Conservation Biology

Essay

Seventy-One Important Questions for the Conservation of Marine Biodiversity

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Abstract: *The ocean provides food, economic activity, and cultural value for a large proportion of humanity. Our knowledge of marine ecosystems lags behind that of terrestrial ecosystems, limiting effective protection of marine resources. We describe the outcome of 2 workshops in 2011 and 2012 to establish a list of important questions, which, if answered, would substantially improve our ability to conserve and manage the world's marine resources. Participants included individuals from academia, government, and nongovernment organizations with broad experience across disciplines, marine ecosystems, and countries that vary in levels of development. Contributors from the fields of science, conservation, industry, and government submitted*

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questions to our workshops, which we distilled into a list of priority research questions. Through this process, we identified 71 key questions. We grouped these into 8 subject categories, each pertaining to a broad component of marine conservation: fisheries, climate change, other anthropogenic threats, ecosystems, marine citizenship, policy, societal and cultural considerations, and scientific enterprise. Our questions address many issues that are specific to marine conservation, and will serve as a road map to funders and researchers to develop programs that can greatly benefit marine conservation.

Keywords: horizon scanning, marine biodiversity, policy, priority setting, research agenda, research questions

Setenta y Un Preguntas Importantes para la Conservación de la Biodiversidad Marina

Resumen: *Los océanos proporcionan alimento, actividad económica y valor cultural para una gran porción de la humanidad. Nuestro conocimiento de los ecosistemas marinos está atrasado con respecto al que tenemos de los ecosistemas terrestres, lo que limita la protección efectiva de los recursos naturales. Describimos el resultado de dos talleres en 2011 y 2012 para establecer una lista de preguntas importantes, las cuales al ser respondidas, mejorarían sustancialmente nuestra habilidad de conservar y manejar los recursos marinos del mundo. Entre los participantes se incluyeron a individuos de la docencia, el gobierno y organizaciones no-gubernamentales, con una amplia experiencia que atraviesa disciplinas, ecosistemas marinos y países que varían en el nivel de desarrollo. Los contribuyentes de los campos de la ciencia, la conservación, la industria y el gobierno, presentaron preguntas a nuestros talleres, las cuales separamos en una lista de preguntas de investigación prioritarias. Por medio de este proceso, identificamos 71 preguntas clave. Las agrupamos en ocho categorías temáticas, cada una perteneciente a un componente amplio de la conservación marina: pesquerías, cambio climático, otras amenazas antropogénicas, ecosistemas, ciudadanía marina, política, consideraciones sociales y culturales, y la iniciativa científica. Nuestras preguntas se dirigen a muchas cuestiones que son específicas de la conservación marina, y servirán como una ruta a seguir para patrocinadores e investigadores que busquen desarrollar programas que puedan beneficiar ampliamente a la conservación marina.*

Palabras Clave: agenda de investigación, biodiversidad marina, escaneo de horizonte, establecimiento de prioridades, política, preguntas de investigación

Introduction

The modern geological era has been termed the *Anthropocene*, in reference to the overwhelming effect of human activities on the global environment (Crutzen 2002). Human-induced overexploitation, ocean acidification and warming, habitat destruction, pollution, and invasions by exotic species all threaten the integrity of marine ecosystems (Crain et al. 2009). The effects from these activities are ubiquitous, extensive, and observable across the entire seascape (Stachowitsch 2003; Halpern et al. 2008).

This degradation of marine ecosystems is of concern because of their critical role in supporting human societies. Some 148 million tonnes of seafood was extracted from the ocean in 2010, contributing 16.6% of the global animal protein intake by humans and generating over US$217.5 billion (FAO 2012). Marine ecosystems provide other important services, including nutrient recycling, carbon sequestration, and coastal protection and lie at the heart of the cultural values of many coastal peoples.

Obtaining a detailed understanding of the causes and effects of anthropogenic impacts can be challenging. Marine research is expensive and logistically difficult due to the size of oceans and the limitations on human ability to access aquatic environments (Norse & Crowder 2005). Marine scientists often depend on expensive technology (e.g., boats, submersibles, scuba equipment), adding costs to projects beyond those typically incurred by terrestrial ecologists. These financial constraints are difficult to overcome given that funding for marine conservation research is an order of magnitude lower than for land-based conservation (Levin & Kochin 2004).

Research prioritization exercises are useful tools for advancing scientific disciplines and have been largely developed in conservation-related fields (Sutherland et al. 2011). These projects help create consensus on research directions that are best able to facilitate management of conservation problems. Exercises designed to identify current gaps in scientific understanding have been conducted at national (Sutherland et al. 2006; Morton et al. 2009) and international levels (Sutherland et al. 2009; Sutherland et al. 2012), as well as within disciplines (Pretty et al. 2010).

We sought to identify a set of questions that, if answered, would contribute substantially to our ability to preserve the long-term integrity of marine ecosystems at a global scale. This synthesis produced 71 questions. We intend this paper to serve as a road map for researchers who wish to generate useful applied research programs, for policy makers and managers who seek to develop new programs, policies, or legislation, and for granting agencies seeking to prioritize funding.

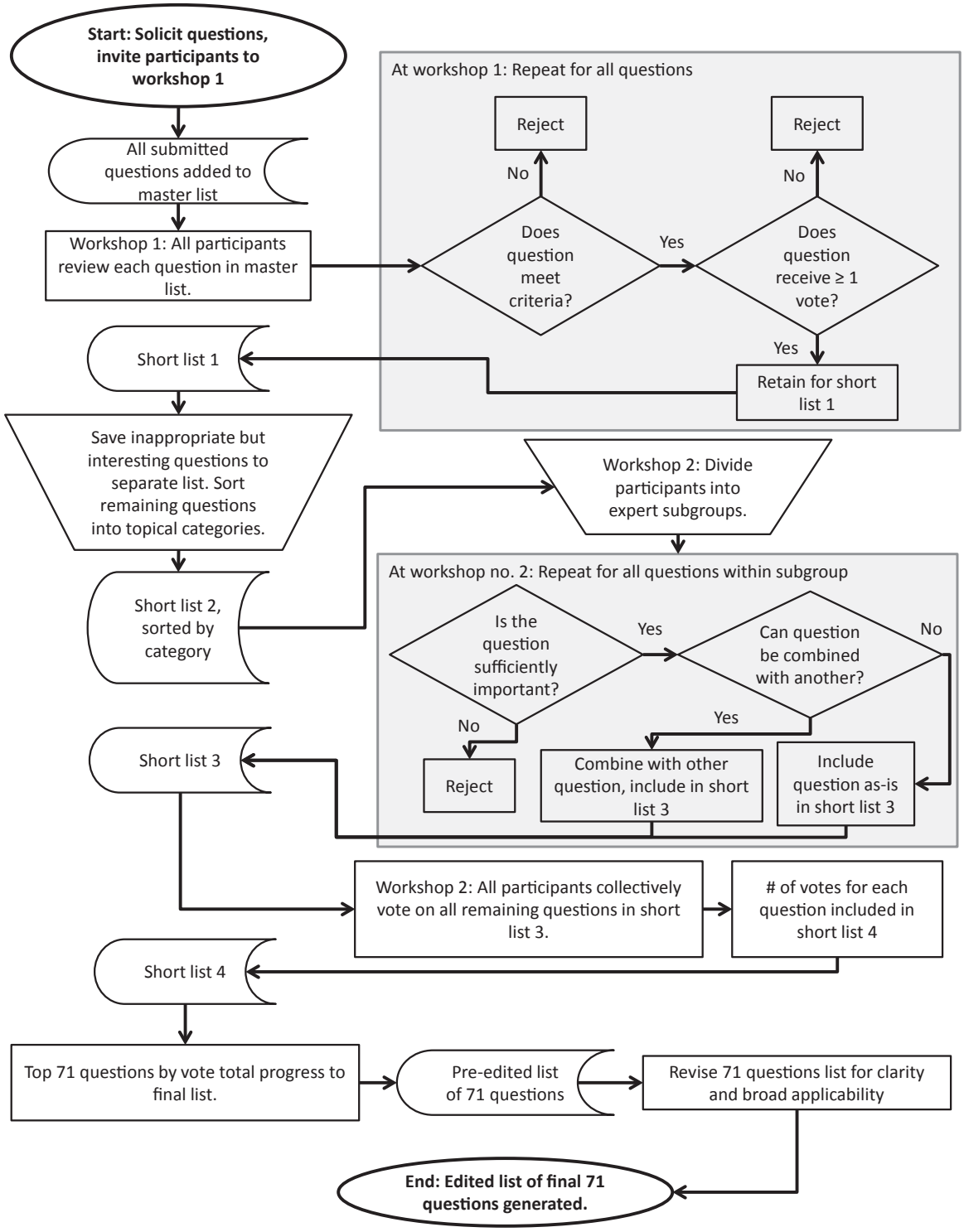

Figure 1. A flow chart summarizing the steps taken to conduct our workshops, wherein we collected questions from the scientific community and identified 71 questions that, if answered, would benefit marine conservation.

Question Derivation

We conducted a pair of 2-d workshops to construct our list of important questions in marine conservation (Fig. 1). A full description of our methods is in Supporting Information. We held the first workshop at the second International Marine Conservation Congress (IMCC) in 2011. At this meeting, 17 participants with expertise in a variety of disciplines reviewed an initial list of 631 questions, which were solicited from participants at IMCC,

professional peer groups, and by the Society for Conservation Biology. We reduced the number of candidate questions to 316 (Supporting Information). These questions were considered at a second workshop held in 2012. Our group voted on these remaining questions, seeking mainly to identify those of global importance whose lack of a complete answer substantially impedes effective conservation. Through this process, we identified our top 71 questions as voted on by the workshop participants.

We grouped the final 71 questions into 8 categories (fisheries, climate change, other anthropogenic threats, ecosystems, marine citizenship, policy, societal and cultural considerations, and scientific enterprise), which are not listed in order of priority. Likewise, the questions are not ranked and the number of questions in each section does not reflect a question's relative importance.

Fisheries Questions

Mass extraction of fish and invertebrate biomass for human use is a major stressor on marine ecosystems. The global extent of fishing is increasing in terms of spatial extent and the depth at which it occurs, opening previously inaccessible refugia to exploitation (Morato et al. 2006; Swartz et al. 2010). Currently 87% of assessed fish stocks are either fully exploited, overexploited, or depleted and thus require effective and precautionary management (FAO 2012). Large marine protected areas (MPAs) closed to fishing are one component of the solution to the problem of overfishing; MPAs can preserve biodiversity and promote recovery of many species (Lester et al. 2009). However, their ability to increase the yield of surrounding fisheries is variable (Hilborn et al. 2004). Strategic research is needed to provide managers with the tools necessary to manage fisheries for long-term sustainability and ecosystem integrity.

(1) How much marine biomass is lost to ghost fishing and what is the most effective way to reduce this source of mortality?
(2) What are the impacts of recreational fishing on marine ecosystems?
(3) How can fishing gear and techniques be improved to minimize habitat damage?
(4) To what degree must foraging needs of top predators and other animal species be considered in our exploitation of fish stocks to ensure healthy ecosystems?
(5) How can the impacts of bycatch from legal and illegal, unreported, and unregulated (IUU) fisheries be reduced to a level that will allow the reversal of declining trends of affected species?
(6) In what circumstances do no-take zones produce benefits to surrounding fisheries?
(7) How prevalent are the negative evolutionary effects of sustainable fishing (e.g., Reznick & Ghalambor 2005) and how can they be minimized?
(8) How can partial fishing closures be used to maximize the benefits of MPA networks?
(9) Under what circumstances can aquaculture produce a net benefit for marine conservation?
(10) What characteristics of eco-labeling programs make them true indicators of a sustainable fishery and to what degree can such programs contribute to the sustainability of global fisheries?
(11) What is the most cost-effective way to prevent IUU harvesting in marine ecosystems?

Climate-Change Questions

Climate models predict that the world's oceans will become increasingly warmer and acidic, sea levels will continue to rise, and storm and ocean circulation patterns will be altered because of anthropogenic inputs of carbon in the atmosphere (IPCC 2013). These changes have critical implications for marine life, including direct effects on species physiology and phenology and indirect effects on patterns of distribution and key ecological interactions (Harley et al. 2006; Pandolfi et al. 2011). In addition, climate change may interact with other anthropogenic stressors, including pollution and harvesting, to erode the resilience (i.e., the ability to resist and recover from disturbances) of marine communities (e.g., Hughes et al. 2003). These changes are likely to alter the effectiveness of current conservation strategies (e.g., MPAs) in unpredictable ways. Therefore, conservation practitioners will require information that supports adaptive management programs.

(12) What are the implications of climate change for small island nations in terms of sea-level rise and their ability to meet international conservation commitments while maintaining local food security?
(13) 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?
(14) How will marine ecosystems and species adapt and respond to the individual and interactive effects of ocean acidification, anoxia, and warming and to what extent is mitigation possible?
(15) What attributes of species (e.g., tropical or temperate, sessile or motile) make them particularly sensitive to stressors attributable to climate change?
(16) What measures can best prevent the extinction and extirpation of geographically constrained species and populations in the face of climate change?
(17) How will global climate change and ocean acidification affect ocean productivity and, ultimately, biodiversity?

(18) How can marine climate refugia be identified and protected to the maximum extent possible?
(19) To what extent will stressors (such as noise, exotic species, and contaminants) increase as polar marine environments warm and become increasingly accessible to human activities and how will these factors affect polar biodiversity?
(20) How will climate change and acidification influence the distribution, richness, relative abundance, and prevalence of diseases and invasive species in the marine environment?
(21) What are the possible ecological impacts of technological mitigation strategies (e.g., coastal defenses) developed to allow human communities to adapt to climate change?
(22) How will human pressures on the seascape shift and change as climate change impacts affect additional areas of the ocean?
(23) How will climate change impact the 3-dimensional distribution, abundance, and dispersal of marine species and what are the implications?
(24) What capacity do marine organisms, particularly sessile species, have to adapt to changing oceanographic conditions?
(25) How will the capacity to sequester carbon in biotic and abiotic components of marine ecosystems change over time?

Other Anthropogenic Effects

Beyond fishing and climate change, a variety of anthropogenic threats endanger the integrity of marine ecosystems. More than 44% of the world's population lives within 150 km of a coast (U.N. 2010). Human activities have resulted in considerable discharges into marine ecosystems (Islam & Tanaka 2004) that have led to anoxic zones (Rabalais 2005), ingestion of inorganic contaminants by marine biota (e.g., Avery-Gomm et al. 2012), the introduction of human pathogens into marine systems (Daszak et al. 2001), and persistent organic pollutants (Braune et al. 2005). Shipping, underwater construction, and related activities have contributed to the spread of invasive species (Bax et al. 2003) and increases in underwater noise levels (e.g., Parsons et al. 2008) and chronic and acute oil spills (e.g., Hjorth & Nielsen 2011). It is known that these activities exacerbate the degradation of marine ecosystems, but their relative impacts and effects when acting synergistically are poorly understood. Furthermore, our ability to mitigate these impacts remains an important unanswered question.

(26) Which strategies can be used to mitigate and manage the effects of the spread of existing and emergence of new marine pathogens?
(27) Which anthropogenic stressors have the largest influence on host–pathogen interactions?
(28) How can the formation of anoxic dead zones be forecasted and prevented and how can conditions leading to dead-zone formation be reversed if they form?
(29) How can the cumulative effects of the use of new technologies (e.g., energy infrastructure) be rapidly and effectively assessed and translated into precautionary policy recommendations?
(30) How should damage from anthropogenic oil release be quantified and what is the ecologically relevant scale for assessment?
(31) What are the technological and biological limitations that prevent effective cleanup of chronic and acute spills of oil and other chemicals and how should these limitations inform social and economic decisions about exploration for and extraction, transport, and use of these substances?
(32) How can the benefits of tourism to marine ecosystems be maximized while minimizing negative impacts?
(33) What effects do urbanization and changing patterns of land use have on coastal, estuarine, and marine biodiversity, and how can policy and practice be integrated to ensure that these effects are mitigated?
(34) To what extent and in which ways does anthropogenic noise affect marine fauna at the population level, particularly species that depend heavily upon sound, and how do impacts accrue over time and space?
(35) What are the relative conservation implications of acute versus chronic anthropogenic stressors?
(36) What are the cumulative and population-level effects of marine environmental contaminants, such as plastics and other refuse?
(37) How can the negative impacts of shipping on marine species and ecosystems (e.g., disturbance to sensitive habitat areas, output of CO_2 and black carbon, underwater noise, and the release of other pollutants during construction and operations) be reduced and public awareness of such impacts be elevated?

Ecosystems

Scientists have a poor understanding of many ecosystem processes due to the practical difficulties of conducting research in the marine environment (Carr et al. 2003) and little knowledge of baseline conditions predating the loss of top predators (Lotze & Worm 2009). Life histories and population dynamics are insufficiently studied for most marine species, making it challenging to forecast response and recovery from human and natural disturbances (Lundquist et al. 2010). Connectivity within and among marine ecosystems, between benthic and pelagic systems, and with neighboring terrestrial systems are also poorly understood (Marcus & Boero 1998). Land-use

plans often fail to consider the broad range of ecosystem services provided by marine environments. As a result, these systems can be undervalued and underprotected, increasing their likelihood of becoming degraded.

(38) How can key large-scale ecological processes be identified, protected, and restored?
(39) How can recovery rates of species that vary among ecosystems be incorporated into the development of conservation targets and metrics of conservation success?
(40) What restoration methods (e.g., in situ habitat restoration, translocation) are most likely to enhance natural marine ecosystem form, function, and services?
(41) Given the variation in characteristics of individual species, how can conservation strategies be implemented to maintain connectivity across taxa, habitats, and scales to ensure resilient marine communities?
(42) To what extent are the changing frequency, intensity, and magnitude of disturbances (both natural and anthropogenic) altering the distribution and abundance of individual species and communities in marine ecosystems?
(43) How can the provision of ecosystem services (known and unknown, quantitative and qualitative) be incorporated into marine conservation planning and management and how do we determine how much of each ecosystem service to protect?
(44) 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 (Bottrill et al. 2008) be applied?
(45) How much emphasis should be placed on identifying and maintaining intraspecific genetic diversity in marine systems?
(46) How can tipping points for marine ecosystems and individual species be identified, what are the consequences of reaching or passing these thresholds, and can these consequences be reversed?

Marine Citizenship

The role of individual citizens is critical to achieving marine conservation goals because people's lifestyle choices and behaviors have significant impacts on the health of marine systems (McKinley & Fletcher 2012). However, the best methods for engaging the public and promoting marine conservation priorities remain controversial (Vincent 2011). Simply informing the general public of environmental issues has proven ineffective at engaging the public in conservation initiatives, and criticisms have been raised that marine conservation professionals oversimplify socioecological linkages and focus too much on charismatic flagship species (Kollmuss & Agyeman 2002). There are many opinions about what approaches are effective in which contexts (Fletcher & Potts 2007). However, there is little consensus in the field, and this lack of direction is precluding effective conservation.

(47) What are the best methods to encourage context-specific behavioral changes to increase conservation of the marine environment and what behaviors are most important to change?
(48) What are the best methods and tools available to engage citizens in marine conservation?
(49) What are the most critical messages, concepts, and skills that should be communicated to, and developed with, citizens to improve societal understanding of marine conservation problems?
(50) What are the best ways to frame marine conservation messages in light of different values and perceptions of the marine environment held by different audiences?

Policy

Marine conservation and resource use policy present challenges at local, national, and international levels. These challenges include balancing competing objectives within and among agencies (Brax 2002), creating implementation frameworks for treaties (Breitmeyer et al. 2006), and guiding decision making when confronted with complex socioecological systems (Watts & Wandesforde-Smith 2006). Policy choices are influenced by internal interests, external pressures, political imperatives, and social values that may conflict with conservation goals (Mooers et al. 2010). The often data-poor nature of marine management creates a difficult environment for producing transparent, equitable policy decisions (Chakalall et al. 2007). These multiple challenges mean that marine policy represents a perfect storm of conservation challenges that blends lack of information with complex governance issues. Scientists play an important role in this process but are limited in their effectiveness because quantitative answers to many policy questions are currently lacking.

(51) How can the effectiveness of, and compliance with, international treaties that influence marine conservation be increased, including at a local level?
(52) 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?
(53) How can effective policy making and evaluation of marine systems be proactively advanced to address implications of shifting historical baselines?
(54) What are the best ways to estimate, evaluate, and manage cumulative impacts and multiple anthropogenic stressors in the marine environment?

(55) What are the best methods to resolve conflicting policies in the marine environment (e.g., terrestrial vs. marine policies, dual mandates of organizations) to achieve marine conservation goals?
(56) How can the success of marine conservation initiatives and policies best be measured and what elements of success may be most readily transferable to other marine areas or conservation activities?
(57) What are the most effective ways of establishing, adaptively managing, and assessing the ecological, social, and economic benefits of MPA networks?
(58) How can marine spatial planning best support marine conservation goals?
(59) How should evidence from multiple disciplines be used most effectively to underpin marine conservation policy making and how should contradictions within the evidence base be resolved?
(60) How should uncertainty, risk, and precaution be incorporated into effective marine conservation policy making?
(61) What scale-specific governance models have supported the achievement of marine conservation goals?
(62) How can the trade of marine species be better regulated, managed, and monitored?
(63) How should novel and emerging marine contaminants be regulated even if their impacts and conservation implications are not fully understood?

Societal and Cultural Considerations

Marine conservation exists within a complex socioecological system in which social and cultural influences affect the achievement of marine conservation goals (Pomeroy et al. 2006). Marine environments give rise to cultural symbols, values, traditions, and practices, but the importance of these aspects are generally less recognized than for their terrestrial counterparts (Jackson 1995). Marine culture can define and cement group identity, providing an important place attachment that can contribute to marine protection (Berkes et al. 2006; Charles & Wilson 2009). Biodiversity and cultural diversity are closely linked (Dunn 2008; Pretty et al. 2009), and the loss of one threatens the other (Millennium Ecosystem Assessment 2005). Conservation efforts are increasingly expected to better integrate with and support human welfare priorities (Rodríguez et al. 2007), particularly where coastal communities are facing growing insecurity (Pomeroy et al. 2006). Accomplishing conservation objectives requires engaging in areas that science often neglects, including intergenerational equity, gender dynamics, children's rights, and food security. Doing so successfully requires targeted research.

(64) How has humankind's various worldviews shaped perceptions, relationships, and narratives related to the marine environment and how do these influence marine conservation?
(65) How can marine conservation support food security, cultural security, and human well-being whilst acknowledging local governance and sovereignty?
(66) How can marine cultural heritage, maritime historical heritage, and biological conservation be best integrated to maximize benefits for all stakeholders?
(67) How are socially just and equitable marine conservation processes and outcomes (incorporating gender, intergenerational, and socioeconomic equity) best developed and delivered?
(68) What lessons derived from conflict management, resolution, and avoidance in other disciplines could be beneficially applied to marine conservation?

Scientific Enterprise

Scientific culture and effort prioritization within science play a critical role in ensuring that research coverage is focused effectively to solve marine conservation challenges. Taxonomy is a branch of science that is necessary for identifying the spatial and temporal patterns of biodiversity, but it is chronically underfunded (Costello et al. 2010). The decline in taxonomic research will likely impact all aspects of marine ecosystem study, from our ability to document rates of extinction to the accurate recognition and identification of native and invasive taxa (e.g., Gordon et al. 2010). In addition, the open sharing of data in standardized formats is critical for marine research and management because many species inhabit ranges that span international and jurisdictional borders. Scientific culture itself, which assigns credit based on publication and peer review of papers and data sets, can delay the public sharing of data, which hinders the timely development of best management practices (Parr & Cummings 2005; Huang et al. 2012). Although scientists are frequently critical of their discipline in this regard (particularly on blogs and social media), little empirical progress has been made in generating optimal solutions that preserve career prospects while facilitating data sharing. Answers to specific questions in this area would greatly enhance our ability to do conservation-relevant research.

(69) How can taxonomic expertise be increased to reduce uncertainty in the conservation and management of marine ecosystems?
(70) How can scientific and management cultures be changed to promote open sharing of data in formats that are accessible (and standardized)?
(71) What strategies can be used to promote long-term integrated multi-disciplinary collaborations?

Discussion

Marine ecosystem management is most effective when backed by sound scientific evidence. Past prioritization exercises in ecology have underemphasized marine issues (e.g., Sutherland et al. 2009), prompting calls for a workshop such as ours to highlight the specific challenges facing global marine conservation (Cooke et al. 2010). However, in accordance with the precautionary principle, an absence of scientific certainty should not be used as an excuse to avoid or delay reasonable conservation action (O'Riordan & Cameron 1994; González-Laxe 2005). Conservation action can and should be immediately taken on many of the subjects addressed by our 71 questions, but we contend that the efficiency of such actions can be greatly improved with focused research.

Though some questions are brief, the research required to answer them will be challenging and complex. We hope this list serves to highlight some of the specific challenges involved in marine management and that it will serve as effective guidance for the establishment and refinement of research programs. In addition, the substantial attention paid to social science recognizes the reality that no amount of scientific research will help us manage the oceans if we ignore the need for strategies that lead to evidence-based, participatory, and transparent management. Hence, we hope this list will spark the development of collaborations between researchers, stakeholders, managers, and governments aimed at moving the world's oceans toward a more sustainable future.

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Supporting Information

Detailed methods used to produce the 71 questions (Appendix S1) are available online. The authors are solely responsible for the content and functionality of these materials. Queries (other than absence of the material) should be directed to the corresponding author.

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