q30)**	**Rank = 2. Ocean productivity (Q30)**	**Rank = 2. Ocean productivity (Q30)**	*Rank = 9. Global biodiversity and ecological function (Q58)*	**Rank = 2. Ocean productivity (Q30)**
4	**Rank = 6. Biodiversity contributions to ecosystem function (Q59)**	*Rank = 3. Ocean acidification (Q37)*	*Rank = 9. Global biodiversity and ecological function (Q58)*	*Rank = 3. Ocean acidification (Q37)*	**Rank = 4. Monitoring cumulative effects (Q60)**	**Rank = 4. Monitoring cumulative effects (Q60)**	**Rank = 6. Biodiversity contributions to ecosystem function (Q59)**
5	*Rank = 9. Global biodiversity and ecological function (Q58)*	**Rank = 6. Biodiversity contributions to ecosystem function (Q59)**	**Rank = 5. Oceanographic data (Q45)**	*Rank = 9. Global biodiversity and ecological function (Q58)*	**Rank = 6. Biodiversity contributions to ecosystem function (Q59)**	**Rank = 2. Ocean productivity (Q30)**	Rank = 10. Benthopelagic coupling (Q67)
6	**Rank = 4. Monitoring cumulative effects (Q60)**	*Rank = 13. Top predator decline (Q32)*	*Rank = 3. Ocean acidification (Q37)*	**Rank = 4. Monitoring cumulative effects (Q60)**	**Rank = 5. Oceanographic data (Q45)**	*Rank = 13. Top predator decline (Q32)*	Rank = 25. Bycatch effects (Q47)
7	Rank = 29. Restoration effectiveness (Q22)	**Rank = 5. Oceanographic data (Q45)**	Rank = 10. Benthopelagic coupling (Q67)	**Rank = 5. Oceanographic data (Q45)**	*Rank = 13. Top predator decline (Q32)*	*Rank = 3. Ocean acidification (Q37)*	Rank = 7. Greenhouse gas flux (Q39)
8	**Rank = 2. Ocean productivity (Q30)**	Rank = 11. Science communication (Q5)	**Rank = 4. Monitoring cumulative effects (Q60)**	Rank = 15. Climate change-induced species dispersal (Q52)	Rank = 8. Climate change mitigation and manipulation (Q51)	**Rank = 5. Oceanographic data (Q45)**	**Rank = 5. Oceanographic data (Q45)**
9	Rank = 11. Science communication (Q5)	Rank = 18. Coral reef management strategies (Q26)	Rank = 7. Greenhouse gas flux (Q39)	Rank = 8. Climate change mitigation and manipulation (Q51)	Rank = 9. Global biodiversity and ecological function (Q58)	Rank = 20. Crossdisciplinary ocean science and management (Q44)	**Rank = 4. Monitoring cumulative effects (Q60)**
10	Rank = 20. Crossdisciplinary ocean science and management (Q44)	*Rank = 9. Global biodiversity and ecological function (Q58)*	Rank = 8. Climate change mitigation and manipulation (Q51)	*Rank = 13. Top predator decline (Q32)*	Rank = 7. Greenhouse gas flux (Q39)	Rank = 25. Bycatch effects (Q47)	*Rank = 13. Top predator decline (Q32)*

Bold denote research question is the top 10 for all seven regions; italics denote it is in the top 10 for four to six of the seven regions.

Table 8 | Contingency table of residuals from Pearson χ^2 tests comparing respondents' fitness level (decile) by region of residence.

Rank	AME	ANZSP	EA	EUR	NA	SCAC	SSEA	Total
Decile 1 (median fitness = 410.9)	12	14	32	66	59	23	13	219
Pearson residual	**2.6**	−1.3	**5.4**	**−2.3**	−1.7	**2.1**	**3.8**	
Decile 2 (median = 457.1)	5	24	17	87	60	18	7	218
Pearson residual	−0.3	1.0	1.2	0.0	−1.6	0.8	1.1	
Decile 3 (median = 481.3)	8	23	14	88	71	8	7	219
Pearson residual	1.0	0.8	0.3	0.1	−0.3	−1.8	1.1	
Decile 4 (median = 500.0)	8	17	9	85	76	21	3	219
Pearson residual	1.0	−0.6	−1.1	−0.3	0.3	1.5	−0.8	
Decile 5 (median = 514.6)	5	13	13	81	79	23	5	219
Pearson residual	−0.3	−1.5	0.1	−0.7	0.6	**2.1**	0.1	
Decile 6 (median = 530.0)	5	22	3	92	75	16	5	218
Pearson residual	−0.3	0.6	**−2.7**	0.5	0.2	0.3	0.1	
Decile 7 (median = 546.7)	4	19	14	87	86	8	1	219
Pearson residual	−0.7	−0.1	0.3	0.0	1.4	−1.8	−1.7	
Decile 8 (median = 563.9)	3	20	9	90	84	12	1	219
Pearson residual	−1.1	0.1	−1.1	0.3	1.2	−0.8	−1.7	
Decile 9 (median = 585.3)	5	18	6	103	73	9	4	218
Pearson residual	−0.3	−0.3	−1.9	1.7	0.0	−1.5	−0.3	
Decile 10 (median = 625.0)	2	26	11	94	73	12	1	219
Pearson residual	−1.6	1.4	−0.5	0.7	−0.1	−0.8	−1.7	
Total	57	196	128	873	736	150	47	2187

Bold highlights | Pearson χ^2 residual | > 2.0.

is recent evidence that environmental scientists are increasingly interested in interpreting, integrating, and advocating science by engaging in the policy process (Singh et al., 2014). The results from this survey suggest that many social scientists' top-ranked priorities (recall **Table 6**—questions on science communication [ranked 1], risk assessment for governance [ranked 2], and ocean literacy messages [ranked 4], for example) fall into this higher-level category. It is important to understand that this does not necessarily mean that social scientists are mandating advocacy, but just that it is possible, and necessary, in the view of many social scientists, to focus research on the behavioral processes, management options, and societal values that constrain or stimulate real transformations toward ocean sustainability.

These higher level research priorities are reflected in some recent national research strategies. For example, NOAA highlights that "Integrating different disciplines, including natural and social sciences, is essential to develop a more holistic understanding of the Earth system…[and that] more and more, mission success depends on a holistic understanding of how natural phenomena are intertwined with human behavior and institutions" (National Oceanic and Atmospheric Administration, 2013, p. 19). The European Environment Agency (2014, p. 25) emphasizes that "Persistent problems such as loss of biodiversity, loss of ecosystem resilience, pollution, overexploitation of resources, and climate change are deeply embedded in our 21st century societal structures, cultures, values and practices…[and that maintaining] our seas will also depend on fundamental shifts in the systems that fulfill our societal needs, coupled with a wider re-evaluation of our values, and how we interact with nature and its resources."

While the results from this survey could, given the large divergence in priorities among natural and social scientists, be interpreted as highlighting great challenges for crossdisciplinary ocean research cooperation, it is also possible to take the position that these patterns of priorities are not actually contradictory. If producers and users of scientific evidence understand that some social scientists focus on research questions that provide information needed to inform policy (as most natural scientists do), but that other social scientists focus on building understanding of the ways and means to transform existing practices (Hirsch Hadorn et al., 2006), then is could be possible to increase systems understanding, catalyze new thinking among scientists (e.g., Pennington et al., 2013) and increase the likelihood that real action will be taken to help improve ocean health and sustainability. It is important to note that the challenge of designing and implementing crossdisciplinary ocean research that supports decision-making for ocean sustainability was, in fact, the third highest research priority among social scientists in this survey.

Crossdisciplinary cooperation, long-term networking across disciplines, accounting for human agency and institutional structure in research, developing large suites of comparative case studies, and redefining what research excellence means are all crucial for sustainability science that aims to address global environmental change (Pahl-Wostl et al., 2013). Crossdisciplinary research teams will also likely increasingly involve social scientists studying their own team's research processes, dynamics and performance (Pennington et al., 2013), and the academic and policy impact of their collaborative research (Hampton and Parker, 2011; Emmett and Zelko, 2014). The drive to better document research impacts

(Donovan, 2007; Bielak et al., 2008; Holmes and Clark, 2008) may also prompt increasing research on scientists' level of policy engagement more generally (e.g, Lawton and Rudd, 2013; Singh et al., 2014). Measures to more effectively deal with modern challenges that exhibit uncertainty along multiple dimensions are needed. The results from this survey demonstrate that some scientists are willing and able to engage in this type of research now but that there are others who may not be or are satisfied to remain in more traditional scientific roles. As Pahl-Wostl et al. (2013, p. 46) note, "Viable methodologies that generate interdisciplinary knowledge and integrate different knowledge cultures are not developed in the abstract, but in practice." Funding availability and the socio-political environment within which scientists work obviously plays a crucial role in creating an enabling environment for ocean-relevant sustainability science.

CONCLUSION

The results from this survey present the "bottom-up" view of scientists working on a wide variety of coastal and ocean challenges around the world. The view of scientists, however, does not reflect the research priorities of society as a whole or government policymakers, in particular. In the future it would be valuable to repeat a simpler variant of this survey with a variety of stakeholders and policy-makers, so that the level of alignment between those groups and scientists could be assessed (e.g., Rudd and Fleishman, 2014), potentially on a periodic (e.g., 5 year) basis so as to track changing priorities over time.

It would also be valuable to systematically compile and compare existing ocean research priorities among government and other organizations. Understanding the range of priorities across industry, society and government could provide some indication for scientists as to how their scientific priorities align with societal needs. For example, the World Bank's "Indispensable Ocean" report, drawn up by a blue ribbon panel that included industry, academic, and government members (Hoegh-Guldberg et al., 2013), emphasized the emerging role of public-private partnerships to address ocean challenges. In Europe, there is an increasing emphasis on productive seas and marine knowledge (European Environment Agency, 2014) as drivers of "blue growth" in the economy (European Commission, 2012). In an ocean infrastructure priorities report (Committee on an Ocean Infrastructure Strategy for U.S. Ocean Research in 2030, 2011). Key research themes included enabling stewardship of the environment, protecting life and property, and promoting sustainable economic vitality. These high-level reports point to an increasingly held view of the ocean as a driver of economic and social well-being, and the importance of safety and security. If that vision of oceans' contributions to human well-being is to be realized, it is critical that ocean health is maintained and restored. As the European Environment Agency (2014, p. 25) highlights, "Our seas are rapidly changing while our dependence on them is growing. We do not fully understand the complex interactions of natural and human-driven changes. But we do know that we are not yet on the path to achieving healthy, clean and productive seas."

Active scientists are among the best positioned individuals to understand the true scope of ocean challenges, to highlight emerging threats to ocean health and their possible effects on human well-being, and to help identify technologies, management and governance systems that either help or hinder transformations to ocean sustainability. The results from this survey highlighted the priorities of scientists from 94 countries and, I hope, provide insights as to how research scanning results can be synthesized and used to target ocean research on questions that, if answered, would be central to achieving ocean sustainability.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: http://www.frontiersin.org/journal/10.3389/fmars.2014.00036/abstract

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