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Contribution to the Theme Section 'Geospatial approaches to support pelagic conservation planning and adaptive management'

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OVERVIEW

Geospatial approaches to support pelagic conservation planning and adaptive management

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ABSTRACT: Place-based management in the open ocean faces unique challenges in delineating boundaries around temporally and spatially dynamic systems that span broad geographic scales and multiple management jurisdictions, especially in the 'high seas'. Geospatial technologies are critical for the successful design of pelagic conservation areas, because they provide information on the spatially and temporally dynamic oceanographic features responsible for driving species distribution and abundance in the open ocean, the movements of protected species, and the spatial patterns of distribution of potential threats. Nevertheless, there are major challenges to implementing these geospatial approaches in the open ocean. This Theme Section seeks to bridge the gap between geospatial science and marine conservation by discussing the use of innovative approaches to support effective marine conservation planning strategies for pelagic ecosystems. We highlight the results of this collection of contributions in 3 main sections: (1) conceptual advances in pelagic conservation; (2) novel information technologies and methodologies; and (3) case studies in the California Current and Pacific Ocean.

KEY WORDS: High seas · Pelagic conservation · Marine protected areas · Spatial methods · Dynamic management

INTRODUCTION

Pelagic ecosystems provide essential habitat for protected species, play a vital role in global climate regulation, support productive fisheries, and represent important ecosystems that require conservation (Hyrenbach et al. 2000, Game et al. 2009). While international conventions call for 10% of all biomes to be protected by 2020 (Convention on Biological Diversity 2006), only approximately 3.4% of the global ocean is currently protected within marine protected areas (MPAs), and just ~0.25% of open oceans and deep seas beyond national jurisdiction are protected (Toonen et al. 2013, Ban et al. 2014b).

Broad-scale oceanographic spatial datasets from satellites, drifters and tagged animals (e.g. sea surface temperature, thermocline depth and strength, oceanographic fronts) can now be freely and easily accessed online, and, when used in species distribution models as proxies in locations with sparse data, provide an interim alternative to *in situ* biological assessments (Shaffer & Costa 2006, Kappes et al.

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2010, Block et al. 2011, Suryan et al. 2012). Further, the use of large comprehensive biogeographic and environmental databases, such as AquaMaps (Ready et al. 2010), the Ocean Biogeographic Information System (OBIS) (Grassle et al. 2000, Halpin et al. 2009), and worldwide atlases of physical and biological ocean data (Le Traon et al. 2009, Roemmich et al. 2009) has recently provided a global data center to better understand species-environment relationships and to support predictive modeling techniques in dynamic marine environments (Halpin et al. 2006, Best et al. 2007, Williams et al. 2014). These recent advances in pelagic conservation planning, tracking and remote sensing technology have provided the basis for a geospatial approach to conservation of the pelagic zone.

Geospatial technologies allow for the mapping and monitoring of oceanographic processes and the patterns of ocean productivity, species distribution, and biodiversity that they produce in the open ocean (Halpin et al. 2006, Palacios et al. 2006, Block et al. 2011, Williams et al. 2014). Despite recent technological advances, there are major challenges to implementing a geospatial approach in the open ocean in order to capture data that represent the temporally and spatially dynamic nature of this environment (e.g. Webb et al. 2010, Trebilco et al. 2011, Maxwell et al. 2014). As a result, place-based management in the open ocean faces unique challenges in defining boundaries around temporally and spatially dynamic systems that span broad geographic scales and multiple management jurisdictions (Game et al. 2009, Ban et al. 2014a,b). Therefore, it is critical to bridge the gap between geospatial science and marine conservation in order to translate innovative geospatial approaches to support effective marine conservation planning strategies for pelagic ecosystems.

This paper is an introduction to the overall Theme Section and is a result of the July 2012 Society for Conservation Biology (SCB) special session 'Geospatial Approaches to Support Pelagic Conservation Planning and Adaptive Management' meeting held in Oakland, CA, USA. The goals of this special session were to (1) stimulate scientific collaboration and innovation to advance techniques for pelagic marine conservation in the California Current; (2) provide a forum to share recent research (i.e. data, tools, methods, findings) and to identify gaps in spatial information and innovative methodologies for pelagic conservation planning; and (3) synthesize the findings and publish the results of the symposium to support effective pelagic conservation in the California Current and beyond. This special session and discussion panel brought together geospatial scientists and marine conservation biologists to address the gaps in marine spatial information. In addition, the special session considered the development of innovative geospatial methods necessary to support effective marine conservation strategies for pelagic ecosystems, to summarize future research and conservation goals, and to discuss the necessary steps to facilitate achieving those goals.

This Theme Section is divided into 3 main groups of papers. The first group provides several foundational articles that offer conceptual advances in pelagic conservation planning and management, and recommendations for addressing the challenges in pelagic MPA design, monitoring and evaluation. The second group highlights geospatial tools available for spatially explicit management of pelagic systems including a case study to support biodiversity in the high seas. The third group concludes with case study examples that feature geospatial approaches to support pelagic conservation and management focusing on the California Current ecosystem and beyond. Several of these case study articles review the challenges associated with the spatial and temporal scales of dynamic spatial datasets. We highlight the results of this collection of contributions in the following 3 main sections organized in terms of (1) conceptual advances in pelagic conservation; (2) novel information technologies and methodologies; and (3) case studies in the California Current and Pacific Ocean.

CONCEPTUAL ADVANCES IN PELAGIC CONSERVATION

The first group of papers begins with a study by Maxwell et al. (2014, this Theme Section), who provide a synthesis of lessons learned and recommendations for managers to address challenges when implementing pelagic protected areas. Few large-scale, pelagic MPAs have been in existence long enough to codify ideal management strategies; however, Maxwell et al. (2014) bring together a series of recommendations and pragmatic approaches to managing such large-scale, dynamic areas, with a specific focus on cost-effective management techniques, even in limited-budget scenarios. Insight into objective setting in pelagic MPA design is given, and the authors provide a thoughtful discussion of the methods available to support management prioritization. In addition, they synthesize information from literature, interviews with managers and an informed discussion that occurred during the 'Pelagic Ecosystems and Management of Marine Protected Areas' meeting, part of the Marine Think Tank held at the International Congress for Conservation Biology (Auckland, New Zealand 2011). Maxwell et al. (2014) also discuss issues related to the enforcement of these large, remote areas. They highlight potential new enforcement technologies and provide clear recommendations to support the considerations necessary for a monitoring program (e.g. participatory monitoring) to inform adaptive management. The authors provide case studies to support the consideration of future partnerships and international collaborations necessary to ensure a common vision for successful and integrated pelagic monitoring, enforcement and management across the high seas and exclusive economic zones (EEZ).

The application of protected areas in the terrestrial environment has long preceded their application in marine environments (Sloan 2002), and this lag is influenced by barriers in the transfer of concepts and ideas between terrestrial and marine ecologists, and by the inherent difficulties associated with the mapping and protection of pelagic habitats. The conservation of biodiversity is one of the most common goals in MPA design and the measure of species and habitat diversity in space and time is an integral component of MPA design, monitoring and evaluation. However, it is unclear whether the 'biodiversity hotspot' concept is always applicable to marine systems. Briscoe et al. (2016, this Theme Section) considered the application of terrestrial conservation principles of hotspot identification to marine systems and provide a clear framework to support hotspot mapping in the open ocean. The ocean is more vast, dynamic and 3-dimensional than the terrestrial landscape (Hyrenbach et al. 2000, Maxwell et al. 2015). As a result, the application of terrestrial conservation hotspot mapping approaches in the pelagic environment has a number of challenges, but also presents a great opportunity to advance our understanding of the patterns and processes in the ocean which are key to supporting pelagic conservation planning. Briscoe et al. (2016) assert that marine conservation biologists must move beyond biodiversity hotspot mapping as a metric for marine conservation planning and focus on trophic productivity hotspots. The authors discuss the temporally persistent, but spatially dynamic nature of the open ocean (e.g. oceanographic fronts), and recommend that trophic productivity hotspots provide a more appropriate metric and proxy for biodiversity in pelagic conservation planning. They provide an important review highlighting the importance of including productivity as a metric for priority setting, the applicability of large, pelagic MPAs to protecting large-scale productive ocean features and their associated diversity, and the need to transition to more adaptive strategies such as dynamic management and mobile MPAs as technologies continue to advance for determining hotspots across temporally and spatially dynamic marine systems.

NOVEL INFORMATION TECHNOLOGIES AND METHODOLOGIES

Recent conceptual and technological advances support the information requirements necessary to map and monitor the oceanographic processes that define spatially explicit patterns of ocean productivity, protected species abundance and biodiversity in the open ocean. This section offers a review of the geospatial (ecoinformatic/mapping/analysis) tools designed to support spatial planning and management discussed at our SCB special session. In particular, Marine Geospatial Ecology Tools (MGET) was identified as a useful geospatial tool to support pelagic conservation monitoring and baseline species distribution modeling. MGET is a free, open-source geoprocessing toolbox that can support a variety of marine research, conservation, and spatial planning problems with specific tools relevant for the pelagic environment (Roberts et al. 2010). For instance, this geospatial tool supports (1) accessing and processing oceanographic data from ArcGIS; (2) identifying ecologically relevant oceanographic features in remote sensing imagery; (3) building predictive species distribution models; (4) modeling habitat connectivity by simulating hydrodynamic dispersal of larvae; and (5) detecting spatiotemporal patterns in fisheries and other time series data (Dunn et al. 2008, 2011, Treml et al. 2012).

In addition to geospatial tools, access to and integration of biophysical information is a critical step in the pelagic conservation planning process. Satellite remote sensing has yielded an uninterrupted, readily accessible, global time series of dynamic oceanographic variables spanning decades; these include sea surface temperature (SST) since 1981 (Casey et al. 2010), sea surface wind speed since 1987 (Zhang et al. 2006), sea surface height and ocean currents since 1992 (Woodworth & Menéndez 2015), and ocean color, chlorophyll concentration, and related biological variables since 1997 and for 1978 to 1986 on a more limited basis (Hu & Campbell 2013). In recent years, important satellites have exceeded designed mission lifetimes, and nations have launched complementary platforms, allowing concurrent observations by multiple orbiters and spurring development of SST and ocean color products that integrate observations from many sensors to reduce data loss due to clouds (e.g. Maritorena et al. 2010, Martin et al. 2012). Large-scale, long-term international initiatives to aggregate *in situ* observations, implement ocean observing systems, and deploy autonomous mobile platforms continue apace (e.g. Levy et al. 2011, Boyer et al. 2013, Rudnick 2016), yielding new and improved global data products, such as high resolution bathymetries and physiographic classifications (e.g. Yesson et al. 2011, Harris et al. 2014) and maps of oceanographic variables that are currently impossible to observe remotely (e.g. Garcia et al. 2014a,b). By integrating satellite and *in situ* observations into assimilating ocean models, oceanographers can now offer global estimates of physical, chemical, and biological variables at depth (Metzger et al. 2014, Gehlen et al. 2015). Finally, new algorithms allow automated identification of ecologically relevant dynamic oceanographic features, such as fronts, eddies, and Lagrangian coherent structures (Kai et al. 2009, Chelton et al. 2011, Belkin & Helber 2015, Haller 2015).

Pelagic conservation measures are often focused on protecting upper trophic level species. Accurately describing and predicting habitats is critical to effective planning and conservation; doing so often requires linking oceanographic variables and other mapped habitat data with geospatially referenced species observations. A number of advances have been made in determining upper trophic 'hotspots', particularly as a result of the Census of Marine Life (CoML). The goal of the CoML was to determine the diversity, distribution and abundance of marine life across taxa, habitats and ocean basins (Costello et al. 2010). With the synthesis of the Tagging of Pacific Predators (TOPP) project, a subproject of CoML, one of the largest multi-species tracking datasets was synthesized to show patterns and hotspots in the Northeast Pacific Ocean (Block et al. 2011). The Census of Fishes, also part of CoML, collated existing global knowledge of fishes across habitats, life stages and methodologies for understanding fish ecology and distribution (O'Dor et al. 2012). Furthermore, the OBIS was developed as part of CoML and has become the primary repository for marine species datasets from around the world (Grassle et al. 2000). OBIS and its subprojects, such as OBIS Spatial Ecological Analysis of Megavertebrate Populations (SEAMAP) that focuses specifically on top predator species, have provided incredible insights into the distribution of marine species all over the globe (e.g. Halpin et al. 2006, Grundlingh et al. 2007, Kot et al. 2010, Webb et al. 2010, Vandepitte et al. 2011). Using OBIS-SEAMAP, Fujioka & Halpin (2014, this Theme Section) provide an example of a spatio-temporal assessment of biodiversity in the high seas (i.e. Sargasso Sea). The authors address challenges related to the temporal assessment of biodiversity in the pelagic environment through this online tool that provides the user with a framework to facilitate dynamic assessments of biodiversity. Best et al. (2012) also applied the online OBIS-SEAMAP geodatabase to create habitat models for pelagic species along the US east coast and Gulf of Mexico.

CASE STUDIES: CALIFORNIA CURRENT AND BEYOND

The challenges of implementing geospatial management approaches in the pelagic environment can be immense due to the complexity of highly dynamic spatial and temporal datasets. Further, highly mobile pelagic organisms utilize dynamic oceanographic features, and we have limited understanding of the threats to these species across both time and space. The 4 case study articles presented in this section review the application and advancement of habitat-based models for pelagic species. Pereira et al. (2014, this Theme Section) tested 3 predictions of silver hake *Merluccius bilinearis* distributions and found that this species demonstrated site-dependent patterns of habitat use in the Gulf of Maine, which may be important for its persistence.

Habitat-based models of cetacean density were the focus of the last 3 articles in this Theme Section. Dransfield et al. (2014, this Theme Section) applied habitat models for humpback whale (*Megaptera novaeangliae*) occurrence within 2 United States National Marine Sanctuaries. The authors' results support the increased understanding of humpback whale habitat preferences, but also provide a thoughtful consideration of the conflict between human uses and cetacean conservation. As predictive modeling in the pelagic environment continues to expand, it will be important to frame these findings in a way that considers and maps the cumulative impacts (see Maxwell et al. 2013) and human activities that may impact pelagic species conservation and management. Dransfield et al. (2014) demonstrated that shipping traffic has decreased in areas of high predicted humpback whale habitat use, but the authors also encourage adaptive management to mitigate ship-strike risk by altering vessel frequency, speed, size and density within and between shipping lanes in the San Francisco Bay area.

Forney et al. (2015, this Theme Section) applied habitat-based density models in the central North Pacific, providing comprehensive consideration of model validation and accuracy. In addition, the authors consider the change in oceanographic data sources as remote sensing has advanced over the years, discussing the implications of evolving satellite technology on model accuracy and uncertainty. The common thread of temporal variability in species distribution modeling is also woven through the Becker et al. (2014, this Theme Section) work and the authors build further on the case studies that focus on habitat-based density models (Becker et al. 2010, 2012a,b). Becker and co-authors modeled cetacean seasonal density along the California Current using temporally dynamic remotely sensed environmental driver data. Becker et al. (2014) eloquently demonstrate the predictive capacity of habitat models to determine cetacean distribution during parts of the year when data are scarce. The seasonal variability captured in most of the predictive models that the authors presented demonstrates the utility and potential for advancing habitat-based models and applying cross-season predictions. In summary, the habitat-based modeling of cetaceans supports the management of human impacts (e.g. vessel traffic, fisheries interactions) and informs the identification of pelagic areas to prioritize for conservation and assist in adaptive management considerations. The case studies featured in this Theme Section highlight the challenges associated with habitat-based modeling across broad geographic areas, under data-limited conditions and in support of conservation of highly mobile species.

EMERGING RESEARCH FRONTIERS

Continued efforts to map and monitor dynamic oceanographic characteristics and static geomorphic features across space and time will provide a strong foundation to support growing efforts to spatially manage the deep sea and open ocean (Chelton et al. 2011, Belkin & Helber 2015). Future research directions should focus on addressing the challenges associated with integrating the dynamic oceanographic datasets available through remote sensing (e.g. SST, chlorophyll α) into products capable of capturing the spatial and temporal variability in the environment, at the scales relevant to pelagic predators and their prey. The oceans are dynamic, spatially complex, multi-dimensional systems, and currently geospatial tools and methods can capture the 3 dimensional complexity in the open ocean, but the temporal component (4th dimension) is a challenge. As more adaptive approaches to management progress under a changing climate (e.g. dynamic ocean management and mobile MPAs; Dunn et al. 2011, Maxwell et al. 2015), it will be critical to support the advancement of geospatial tools that allow for temporally dynamic data visualization and analysis.

Models that explain the shifts in distribution already occurring as a result of climate change are critical to understanding how predictive habitat modeling can be used to produce scenarios of how habitats might shift as climate change continues. Pinsky et al. (2013) showed how climate-induced changes in marine species distribution varied widely over large spatial scales. They attribute the variability they found in response to climate velocities, or 'the rate and direction that climate shifts across the landscape' (Pinsky et al. 2013, p. 1239), to local context rather than species characteristics, which has important implications for using localized data to inform future shifts in habitat. Hazen et al. (2012) use predictive habitat modeling techniques to suggest that with climate change we will see up to a 35% change in core habitat of a suite of top marine predators, and a general shift northward. Other modeling techniques have shown the impact of climate shifts across entire food chains, including potential impacts on fish biomass and subsequent movements of fishing fleets (Howell et al. 2013). Looking to the future in planning spatial conservation measures is critical as environments, species and humans shift in response to changing conditions.

As remote sensing technologies continue to advance, scientists have the ability to use widely available global biophysical datasets and spatial predictive models to help inform MPA design in dynamic and remote environments. The ability to statistically define habitats and prey aggregations in the absence of data in the pelagic environment is advancing rapidly. These advances involve determining what metrics most accurately define bathymetric and hydrographic habitats (e.g. Suryan et al. 2012, Michael et al. 2014) and what modeling techniques most accurately relate animal distribution to these environmental variables (Wingfield et al. 2011), as well as models that explicitly take energetics, movement and environment into account (Suryan et al. 2006). For example, Pikesley et al. (2013) illustrate the first application of ensemble models for quantifying the habitat of olive ridley sea turtles *Lepidochelys olivacea*. This novel approach integrates multiple models into a single powerful prediction (Araújo & New 2007).

Habitat-based modeling must advance and integrate validation tools into the modeling process. The study of uncertainty (e.g. confusion matrix, sensitivity analysis) and the mapping of uncertainty as a visual assessment tool will be critical to the validation and communication of uncertainty. Further, there is a clear need to focus on bridging the gap between the communication of model uncertainty and the translation of modeling results to policy makers. Pelagic conservation planning processes will aim to encompass metrics of interest, such as diversity or productivity of marine systems. By capturing such metrics, it is implied that ecologically important processes, features or components of the systems will be protected.

One of the key questions brought to the forefront in recent years is whether productivity and diversity are linked and coupled in space and time in marine systems. In terrestrial systems, plants are the main primary producers. Plants are relatively long-lived, stationary in space and time (Tang et al. 2006); thus the widely held paradigm is that increasing productivity results in increased diversity in terrestrial systems as a diversity of upper trophic level species are found in these relatively stationary productivity 'hotspots' (Gaston 2000, Richmond et al. 2007). In contrast, primary production in the ocean is dominated by phytoplankton that move dynamically in space in time, with changing ocean conditions such as currents and upwelling (Levin 1994, Carr et al. 2003, Lourie & Vincent 2004). Furthermore, the long trophic links between primary producers and upper-level consumers introduce potential spatio-temporal lags between areas of elevated primary production and localized foraging hotspots for marine predators (e.g. Hyrenbach et al. 2000, Hooker at al. 2011). Thus, a more accurate understanding of the mechanistic links between the productivity and diversity of both planktonic and nektonic organisms is essential to developing comprehensive targets for conservation planning in pelagic ecosystems.

As we transition toward ecosystem-based approaches that fully integrate the biophysical system, social system, economic system and marine governance, we need to embrace the complexity of human relationships with ecosystems in order to develop and implement viable management strategies (Fulton et al. 2011). Although social data are recognized as important for understanding a system (Naidoo et al. 2006, Stephenson & Mascia 2009), approaches that characterize the human dimensions of marine ecosystems remain fragmented, sectoral, coastal or even land-based, and limited in scope. This may be due largely to disparities in data availability and lack of familiarity with social science research methods among practitioners (Koehn et al. 2013, Kittinger et al. 2014, Le Cornu et al. 2014). Although characterizing social data can be challenging (e.g. Knight et al. 2010), researchers are developing innovative techniques to map human dimensions in ocean environments (e.g. St. Martin 2001, Pittman et al. 2011, Klain & Chan 2012, see Koehn et al. 2013 for a review). In marine systems, understanding the 3 dimensional spatial distribution of activities can help practitioners optimize spatial plans to maximize benefits among user groups (White et al. 2012). Despite recent advances in the integration of social data into marine spatial planning (Richardson et al. 2006, Klein et al. 2008, Ban & Klein 2009, Ban et al. 2014b), practical approaches for incorporating human dimensions in marine governance and linking them to biophysical attributes are limited (Dahl et al. 2009). Future research should focus on the dynamic spatial integration of social data with biophysical datasets in the pelagic environment to support conservation planning across a peopled seascape.

CONCLUSION

The articles in this Theme Section address new directions in pelagic conservation and management, with specific application to the California Current, and more broadly other boundary currents and oceanic habitats. Challenges exist for implementing geospatial management approaches in the pelagic environment, given the lack of comprehensive biophysical and social datasets, the large spatial scales of the oceanic habitat features, and the inherent dynamic nature of the habitats and the distributions of anthropogenic threats and protected species distributions. However, this compilation of articles provides the latest lessons learned to facilitate the successful implementation of comprehensive marine spatial planning of the pelagic environment. In particular, we sought to identify key commonalities (i.e. concepts, knowledge, data, tools) for the design of spatial management measures. Further, several articles in this Theme Section provide recommendations for pelagic MPA design, implementation, or evaluation based on reviews of the current direction of spatial planning for pelagic ecosystems and recent conceptual advances and technological developments.

Conservation practitioners require syntheses of the lessons learned from recent conservation efforts in pelagic ecosystems around the world, in order to apply these lessons to successfully implement future spatial planning in the marine environment. There is a unique set of economic, logistical, and biophysical challenges that must be considered in these pelagic areas. The dynamic nature of pelagic species and environmental gradients makes the feasibility of spatial management in the pelagic ocean challenging and necessitates the use of geospatial technology. It is our hope that the research presented in this Theme Section will provide key case studies to advance the use of geospatial technologies in support of pelagic conservation in the California Current, and beyond.

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