Marine Geomorphology in the Design of Marine Reserve Networks

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Abstract

Marine environments, key life-support systems for the earth, are under severe threat. Issues associated with managing these common property resources are complex and interrelated. Networks of marine reserves can be valuable for mitigating threats to marine systems, yet the successful design and implementation of such networks has been limited. Efficient ways to conserve marine environments are urgently needed. This focus section of *The Professional Geographer* explores the development of marine reserve networks based on geomorphology, fish biology, ecological connectivity, and appropriate governance. The articles in this focus section offer examples of the following: 1) distinctive reef geomorphology dictating the spawning locations of reef fishes, which in turn serve as critical source sites for the replenishment of distant reefs by means of larval transport, 2) an example of a simplified oceanographic model that predicts larval transport from fish breeding sites to important nursery areas, and 3) a case study of the development of a marine reserve network that illustrates key elements of a successful strategy. In sum, this focus section offers case studies that show the value of marine geomorphology, oceanographic connectivity and stakeholder involvement as key elements of multi-disciplinary geographic studies applied to the design of marine reserve networks. Geographers can further contribute to the conservation and management of coastal and marine ecosystems in many ways that involve sub-disciplines of remote sensing and GIS, political and economic geography, political ecology, and ethnography.

Key Words: spatial planning, geomorphology, marine reserves, spawning, connectivity, governance of common property resources

Introduction

Marine waters cover 71% of the earth's surface. They serve a key role in controlling earth's climate and supporting human economies and social welfare. The annual value of coastal and marine ecosystem services was estimated at $22.6 trillion, more than double that of terrestrial ecosystem services, $10.7 trillion, while global gross domestic product was estimated at $18 trillion (Costanza et al. 1997). Nearly half of the world's population lives within 200 km of a coastline and that figure is likely to double by 2025 (Creel 2003). As the receiving basin for runoff and pollution and the last true commons left on earth, marine waters are being degraded due to ocean acidification, overfishing, pollution, and habitat destruction; yet they continue to be managed poorly (Millennium Ecosystem Assessment 2005; Hoegh-Guldberg et al. 2007). The human and financial resources available for marine conservation and management are estimated as two orders of magnitude lower than required (Balmford et al. 2004). Understandably, efficient ways to conserve marine environments are urgently needed and have been the focus of increasing scientific and political attention.

It has been ten years since *The Professional Geographer* has addressed marine environments in a focus section (Steinberg 1999). That section illustrated the wide and growing body of geographic studies on marine and coastal environments from physical, human, political, and economic perspectives. Geographers have increasingly focused on marine ecosystem dynamics and management during the last decade (e.g., St. Martin 2001; Burne and Parvey 2002; Psuty, Steinberg, and Wright 2004; Lunn and Dearden 2006; Prigent et al. 2008), yet these efforts are still limited compared to the disciplinary emphasis on terrestrial landscapes. Rather than attempt to review all new marine geographic studies, this article offers examples of the diversity of contributions that geographers have made to marine and coastal management, and demonstrates ways in which geographers could offer a more holistic approach to this vast study area. The overall objective of the focus section is to promote improved planning for marine reserve networks through the use of geomorphologic habitat proxies, studies of ecological habitat connectivity and the involvement of local fishers and their local knowledge to conserve reef fish spawning aggregations.

We organized four sessions at the 2008 Association of American Geographers (AAG) Annual Meeting under the common theme, "Marine Geomorphology as a Determinant for Essential Life Habitat: An Ecosystem Management Approach to Planning for Marine Reserve Networks" (Wright and Heyman 2008a). The sessions were co-sponsored by three specialty groups of the AAG: Coastal and Marine, Geographic Information Science and Systems, and Biogeography. The unifying goal of these sessions was to examine critically the growing body of data suggesting that, even more than in terrestrial environments, the underlying geology and geomorphology of marine environments dictates the location of critical life habitats for a variety of species. The broad implications of these findings suggest that geomorphology might be used as a proxy for (or at least help to identify) critical life habitat for marine species, and thus serve to advance the applications of ecosystem-based management (EBM), the design of marine reserve networks, and marine spatial planning more generally.

The intentions of this lead article of this focus section are two-fold; 1) to engage a wide array of scholars about the values and condition of marine waters, and ways in which geographers can further contribute to marine and coastal management, and 2) to provide the context for the articles in this section that together focus on the design of marine reserves based on principles of geomorphology, environmental biology of fishes, connectivity, and the involvement of stakeholders in governance. The article navigates relevant background literature to explain key terms, concepts, and themes. The scope is necessarily broad and includes sections on the status and trends in marine fisheries and ecosystems, biology of marine fishes, marine geomorphology as proxy for marine habitats, marine remote sensing and habitat mapping, marine ecosystem based management, connectivity and larval transport, fisher traditional ecological knowledge (TEK), and stakeholder involvement in and governance of common property resources. These disparate themes converge to address marine ecosystem-based management (EBM) and marine spatial planning and form a synthesis of the focus section. This article thus serves as an introduction to and synthesis of the articles in the focus section and a review of the wide-ranging and important roles that geographers play in marine conservation and management.

Status and Trends in Marine Fisheries and Ecosystems

Seafood produced from marine fisheries and aquaculture provides about 15 percent of the protein consumed by humans, more than 50 percent in small island developing states, and is the world's most highly traded food internationally. Net exports of fish and fishery products were valued at US$24.6 billion in 2006, representing 194 participating countries (FAO 2009). Our global dependence on marine fisheries and associated marine ecosystems is not often considered for its important role in global food security (Smith et al. 2010). Nonetheless, marine fisheries resources and the habitats on which they depend are either fully exploited or in decline throughout the world (National Research Council 1999; Food and Agriculture Organization 2004, 2009; U.S. Commission on Ocean Policy 2004; Millennium Ecosystem Assessment 2005). Low-latitude areas, e.g., the Caribbean, which harbor coral reef environments and a high proportion of the world's biodiversity, exhibit rapid declining trends that are consistent with global averages (Burke and Maidens 2004). These low latitude areas also have a high percentage of the world's poor, a higher percentage of people that are directly dependent on marine resources for protein and livelihoods, and often less effective governance structures (FAO 2009). Three case studies in this issue (Heyman; Coleman, Koenig and Scanlon; Gleason, Reid and Kellison) focus on the Gulf and Caribbean Region, providing a look at areas low latitude areas, but have a variety of governance arrangements. The final study (Fischer et al. this issue) is from the California coast where resources for governance are more plentiful, though the study proposes a cost-effective way to go about marine conservation planning that could be applied in other areas.

There is strong and growing evidence that industrial fisheries are, by nature, unsustainable and have lead to declines in marine and fishery resources, particularly large predators (Pauly et al. 2002; Meyers and Worm 2003). There is also growing realization that a variety of additional factors are affecting the health, resilience, biodiversity and productivity of marine waters, and the ocean's ability to produce the variety of ecosystem services on which societies depend (Worm et al. 2006). Recreational fisheries, for example, can have enormous effects on fished stocks. Coleman et al. (2004) report that 64% of the landings for species of concern in the Gulf of Mexico are harvested within recreational fisheries. This is particularly the case when recreational fishers target vulnerable times and places in fishes' life history (see the next section). Recreational fishers are numerous yet typically smaller producers than commercial fishers, and have strong links to local tourism economies. As a result their impacts and needs for careful management and regulation have been largely overlooked (Coleman et al. 2004).

Overfishing alters marine environments in a variety of ways. Jackson et al. (2001) have shown that overfishing over centuries has dramatically altered marine environments. They used historical data gleaned from paleo-ecological sedimentary records, archaeological records of human coastal settlements dating back 10,000 years, and historical records and charts dating back to the 15th century. Pauly et al. (1998) describes “fishing down the food web” as the trophic consequences of overfishing whereby societal preference for large predatory species has created a serial top-down depletion that is having cascading effects throughout marine ecosystems. Global environmental changes also contribute directly to observed declines in marine ecosystem health and fisheries harvests. Hoegh-Guldberg et al. (2007) illustrate how rising ocean temperatures and acid concentrations have together contributed to the global decline in coral reef habitat extent and health. River-born sediments, nutrients, pesticides and herbicides from upland agriculture, industry and urban areas are also having major effects on coastal and marine ecosystems. The most deleterious effects are generally on nearshore habitats such as mangroves, seagrasses, and estuaries, which often serve as nursery grounds for a variety of species (Beck et al. 2001).

Management responses to the plethora of threats to marine systems are as varied as the problems. Unfortunately, sectoral, single-species top-down approaches that have been imposed by fisheries regulators and management agencies have rarely proven effective. Worm et al. (2009) suggest that solutions to the global fisheries crisis must not focus simply on marine fisheries management interventions. Many authors have suggested a much more holistic approach to fisheries and marine management that is based on maintaining healthy and resilient marine ecosystems, recognizes connectivity, is spatially explicit, and is implemented through broad sector participation at the largest possible scales (e.g., Crowder et al. 2008; Palumbi et al. 2009; Worm et al. 2009; Norse 2010; section on management of common property recourses below).

Biology of Marine Fishes as Relevant to Marine Management

Distinct from terrestrial organisms, many marine fish species incorporate three periods of dispersal during their life history – a period of pelagic larval dispersal, ontogenetic habitat shifts through juvenile development, and seasonal adult migration for reproduction. While there are some species that remain sedentary as adults and others that have very limited larval dispersal, nearly all fish release pelagic eggs (Claydon 2004). The persistence of each species, and by extension, the overall resilience of marine systems, therefore depends on the availability of healthy areas for each life stage and successful movement or connectivity between them (Leis 1987; Roberts 1997; Peterson et al. 2000; Beck et al. 2001; Grober-Dunsmore and Keller 2008).

Most large-bodied, long-lived reef fishes do not spawn within their home range. Instead, they perform seasonal migrations for broadcast spawning from within transient aggregations to produce masses of pelagic larvae for dispersal (Claydon 2004). Fishes commonly migrate great distances to spawn within aggregations that occur at specific times and places (Johannes 1978; Thresher 1984; Leis 1987; Domeier and Colin 1997). Spawning aggregations of reef fish present easy targets for fishermen with unusually high densities of fishes at predictable times and areas (Johannes 1998; Sadovy De Mitcheson et al., 2008). Though some species appear more vulnerable to aggregation fishing than others, even light levels of fishing appear to affect the viability and health of spawning aggregations (Koenig et al. 1996; Sadovy and Domeier 2005). Fishing a species during its spawning aggregation has invariably led to declines and in many cases localized extirpations (Johannes 1998; Sala, Starr, and Ballesteros 2001; Claro and Lindeman 2003; Sadovy De Mitcheson et al. 2008). Protecting reef fish spawning aggregations is an obvious conservation strategy (Johannes 1998) consistent with ecosystem-based fishery management (Pikitch et al. 2004, and see below). Nonetheless, clear patterns of the timing and location of *multi-species* reef fish spawning aggregations are beginning to emerge. Several of the articles in this focus section examine explicitly the geomorphologically–based marine habitats associated with spawning aggregations (Heyman; Gleason, Reid and Kellison; Coleman, Koenig and Scanlon).

Marine Geomorphology as Proxy for Marine Habitats

Marine environments and their associated biota are dictated by their physical oceanographic and geographic setting at all scales. Classic geomorphological studies of landform have been eclipsed by more modern studies of process and dynamics (Psuty, Steinberg, and Wright 2004; Wright and Heyman 2008b). However, in marine environments, where bathymetric data are limited in scale and extent, landform (or submarine shape and form) studies are highly relevant and yet still somewhat rare. Yet geographic setting is fundamental in defining the structure and function of marine ecosystems. Coastal margin shapes (trailing versus leading edge coasts), for example, are created by tectonic activity. Underlying geology provides the basis for the development of benthic habitats (e.g., sediment versus rock). Water column properties such as temperature range, seasonal light variation, and tidal variation are functions of latitude. Species composition varies with hemisphere and region. The arrival and departure of regularly occurring but stochastic ocean gyres control local oceanic conditions. Far-field and localized winds influence wave height, period, and intensity and each of these is attenuated by local structure. At smaller scales, biotic habitats provide structure for other species (e.g., coral reefs provide habitat for marine plants, invertebrates and fishes). Indeed, coral reef habitats have been suggested as surrogates for species, ecological functions and ecosystem services (Mumby et al. 2008).

Ecosystems consist of both biotic and abiotic components and their interactions. The diversity and density of species and their ecological relationships are generally difficult to observe and quantify particularly over large geographic areas, but communities of organisms are generally constrained by their physical environment. Marine biogeography probably began with the observations of Charles Darwin. More recently there have been various attempts to classify, characterize, and map marine environments at various scales (e.g., Hedgpath 1957a, b; Hayden, Ray and Dolan 1984; Lanier, Romsos and Goldfinger 2007). There are a growing number of authors who suggest that abiotic ecosystem attributes can be used as surrogates for the identification, mapping and conservation of biotic components of ecosystems. This approach is fundamental to landscape ecology and though challenging, is being increasingly adopted for marine systems (Pittman, McAlpine and Pittman 2004; Pittman, Caldow and Hile 2007; Grober-Dunsmore et al. 2008; Costello 2009).

Hierarchical classifications can be used to develop marine conservation strategies at regional, national and global levels. Zacharias et al. (1998) offer an ecosystem classification scheme for British Columbia. Roff and Tayor (2000) provide an example of this approach used for the marine waters of Canada, the country with the longest coast and bordering three oceans. The hierarchical geophysical approach is supported by available data derived from remote sensing, bathymetric maps, and ocean circulation patterns (Zacharias and Roff 2000). Oceanographic and physiographic data are used to derive a consistent set of habitat classifications that together make up the seascape. Roff, Taylor and Laughren (2003) argue that geophysical surrogates for marine community types are fundamental to understanding biotic distribution and thus the most practical foundation for marine planning, management and conservation. In the same vein, geomorphology serves as a basis for a national conservation framework for the marine waters of Australia (Burne and Parvey 2002; Heap and Harris 2008) Global marine classifications following a similar geophysical approach are beginning to emerge as a basis for global marine planning and management (e.g., Andréfouët et al. 2008; Spalding et al. 2008).

A growing number of studies in a variety of locations are testing the validity of geophysical classification systems used to identify biological habitats (e.g., Wilson et al. 2007; Erdey-Heydorn 2008; Impietro, Young and Kvitek 2008; Kracker, Kendall and McFall 2008; Wedding and Friedlander 2008). These articles support the concept with specific examples; they refine techniques and applications for marine and coastal planning, conservation, and marine reserve network design.

There is emerging evidence that many species that migrate to spawn aggregate at locations with particular geomorphic structures: generally abrupt discontinuities in surrounding structure such as reef promontories, uplifted ridges, and shelf edges. Several articles provided in this focus section (Gleason, Kellison and Reid; Coleman, Koenig, and Scanlon; and Heyman) provide evidence from east and west Florida and Belize, respectively, to support this claim. These patterns are further supported by the locations of reef fish spawning aggregations at similar geomorphological features in Cuba, the Cayman Islands, and other areas (Claro and Lindeman 2003; Whaylen et al. 2004; Kobara and Heyman 2008; 2010). Collisions between large-scale ocean currents (e.g., gyres) and abrupt changes in geomorphology alter localized oceanic conditions. These oceanographic and physical discontinuities create underlying ecosystem processes and/or conditions to which many species have been attracted over evolutionary time (Heyman and Kjerfve 2008). Together these serve as examples and provide evidence for the larger concept that geology and geomorphology must be taken into account in the design of ecosystem-based management strategies.

Marine Remote-sensing, Bathymetric Mapping and Habitat Classifications

In spite of the critical need for geomorphology and hence marine habitat information, the collective effort to map the seafloor has only produced accurate coverage for 5-10% of the world's seafloor (Sandwell et al. 2003; Wright 2003). Nonetheless, satellite- and aircraft-based remote sensing techniques, ship-based single and multi-beam techniques, videography from free-swimming and towed diver surveys, remotely-operated vehicles, and submersible, and computer-assisted geoprocessing advances have all contributed to a greater availability of marine habitat mapping techniques and products (as reviewed by Green et al. 1996; Wright 1999; Wright and Heyman 2008b). And as a result there have been dramatic increases in the extent and quality of marine geomorphological habitat characterizations and interpretations (e.g., Wright, Donahue, and Naar 2002; Aswani and Lauer 2006; Lanier, Romsos, and Goldfinger 2007; Wilson et al. 2007; Kendall and Miller 2008).

In addition to habitat mapping, a discussion of geographically-based marine reserve network designs would be incomplete without mention of the scores of GIS-based spatial algorithms that have been developed for marine reserve planning and decision support (NatureServe 2008). One of the most notable is the suite of algorithms known as MARine reserve design using spatially eXplicit ANnealing or MARXAN (Ball and Possingham 2000; Possingham, Ball, and Andelman 2000; Leslie et al. 2003; Klein et al. 2008). MARXAN uses stochastic optimization routines to generate viable spatial reserve solutions that optimize coverage of pre-selected biological criteria, while minimizing the cost of the reserve network.

Marine Ecosystem-Based Management (EBM)

McLeod et al. (2005) define EBM as an adaptive resource management approach that incorporates ecosystem processes and their responses to environmental perturbations while addressing the complexity of both natural processes and human social systems (e.g., fishing communities, conservation organizations, local resource users, academic and research scientists, community members with traditional knowledge, and other stakeholders). EBM should increase the resilience of marine systems in the face of increasing local and global threats (Levin and Lubchenco 2008).

Marine ecosystem-based management was once and still is common in a number of Pacific Island Nations, where modern impacts have been relatively limited. These "traditional management" techniques have a great deal in common with what is presently being called EBM. Industrialized nations are just now rediscovering these simple principles, which are particularly valuable for marine systems with high diversity. Coral reef ecosystems are high in diversity and their fisheries are concomitantly diverse; many species are targeted in small numbers. Reef fisheries are therefore difficult to manage with conventional, single-species management means such as quotas, size and bag limits, or closed seasons (Koenig et al. 2000). Instead, an ecosystem-based fishery management (EBFM) approach may be more effective (Pikitch et al. 2004). This approach, which differs slightly from EBM but is complementary, recognizes the interdependence between protection of critical life habitat and multi-species *fishery production*. Ecosystem functions and critical life habitat, such as spawning and nursery grounds, are protected from destructive fishing practices in order to promote sustainable harvests (Koenig et al. 2000; Pikitch et al. 2004). Recognizing that marine management includes more than just fishing, recent studies are urgently recommending broader EBM (e.g., McLeod et al. 2005; Crowder et al. 2008; Christie et al. 2007) in order to account for impacts on non-target fisheries resources and habitats (e.g., non-point source pollution) and to include more of a participatory approach to management with broad stakeholder involvement. In part because both EBM and EBFM are new and complex in modern cultures, recent successful examples are uncommon

(Crowder et al. 2008). Heyman (this issue) provides a case study from Belize where the broad participation of a diverse group of stakeholders (including local fisherman) and a detailed analysis of geomorphology and its association with the biology of exploited species, play critical roles in the development of a national network of marine reserves. Indeed, most scientists agree in principle that large and functional marine reserve networks that provide connectivity between various critical habitats do form an essential (but not sufficient) component of any EBM or EBFM approach (e.g., National Research Council 1999 and 2001; McLeod et al. 2005; Halpern et al. 2008; Norse 2010).

Marine reserves are therefore considered effective tools to manage fisheries and mitigate pressures on marine biodiversity (Roberts 1997; National Research Council 1999 and 2001; Allison et al. 2003; Hastings and Botsford 2003). The optimal design of reserve networks has received a great deal of attention from modelers, ecologists, and managers, but generally the practical utility of these models, and their outputs have been limited by the lack of biological data (e.g., distribution of species, larval behavior) with which to run the models (Roberts 1997; Halpern 2003; Halpern and Warner 2003; Hastings and Botsford 2003; Berkeley et al. 2004; U.S. Commission on Ocean Policy 2004).

There is an urgent need to rapidly expand the coverage of marine reserve networks in order to promote marine ecosystem management. Deciding where to place these reserves is a daunting task, particularly given political opposition and the paucity of available data on which to make decisions. Since bathymetric data has been primarily collected to assist navigation, the world’s ports and large areas of shallow US coastal waters have been extensively mapped. Beyond that, however, there exists astonishingly little fine-scale marine bathymetric data especially for deep and remote areas. Sparsely available marine biogeographical data represent an even greater knowledge gap. We propose that geomorphological habitat proxies, based on the best available bathymetric data, can assist managers in making timely recommendations for inclusion of critical habitats within marine reserve networks. We urge, therefore, that bathymetric data collection and habitat mapping efforts be expanded to this end.

Connectivity and Larval Transport

Maintaining "connectivity" between ecosystem components is critical for their effective maintenance, resilience and survival, and therefore must be considered in the design of marine reserve networks (Roberts 1997). Even if sufficient critical habitats are encompassed within the reserve network, managers are cognizant that most species immigrate and emigrate from reserves, both by swimming and by larval transport. Roberts et al. (2001) illustrate the positive "spillover effect" of reserves on adjacent fisheries. A variety of studies have addressed larval connectivity, generally through numerical circulation modeling. Warner, Swearer and Caselle (2000) evaluate the relative importance of larval retention versus long-distance transport of gametes for the design of marine reserve networks.

Fischer et al. (this issue) introduce an alternate approach, which focuses on larval exchange as a critical factor in marine reserve network design. They have developed a two-dimensional, GIS-based diffusion model for representing larval dispersal distributions based only on bathymetry and coastal oceanographic circulation patterns. The method holds great promise for practitioners attempting to design marine reserves with limited time and oceanographic information (i.e., limited access to complex particle-tracking models which may not even be available for a region in which a reserve network is being designed). The method is superior to standard one-dimensional approaches currently in use that estimate dispersal along a coastline in an advection-diffusion framework (e.g., Okubo and Levin 2002). Connectivity research is clearly an important area requiring further study and provides another valuable avenue for interested geographers with skills in biogeography and physical processes.

Traditional Ecological Knowledge (TEK)

Fishers have developed local or traditional ecological knowledge (TEK) of the resources that they depend on based on their daily interactions with these resources over long time periods (Berkes 1999). Fishers thus have a great deal to offer scientists and managers in terms of holistic understanding of marine ecosystem dynamics in the areas they know well (Johannes 1978; Johannes 1998). TEK has been gathered, synthesized and passed on orally, often in the form of anecdotes (Agrawal 1995; Johannes and Neiss 2007). TEK is therefore context-specific, untested, sometimes unreliable, and until recently, very difficult for classically-trained ecologists, oceanographers, or fisheries managers to accept, incorporate, or mesh with their own studies (Johannes and Neis 2007; Shakaroff and Campbell 2007). As a result, there exist far too many examples of marine research and management programs that have ignored fishers and their local knowledge (Johannes, Freeman and Hamilton 2000). The consequences of ignoring fishers' knowledge include ignorant conclusions in stock assessments that have missed known seasonality or migration patterns, or worse, fisheries collapses. In Tarawa, Kiribati, for example, annual spawning runs of bonefish were almost completely destroyed when causeways were built between islands surrounding the atoll that blocked seasonal spawning migrations. Based on interviews with older, experienced fishers from remote villages, a single relict spawning run was discovered and subsequently managed; leading to resurgence in the bonefish population (Johannes, Freeman and Hamilton 2000). In another case highlighted in this focus section, marine protected area boundaries in Florida's Carysfort Reef were drawn to include a spawning aggregation, but inadvertently excluded an adjacent, but locally well-known black grouper spawning site (Gleason, Reid and Kellison, this issue). As will be developed in the following section, however, the divide between traditional ecological knowledge and that derived from scientists is not insurmountable (Agrawal 1995). Fishers' knowledge may be particularly valuable to scientists as we try to move to ecosystem-based management (as noted in the section above) though scholars must be cognizant of delicate political, cultural, and power-relationships and issues that arise in this type of research (Shakeroff and Campbell 2007). The time has come for putting fishers' knowledge *back* to work for conservation and marine resource management (Haggan, Neiss and Baird 2007).

We emphasize "*back to work*" because there are myriad examples of pre-industrial societies effectively managing their fisheries based on TEK and local management structures, particularly in the Indo-Pacific (e.g., Johannes 1978; Berkes 1999). Unfortunately, however, many local traditional marine management systems are being abandoned or eclipsed by the onset and interaction with industrial fishing and modern centralized governance, often with negative effects on resources (e.g., McClanahan et al. 1997). Since local fishers' involvement in management is predicated on both their understanding of the complex systems in question, as well as their personal stake in the effective management of those resources, their involvement can lead to effective ecosystem-based management solutions with high compliance. Modern examples are becoming more common (e.g., Drew 2005; Prigent et al. 2008). Indeed, most modern scholars and managers consider the involvement of fishers and their TEK as an integral component of effective fisheries management and ocean governance (Berkes, Coulding, and Folke 2000; Berkes 2004; US Commission on Ocean Policy 2004; National Research Council 1999, 2000). Importantly for geographers, carefully planned and implemented studies of TEK and their integration with other traditional disciplinary studies are equally valuable and needed on land and in the sea.

Stakeholder Involvement in, and Governance of Common Property Resources

The world's oceans are the largest and most important of our common property resources. Their management has suffered the tragedy of the commons (Hardin 1968), and this has recently been attributed to insufficient governance by appropriate and effective institutions (Dietz, Ostrom and Stern 2003). Crowder et al. (2006) indicate that declining marine ecosystem health is largely due to spatial and temporal mismatches between the scale of ecosystems and the jurisdiction of their management institutions (e.g., species that migrate across national boundaries). Their article articulates the need for large scale ocean zoning based on, ". . . underlying topography, oceanography, and the distribution of biotic communities." An increasing number of articles have argued that effective marine area governance may be predicated on the involvement of appropriate stakeholders, particularly fishers, in the process of adaptive management (e.g., St. Martin 2001; Christie et al. 2005; Christie and White 2007). Others have argued that marine systems can be viewed as complex and coupled social-ecological systems so their management should be addressed using a multi-disciplinary approach that addresses the interactions among resources, resource users and governance institutions (Mahon, McConney and Roy 2008; McClanahan et al. 2008).

Comprehensive ocean zoning represents the convergence of inclusive governance and ecosystem-based management and thus serves to mitigate conflicts in ocean use and to promote sustainability in fisheries and marine ecosystems (Halpern et al. 2008; Norse 2010). Ocean zoning is implicitly spatial. St. Martin and Hall-Arber (2008a) suggest that while many physical properties of marine systems are increasingly well expressed in marine GIS systems for planning, community resource use is less well represented. Recent studies seek to fill this gap by offering methods to work with fishers to map their resource use in GIS layers that can be considered as an integral component in marine spatial planning (Lunn and Dearden 2006; St. Martin and Hall-Arber 2008 a,b). Planning and management of the Great Barrier Reef Marine Park, for example, included comprehensive stakeholder involvement including GIS data layers showing resource use (Day 2002). There are a growing number of examples of the co-management of common property coastal and marine resources that illustrate the concepts in this section. For example, community-based cooperatives contribute to the sustainable management of the Sian Ka'an Biosphere Reserve in Mexico. As part of their involvement, they manage cooperatively a sustainable lobster fishery through good governance, transparency, and solid science (Sosa-Cordero, Liceaga-Correo and Seijo 2008). Integrated coastal management programs have also seen some success in the Philippines (White, Dguit and Jatulan 2006) and Trinidad and Tobago (Tompkins, Adger and Brown 2002). These studies provide local examples addressing commons management but the issue remains as one of the world's greatest challenges (Ostrom et al. 1999).

Synthesis of the Focus Section

While this focus section is far from comprehensive, this lead article and the articles herein provide foundational data and holistic approaches to address declining health and resilience of ocean resources. We argue for the expansion of marine ecosystem-based spatial management based on integrated multi-disciplinary studies of underlying geomorphology as a proxy for marine habitats, studies of marine connectivity, fishers' traditional ecological knowledge, the critical analysis of institutions and governance, and the broad involvement of stakeholders in the entire process.

The articles in this section focus on the ecology and management of tangible and specific subset of ocean governance and management issues and areas – the ecology and management of reef fish breeding areas. We recommend extensive documentation of the timing and location of multi-species spawning aggregation areas starting with geomorphology and fisher interviews as primary sources of information. The protection of these critical breeding and feeding habitats, through cooperative management, within seascape networks of reserves, will contribute to regional reef ecosystem resilience.

In summary, the five articles collected here illustrate:

1. state-of-the-art examples of how researchers have classified, integrated, and analyzed physical and ecological data sources to reveal geomorphology as a proxy for marine habitat, specifically, reef fish spawning aggregations (Gleason, Reid and Kellison, this issue; Heyman this issue; Coleman, Koenig and Scanlon this issue);
2. how spatial models of larval transport can illustrate the connectivity between spawning areas and nursery grounds via ocean currents (Fischer et al. this issue); and
3. how these scientific results, along with the active participation of stakeholders (such as fishers and their TEK), can be effectively used in the design of functional marine reserve networks, hence a demonstration of marine EBM in action (Heyman this issue)

These articles provide compelling examples of the important role of geographic inquiry and its applications in marine environments. As a discipline, geography is eclectic and multi-disciplinary, yet holistic and integrative. This focus section endeavors to provide that breadth (marine geomorphology, marine ecology, marine spatial planning based on ecosystem principles, stakeholder participation in governance of common property resources, and the design of functional marine reserve networks) along with depth of inquiry into a representative set of case studies that illustrates the breath but focuses on largely one issue – marine spatial planning that aims to conserve vulnerable and valuable reef fish spawning aggregations and their connectivity, based on studies of geomorphology as a proxy for habitat, modeling studies of marine connectivity, and through the involvement and participation of fishers and their TEK.

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