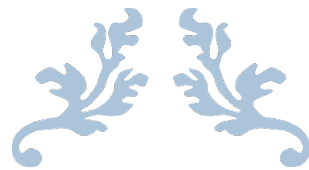


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EMPOWERING THE OCEAN

Resilience Thinking as a Policy Tool for the Management of Marine Protected Areas



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1. Executive Summary

Resilience thinking provides an intuitive and broadly applicable framework for characterizing the dynamics of social-ecological systems (SES). Under such a framework, both human communities and natural ecosystems are considered holistically as complex adaptive systems, with interactions between components at various spatial and temporal scales. This paper views marine protected areas (MPAs) as providing the most cutting-edge examples of resilience thinking being applied to environmental management in the United States, often under the umbrella of ecosystem-based management (EBM). Management strategies for some MPAs are reliant on an incorporation of human and natural elements into an inclusive social-ecological systems framework, an approach which shows promise for the successful preservation of marine resources in the future.

A resilience-based EBM program (this paper uses the term ‘resilience management’) for marine social-ecological systems involves keen insight into the systems’ adaptive cycles, capacity for adaptive management, extensive and prudent monitoring, incorporation of a wide variety of driver and indicator models, cooperation between various stakeholders, and the ability to function with limited monetary resources. In this paper I analyze the successes and shortfalls of EBM programs for three different MPAs in the United States: the Monterey Bay National Marine Sanctuary off the coast of California, the Florida Keys National Marine Sanctuary, and the Papahānaumokuākea Marine Preserve northwest of Hawaii. By exploring the current management programs for these areas, it is possible to draw a series of principles for the application of resilience thinking to marine resource management.

The end goal of this paper is to facilitate an adaptation of resilience thinking and EBM principles from scientific literature to managerial practice. I offer a series of concrete recommendations for

managers working with MPAs to incorporate an EBM approach rooted in resilience thinking into their management programs. It can be concluded that synthesizing resilience concepts and an EBM framework to the operational goals of MPAs will be beneficial—and to some degree necessary—for the preservation of U.S. marine resources in the face of increased climate change and other human impacts in the coming decades.

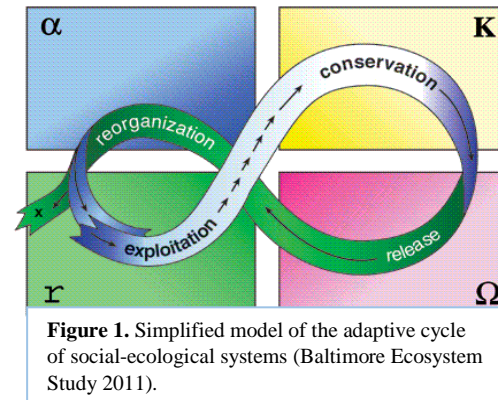
2. Background

2.1. Dynamics of Socio-Ecological Systems

Traditional environmental management frameworks tend to compartmentalize ecosystems into human and natural spheres, assuming that those who use natural resources (and those who manage them) exist outside of the systems wherein the resources are produced and extracted (Walker et al. 2002). There tends to follow from this a command-and-control structure for natural resource management, with managers and regulatory agencies focusing on maintaining pollution and resource extraction within specific optimal levels in order to keep a finite area at its perceived “equilibrium” state (Folke 2006). However, a growing body of literature exists which seeks to characterize management areas not as self-contained units of nature acted upon by humans from the outside, but as complex adaptive systems (CAS) which are composed of many levels of organization with a constancy of interactions among the various components (Walker et al. 2006, Folke 2006, Walker et al. 2002,).

Models of social-ecological systems demonstrate four phases of transition—known as adaptive cycles—which are undergone at various rates and to various degrees. The first phase is the growth or exploitation phase (*r*) which is characterized by increasing biodiversity, high resilience (the ability of a system to maintain itself), and a rapid growth in the complexity of structural

connections between the system's components. An example of this would be the process of primary ecological succession, such as that following a forest fire or volcanic eruption. The second phase continues the trend of increasing interconnectivity, but with a decline in flexibility and therefore a greater susceptibility to outside disturbances—this is known as the conservation (K) phase. The



disturbances experienced during the (K) phase eventually lead to phase three, the release phase (Ω) when the system's structures are broken down and relationships between components are disintegrated. The final phase is the reorganization (α) phase, where novelty can take hold and the system sets itself up, in a sense, for a new (r) phase which may be similar or very different from the previous one. These phases of adaptive cycles have been observed in many different types of systems including economic, psychological, and social-ecological systems (Garmestani and Benson 2013, Walker et al. 2006).

This model helps to further an understanding of SES's as complex adaptive systems with interactions both within and between many different scales. The SES framework allows researchers and managers to approach environmental management initiatives from a holistic perspective, providing an intuitive approach to mitigating ecological stress and planning for the future (Epstein et al. 2013, Folke 2006).

2.2. Applied Resilience Thinking

Developing models for the adaptive cycle of social-ecological systems provides a framework for studying their resilience, which is the system's ability to experience internal shifts and outside shocks without transforming into a different system with fundamentally different features

(Garmestani and Benson 2013, Walker & Salt 2006). Understanding system resilience is essential to achieving environmental goals within an SES framework—by researching and estimating (where quantifying is impractical or impossible) the limits imposed upon SES's by the nature of their various interconnected components, we can assemble a set of management initiatives which minimize anthropogenic impacts on the system's resilience.

Managing for resilience requires a system of monitoring which incorporates an ecological perspective to understanding the adaptive cycle of a given system (Epstein et al. 2013, Levin et al. 2009). When management areas are understood as complex adaptive systems which interact with natural and manmade factors both within and outside of the system, we can begin to forecast the types and degrees of changes the system will undergo when subjected to outside shocks. We know that all SES's have a degree of self-reinforcing resilience which acts as a buffer to both acute and prolonged impacts affecting the system, keeping the system within its thresholds. In the face of increased human impacts on natural elements of systems—acute impacts such as oil spills and slower variables such as global climate change—managers ought to focus on understanding and reinforcing the natural configurations of the system and identifying where and how resilience can be gained or lost. This can improve management programs by allowing greater predictability of potential outcomes under uncertain future scenarios (Anderies et al. 2006, Walker et al. 2006).

Resilience management means linking the adaptive cycle of an ecosystem with manmade environmental impacts, economic factors, public and private management efforts, and other human activities. It can be useful to analyze components of SES's individually, and then incorporate this analysis into the system as a whole. Difficulties in resilience analysis arise due to the apparent magnitude of necessary monitoring; the more connections between a system's

elements are identified, the more intensive and complex monitoring becomes. On the surface it appears much easier to identify a system's "equilibrium state" and the optimal levels of various components (pollutants, populations of a given species, etc.) as with traditional command-and-control management. However, these types of management strategies have consistently shown to be ineffective at preserving system resilience, even while they may achieve short-term environmental goals (Garmestani & Benson 2013, Epstein et al. 2013, Walker & Salt 2006).

A resilience-based approach will be increasingly necessary in the years to come—but how can resilience management be achieved in spite of the high cost and technical requirements of monitoring so many interconnected relationships within a system? This question—the issue of practicality and cost-effectiveness—has prevented a resilience framework from being applied to environmental management efforts at a large scale (Garmestani & Benson 2013, Epstein et al. 2013, Walker et al. 2006, Folke 2006). The emerging discipline of ecosystem-based management (which includes resilience analysis and a holistic approach) has been considered as an option for marine areas in the past 10 years (Halpern et al. 2010, Levin et al. 2009, Ruckelshaus et al. 2008, Leslie & McLeod 2007, Arkema et al. 2006). This forms the basis for a resilience management program (see Section 2.5).

In order for resource-limited management programs to achieve desired outcomes under a resilience framework, co-production and adaptive management are important policy tools (Garmestani & Benson 2013, Briske et al. 2008, Anderies et al. 2006). A co-production management strategy (also termed **co-management**) seeks to involve a variety of stakeholders in environmental efforts—this operates under the principle that diversity and community involvement can lead to stability (and increased resilience). This can also help to alleviate funding issues by involving agencies, employees, and volunteers from various sectors and levels

of government. Specific resources can be allocated from various budgets and contracted to outside organizations when desirable, lessening the financial pressure on the principal management agency (NOAA in the case of marine protected areas). **Adaptive management** depends on a constant progression of our understanding of social-ecological systems, and seeks to improve resilience through frequent program evaluation and adjustment of objectives (Levin et al. 2009, Plummer & Armitage 2006, Walker & Salt 2006, Tompkins & Adger 2004). Both co-management and adaptive management are shown to improve systems resilience in many cases—especially in marine areas—and should be considered crucial to a resilience management program.

2.3. Marine Protected Areas

Marine protected areas (MPA's) in the United States are operated by the U.S. National Ocean Service and National Marine Fisheries Service, which are subdivisions of the National Oceanic and Atmospheric Administration (NOAA), often in cooperation with other agencies and organizations. As many as 41% of marine waters within the United States are protected in some way, with around 1% being designated as “highly protected” no-take zones (NOAA 2014).

Altogether there are more than 1,600 MPAs operated by the National Ocean Surface within U.S. waters. These span a wide variety of natural environments and serve many different purposes.

However, the nation's MPAs (and marine areas as a whole) face threats both from direct and indirect anthropogenic sources, and will likely require an overhaul of management strategies if collapsing fisheries, irreversible decline in coral cover, and loss of essential ecosystem services are to be averted.

2.3.1. Importance and Value of Protecting Marine Areas

Marine protected areas are beneficial to the preservation of oceanic biodiversity (Selig & Bruno 2010, Levin et al. 2009, Hoegh-Guldberg & Bruno 2010), the sustainability of both market and

non-market marine resources (Hoegh-Guldberg & Bruno 2010, Sanchirico et al. 2002, Salm & Clark 2000), and the advancement of economic sectors such as commercial fisheries, beach tourism, and recreational fishing and scuba diving (Christie et al. 2010, Selig & Bruno 2010, Levin et al. 2009, Hughes et al. 2005). MPAs help to prevent overfishing and allow for the recovering of fish stocks in overfished areas. MPAs also demonstrate a “spillover effect” wherein fish species reproducing within the protected area are able to repopulate beyond the area’s borders via dispersal of larvae (Christie et al. 2010). This replenishment is important for the economic viability of commercial fishing.

Marine protected areas help to sustain vital ecological processes, and many MPAs encompass entire ecosystems with unique population dynamics (Salm & Clark 2000). Because of the complexities of speciation and dispersal of marine species around the globe, many marine ecosystems take unique forms. Even within a given latitudinal range, marine ecosystems often display different species distributions, interactions between biotic and abiotic components, and adaptive cycles (Hoegh-Guldberg & Bruno 2010, Salm & Clark 2000). The biodiversity of marine ecosystems is therefore highly varied and complex, and has yielded benefits to medicine, ecology, biology, and other areas (Sanchirico et al. 2002). As many as 741,000 species of marine organisms may yet remain undiscovered, and protecting marine ecosystems can help to prevent them from being driven to extinction before they can be sampled (Appletans et al. 2012).

Often the primary incentive for establishing MPAs is to sustain a wealth of both market and non-market resources. “Market resources” are services such as fisheries and tourism—preserving these resources has a direct economic incentive, and current management strategies have found some success in conserving them in the short term (NOAA 2014, Selig & Bruno 2010, Levin et al. 2009). “Non-market resources” are ecosystem services such as shoreline protection from coral

reefs, biodiversity preservation (and associated medical advancements), benefits to scientific research, and other indirect benefits to human health and the environment. Well-managed MPAs also serve to involve the community directly in marine activities, which in turn leads to economic and environmental benefits.

Coral reef ecosystems are especially vulnerable to ecological stressors, and many reefs are in serious need of effective management (Hoegh-Guldberg & Bruno 2010). Marine protected areas have shown to help prevent coral loss. A 2010 study compared coral biomass decline over a period of 50 years in both protected and unprotected areas and demonstrated that loss accelerated in unprotected reef areas, whereas in protected areas, coral decline tended to level off and eventually halt (Selig & Bruno 2010). Coral reefs are of particular interest in the study of ecological resilience, as the dynamics of reef resilience are already being applied to management strategies in some areas (Hughes et al. 2010, Hoegh-Guldberg & Bruno 2010, McCook et al. 2009, Kleypas & Yates 2009). Reef resilience benefits from the establishment and effective management of spacious, interconnected marine protected areas as well as from community involvement (Hughes et al. 2010, Christie et al. 2010, McCook et al. 2009). Although the resilience of coral ecosystems is still a new area of study, it provides one of the first concrete examples of an SES framework being applied to the management of marine areas. The difficulties faced by marine managers in their efforts to maximize reef resilience—chief among them illegal fishing, climate impacts, and monitoring difficulties—paint a picture of some challenges which arise along the path to effective resilience management of marine protected areas (Hughes et al. 2010, Selig & Bruno 2010, McCook et al. 2009, Sanchirico et al. 2002).

2.3.2. Direct Impacts from Human Activities

Some of the most pressing risks to marine environments come from direct human impacts, chief among them pollution and overfishing (both of which occur through legal as well as illegal channels). Direct impacts stem from activities driven by economic incentives, and are exacerbated by international regulatory variations and contemporary industrial procedures which are typically resistant to changes in the regulatory framework. Increased marine conservation efforts and stakeholder involvement can help to mitigate direct impacts, and MPAs have demonstrated some success at preventing excessive pollution and depletion of fish stocks. However, this appears to depend on how effectively they are managed, the amount of funding available, and the level of protection enforced within the areas' borders (NOAA 2014, Selig & Bruno 2010, Dalton & Jin 2010, Levin et al. 2009).

Pollution—especially nonpoint-source pollution—presents a wide range of lethal and sub-lethal threats to marine life. Some of the most significant sources of pollution are phosphorous and nitrogen runoff from agricultural activities, dumping of hazardous and solid waste from industrial processes, oil spills, and accumulation of plastics and other non-biodegradable materials (Slomp 2011, McCook et al. 2009). Because many of these pollutants are generated on land, it can be difficult to confront them through the processes of designating and managing MPAs. In many cases, marine pollution can be reduced through more significant regulation of land-based activities; this is especially true for issues such as nutrient runoff from agricultural activities which create anoxic zones such as the infamous 'Dead Zone' in the Gulf of Mexico. Additionally, better recycling programs and incentives for industries to dispose of waste materials properly (generally following under the jurisdiction of the Environmental Protection Agency and various state-led agencies in the U.S.) can reduce the amount of pollutants entering sensitive marine areas (Slomp 2011, Levin et al. 2009, Salm & Clark 2000). This in turn

decreases the impacts of outside stressors on marine ecosystems and protected areas, and makes MPAs easier to manage effectively.

Oil spills differ from other sources of marine pollution in that most stages of the extraction, refining, transportation, and distribution process are oftentimes carried out in or near marine environments. Marine spills come in the form of difficult-to-track discharges from vessels, as well as more infrequent, catastrophic, and highly publicized spills which result from breakdowns of offshore oil rigs. Marine protected areas as they are currently managed have not demonstrated much success at reducing oil spills overall, although factors such as scale of protection, boat traffic restrictions etc. have shown an effect on the frequency and severity of spills (Dalton & Jin 2010). Oil spills have a ubiquitous and drastic impact on marine life, often lasting for years after the spill event despite federally managed cleanup efforts (Dalton & Jin 2010, Hoegh-Guldberg et al. 2009)

Overfishing was a pervasive problem throughout the 20th century and remains so in many areas of the world today. Increased regulations, quotas, enforcement of legal liabilities, and widespread monitoring has allowed many of the once-overfished populations within United States waters to achieve a return to sustainable levels, although there is still much work to be done (NOAA 2014, Selig & Bruno 2010, Christie et al. 2010). The role of marine protected areas in preserving the economic viability and reproductive sustainability of fish populations remains unclear, although they almost certainly have a neutral effect at worst. Recent research has shown statistically significant increases in the dispersal of fish larvae, which leads to increases in stocks, in areas surrounding many effectively managed MPA's (Christie et al. 2010). However, because only 1% of U.S. waters are designated as no-take zones, the benefits of MPAs to overfished populations within the U.S. Exclusive Economic Zone (EEZ) may be insignificant, and other management

strategies aimed at sustainable fishing may be more desirable (NOAA 2014). The National Marine Fisheries Service has expressed a desire to move towards an ecosystem-based fisheries management approach, which is consistent with a resilience approach to managing the nation's network of MPAs (Halpern et al. 2010, Ruckelshaus et al. 2008, Arkema et al. 2006)

2.3.3. Impacts from Climate Change

Anthropogenic climate change is causing changes to social-ecological systems worldwide through a rapid increase in atmospheric carbon dioxide concentrations. These processes have occurred since the Industrial Revolution and have been linked to rising sea levels, ocean acidification, changes in population dynamics and migratory patterns, changes in the spread of disease vectors, and other effects which, although difficult to predict with accuracy, are very clearly observable and well-documented in recent studies (IPCC 2013, Doney et al. 2012, Hoegh-Guldberg & Bruno 2010, McCook et al. 2009, Pörtner et al. 2007, Harley et al. 2006). Research has shown that climate change is rapidly pushing marine ecosystems into conditions which have not been seen in millions of years, and the degree to which ecosystems will be able to adapt to such unparalleled changes is uncertain. For this reason it is essential that we further our understanding of the resilience and adaptive cycles of marine ecosystems so as to predict how best to deal with climate change from a managerial perspective.

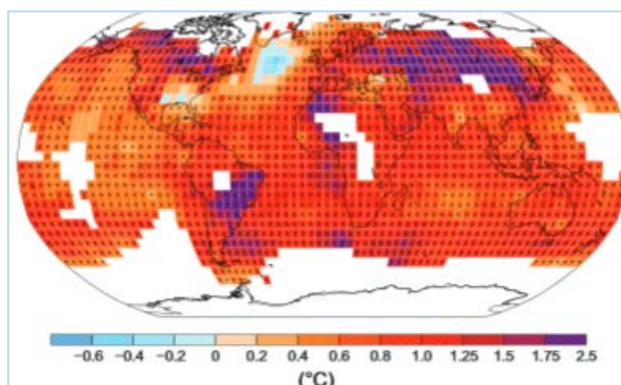


Figure 2. Increases in global average surface temperatures, 1901-2012 (IPCC 2013).

Many of the most pronounced effects of climate change on the world's oceans are occurring within coral reef ecosystems. Increased atmospheric CO₂ causes the pH balance of the world's oceans to fall in a process known as ocean acidification. In

addition, climate change causes an increase in average sea surface temperatures as well as a higher frequency of isolated warm-water events known as “hot spots” (Hoegh-Guldberg & Bruno 2010, McCook et al. 2009). These chemical and thermal stressors are associated with accelerating coral degradation and habitat loss for many of the world’s fish species. Coral reef ecosystems support a large portion of the tourism industry in the tropics, provide protection from coastal storm surges, sustain nearly 50% of the world’s fisheries, and are second only to rainforests in biodiversity. The ecosystem services that they provide to the world’s economy are valued at over \$300 billion dollars annually, and much of this value is concentrated around developing countries and coastal communities which otherwise have few resources. Loss of coral ecosystems—which have already declined by 50% to 80% in many parts of the globe—would result in severe consequences for many areas which are already highly vulnerable to the effects of global climate change (IPCC 2013, Hoegh-Guldberg & Bruno 2010). Some of the strongest evidence of climate change stressors and their impacts on marine environments is centered on coral reefs, and research has indicated that understanding and managing for resilience is likely to be the most effective policy tool for preserving reef resources in the years to come (Huelsenbeck 2012, Hughes et al. 2010, Hoegh-Guldberg & Bruno 2010, McCook et al. 2009, Kleypas & Yates 2009, Donner 2009).

Altogether, climate change is expected to present drastic challenges for marine resource managers in the near and distant future—challenges which may be best understood from a resilience perspective which seeks to understand the complex multi-scale dynamics of marine social-ecological systems (Hughes et al. 2010, Hoegh-Guldberg & Bruno 2010). By focusing research and monitoring efforts on developing models of marine SES components, interactions, and responses to chemical and thermal changes, we can better assess the risk posed to these

systems by ongoing global climate change. Further research into the system dynamics and resilience of marine ecosystems will facilitate the development of management strategies in the face of uncertainty.

2.4. Legal Framework

The development and enforcement of specific policies for managing marine protected areas varies based on the organizations involved in management. However, a number of federal environmental laws form the legal basis for protection of all marine protected areas in the United States. The authority of NOAA and other agencies in enforcing protective measures for MPAs is limited by their specific mandates as delineated in a number of statutes. However, it is also possible for states and localities to mandate additional protective measures and thereby increase the authority of regulatory and law enforcement agencies working in marine areas. Many of the laws currently in effect could provide a vehicle for the development of a resilience management approach—or at the least, would not hinder any steps taken towards such an approach. The legal framework is the starting point for the development of both the structure and the various functions of regulatory agencies, and therefore it can also form the root of resilience management strategies (NOAA 2014, Salm & Clark 2000).

The following is a list of major pieces of legislation which pertain to the protection of marine environments, with brief discussions as to how they may be applied to a resilience management approach:

- The National Environmental Policy Act (NEPA) of 1969 requires federal agencies to prepare an environmental assessment for all actions which may affect the quality of the environment. This plays an important role in the process of establishing marine protected areas—although areas dedicated to ecosystem preservation are likely to help rather than

harm environmental quality, areas dedicated to activities commercial fishing and tourism require that care be taken to avoid environmental damage. NOAA derives the bulk of its statutory authority from NEPA, and is committed to fully integrating the law into its planning and decision-making process (NOAA 2014). In order to facilitate a resilience approach, environmental assessments (EA) and impact statements (EIS) ought to contain analyses of the system dynamics of the affected area (and the greater SES). Reports should attempt to estimate the system's thresholds of resilience to any significant actions to be undertaken in the area, and provide measurable indicators of any potential changes to specific crucial system dynamics and resilience as a whole.

- The Coastal Zone Management Act (CZMA) of 1972 encourages states to preserve certain areas of coastline, setting them aside from development. The CZMA requires states to balance economic development of coastline with preservation goals for coastal areas. The federal government covers 85% of the costs of state-level coastal management programs. Coastal communities, beaches, and offshore industrial operations are important components of marine SES and must be considered alongside natural components if ecosystem health and resilience are to be managed successfully.
- The Endangered Species Act (ESA) of 1973 provides for the protection of endangered and threatened species in both terrestrial and marine environments. The Marine Mammal Protection Act (MMPA) of 1972 has a similar mission, and prevents the taking and importation of all marine mammal products in the United States or by U.S. citizens in international waters. The National Marine Fisheries Service (NMFS) is responsible for

implementing the ESA and MMPA in oceanic biomes. The presence and prevalence of indigenous species are important indicators of ecosystem stability, and numerous interactions between system components contribute to the success or failure of endangered species conservation efforts. By understanding the various interconnected factors affecting endangered species within a given social-ecological system, the size of these valuable populations can be used as a metric for measuring and analyzing the system's resilience.

- Executive Order 13158, issued in 2000, required the Department of Commerce (under its subsidiary, NOAA) to strengthen and expand the national system of marine protected areas, including National Marine Sanctuaries, commercial fisheries, and other types of single-use and multi-use sites (NOAA 2014). This order forms the primary basis for NOAA's activities in U.S. marine waters, and cements the agency's legal authority in protecting submerged cultural and biological resources within the U.S. EEZ.
- Executive Order 13547, issued in 2010, created a National Ocean Council to oversee the operation of the national system of MPAs and to foster stronger connections and communication between federal and state agencies involved in marine management (Ethridge et al. 2010, White House 2010). The primary directive of the National Ocean Council is to cultivate a group of management programs based on a "comprehensive, adaptive approach to issues of conservation, economic activity, user conflict, and sustainable use" (Ethridge et al. 2010). Executive Order 13547 also requires the integration of climate change science into marine management. This program (termed "marine spatial planning" by the National Ocean Council) is based on a holistic perspective, encourages

frequent monitoring and evaluation, and is conducive to a resilience management approach.

- There are a number of land-based environmental laws and regulations which indirectly affect the health of marine ecosystems. These generally fall under the jurisdiction of the Environmental Protection Agency (EPA). Some laws enforced by the EPA which play a role in curbing sources of marine pollution are the Pollution Prevention Act (PPA), the Oil Pollution Act (OPA), the Resource Conservation and Recovery Act (RCRA), the Toxic Substances Control Act (TSCA), the Clean Air Act (CAA), and the Clean Water Act (CWA), among others. The EPA commonly works with stakeholders such as the Department of Natural Resources, the Department of Agriculture, corporations, and a number of state-led agencies in order to achieve the regulatory limits imposed by these laws. In doing so, the amount of damage to marine ecosystems from hazardous waste, oil spills, agricultural runoff, pesticides, volatile organic compounds, criteria air pollutants, and (more recently) greenhouse gas emissions is reduced or limited to some degree. The presence of MPAs can provide land-based organizations with substantial leverage in achieving their regulatory goals. Bearing this in mind, those involved with managing the resilience of marine ecosystems ought to keep an open dialogue with the EPA and other land-based agencies in order to co-manage terrestrial activities which indirectly result in damage to offshore environments.

In addition to federal laws and regulations, local rules and practices can also inform management programs. Understanding the laws which provide the conceptual basis for marine conservation is useful for the establishment of new MPAs, and for effective management of existing MPAs (Salm & Clark 2000). The legal authority for enforcing MPA rules and regulations is often

distributed among various entities—for example, protection of marine mammals is mainly the responsibility of the NMFS, addressing threats to coastal ecosystems is a stated duty of the National Ocean Service, hazardous waste discharges are regulated by the EPA, and so forth. This necessitates a co-management ethic for MPAs in order to synthesize the various tenants of U.S. environmental policy for the protection of marine areas. It is also important that managerial entities working in MPAs have clearly defined objectives that are consistent with the stated goals of the existing legal framework.

2.5. Trends in Marine Management: Command-and-Control vs. Ecosystem-Based Management

The United States' national system of MPAs was formally established in the year 2000 by Executive Order 13158 (NOAA 2014). This order directed the Department of Commerce (of which NOAA is a subsidiary), the Department of the Interior, and other federal agencies to work with state and local organizations to develop a comprehensive network of MPAs. The current system is managed by agencies at all levels of government. Although all marine protected areas in the United States are primarily under the jurisdiction of the National Ocean Service, each one is managed by a different combination of agencies and organizations. Therefore each MPA is operated with its own unique set of objectives and regulatory frameworks, with different stakeholders, levels of enforcement, and systems of monitoring and program assessment. Despite this, a number of established precedents and emerging trends for the management of MPAs can be discerned from the current national system.

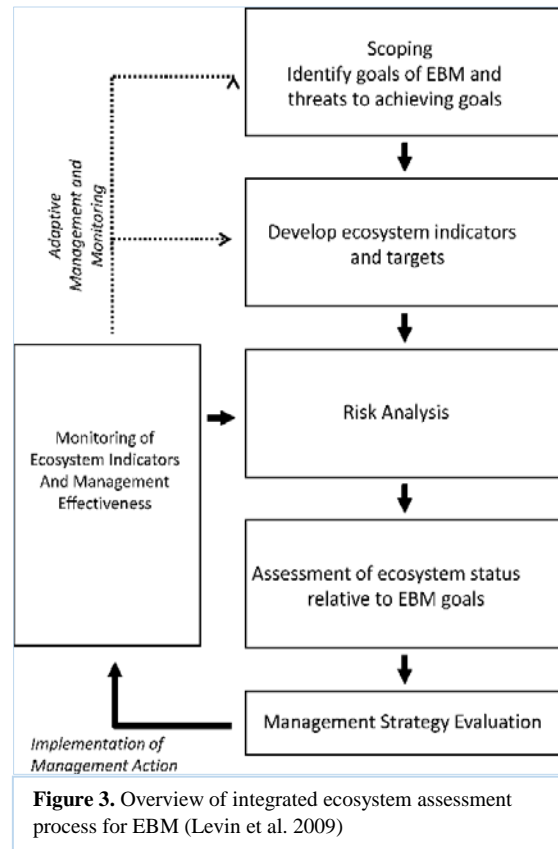
Traditionally, management of marine areas in the United States has focused on limiting certain activities within a given physical region, while allowing and enhancing other activities (Halpern et al. 2010, Levin et al. 2009, Leslie & McLeod 2007, Salm & Clark 2000). Ocean zoning—often termed marine spatial planning—is a central feature of current management practices, with

MPAs categorized as No Access, No Take, No Impact, Uniform Multiple Use, Zoned Multiple Use, or Zoned w/No Take Areas (NOAA 2014). Most MPAs are multi-use sites which allow recreational activities such as boating, surfing, and diving as well as some degree of commercial fishing. Focus is generally given to extractive activities such as fishing, drilling, and tourism, with each MPA being dedicated to a particular set

of uses (NOAA 2014, Halpern et al. 2010, Salm & Clark 2000). This is a quintessential example of command-and-control management; the focus is placed on controlling specific quantifiable aspects of the system (such as fish biomass or inflow of pollutants) rather than long-term preservation of the ecosystem as a whole. However, this is not always the case—as mentioned previously, about 1% of U.S. waters are protected from all commercial activity besides non-extractive tourism (NOAA 2014). Thus, MPAs in the United States can range from marine sanctuaries with no-take rules and

limited public access to fully operational commercial fisheries. This disparity in management perspective and regulatory extent makes it difficult to evaluate the effectiveness of MPAs as a whole at achieving national marine policy goals (Halpern et al. 2010, Levin et al. 2009).

The principal holistic management paradigm which has been applied to marine areas in recent years is **ecosystem-based management** (EBM). The science and implementation of EBM are based on a holistic conceptualization of protected areas as social-ecological systems which



follow adaptive cycles and are affected by human activities on multiple scales (Halpern et al. 2010, Ruckelshaus et al. 2008). EBM has been explored in the literature over the past decade as a promising option for marine management (Halpern et al. 2010, McCook et al. 2009, Levin et al. 2009, Ruckelshaus et al. 2008, Leslie & McLeod 2007, Arkema et al. 2006). In recent years NOAA has adopted a program of integrated ecosystem assessments (IEA) in order to achieve EBM criteria. IEAs analyze relevant natural and socioeconomic factors relating to specific management goals (Levin et al. 2009). There are five steps in this process as outlined by Levin et al. in 2009: scoping, indicator development, risk analysis, management strategy evaluation, and ecosystem assessment. Integrated ecosystem assessments further the goals of EBM by providing managers with a concrete picture of the complex interactions between parts of a social-ecological system, including the levels of risk from human activities and observable indicators of ecosystem stress. Currently EBM has a much greater presence in the literature than it does in practice; one exception to this is the NMFS' recent shift towards an ecosystem-based approach to managing U.S. fisheries (NOAA 2014).

The principles of EBM form the basis for a resilience management approach, and resilience management can be viewed as a form of EBM which emphasizes system resilience as the central focal point of program development, implementation, monitoring, and assessment. This is not inconsistent with current EBM literature and practice; rather, resilience management seeks to streamline EBM policies—and make them more accessible to management agencies—by focusing specifically on resilience rather than the complex assortment of EBM criteria that currently exists in the literature (Halpern et al. 2010, Levin et al. 2009, Ruckelshaus et al. 2008, Leslie & McLeod 2007, Arkema et al. 2006). Definitions and criteria for EBM are not uniform among either scientists or managers (Halpern et al. 2010, McCook et al. 2009, Arkema et al.

2006) and therefore it is difficult to connect the concepts of EBM with the operational goals of management agencies. Resilience thinking can help bridge this gap by focusing management activities on assessing the sources of system resilience and the processes by which humans' use of ecosystem goods and services affect these sources. This may help scientists and managers forge a common path for achieving an EBM framework for the U.S. network of MPAs (see Section 4).

3. Case Studies

The following case studies explore varying degrees and types of ecosystem-based management of marine protected areas. Three MPAs within U.S. waters are examined, with an exploration of the successes and shortfalls of each management program. The examples are **not** indicative of U.S. MPAs as a whole; rather they present three of the most comprehensively protected areas which have demonstrated resilience management strategies and an ecosystem-based approach. All three areas are evaluated for both intended and demonstrated success at achieving ten specific ecosystem-based management principles (as outlined by Arkema et al. in 2006). The case studies demonstrate that the three areas in question operate under management frameworks which include EBM principles and goals. The degree to which EBM criteria are applied to management initiatives varies and, in the case of some criteria, is uncertain. Each of the three areas may be able to achieve greater success at achieving desired outcomes through EBM by focusing on a resilience-based approach as outlined in this paper.

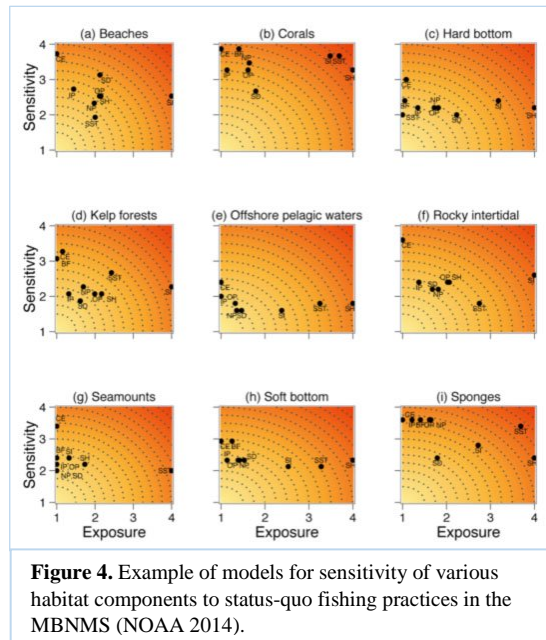
3.1. Monterey Bay National Marine Sanctuary

The Monterey Bay National Marine Sanctuary (MBNMS) was established in 1992 and currently spans an area of 4,601 square nautical miles off the coast of California from San Francisco in the

north to Cambria in the south (covering about 25% of California's coastline). The MBNMS was established for the purposes of "managing and protecting the conservation, recreational, ecological, historical, research, educational, and aesthetic resources and qualities of the area" (NOAA 2008). The Sanctuary encompasses one of the largest embayments along the Pacific Coast and is of particular interest to scientists and resource managers due to its unique bathymetric features which support a diverse array of marine species, including 34 species of marine mammals and at least 700 species of fish, shorebirds, and seabirds (NOAA 2014). The Sanctuary is an integrated multiple-use site: it functions as a research hub, a valuable commercial fishery, and a widely-used recreational destination (NOAA 2014).

Certain activities within the MBNMS are restricted or prohibited according to Subpart M of Title 15, Part 922 of the U.S. Federal Code of Regulations. Prohibited activities include oil, gas, and mineral exploration; discharge and deposition of hazardous materials; drilling; disturbing or possessing any historical resource within the sanctuary; disturbing or possessing any marine mammal, sea turtle or bird; and intentionally attracting white sharks. Other activities such as personal motorized watercraft operation, fishing, dredging for coastal development and maintenance, and deposition of federally permitted dredge material are restricted to specific areas within the Sanctuary (Title 15, Section 922.132). These prohibitions and restrictions are intended to provide the maximum amount of protection possible for the area's marine cultural and biological resources, while still allowing for sustainable recreation and commercial fishing.

Management of the MBNMS is approached from an EBM perspective as part of NOAA's California Current Integrated Ecosystem Assessment program (CCIEA). The CCIEA is a detailed analysis of the physical and biological components of the California Current Large Marine Ecosystem (CCLME), which spans from the coast of Alaska in the north to Baja California, Mexico in the south (CCIEA 2012). This report identifies a plethora of indicators of



ecosystem health and future economic viability in the CCLME, and uses extensive modeling to project the effects of hypothetical future scenarios on the various indicators. Ecosystem-wide modeling of this nature provides a vivid picture of the drivers of change and responses by the myriad ecosystem components, including human communities.

Although the information presented by the CCIEA is extremely comprehensive, the extent to which it is

being applied by the MBNMS appears uncertain. The CCIEA operates primarily from a perspective of fishery management, and the effects of various drivers on ecosystem resources such as biodiversity, recreation, scientific research, shoreline protection et cetera are not broadly explored (CCIEA 2012). However, certain aspects of the CCIEA have focused specifically on the MBNMS, and on its management. A variety of models have been developed which analyze the effects of various management strategies on certain indicators such as the prevalence of protected species and the diversity of benthic organisms in bottom trawl analyses (NOAA 2014). As the report admits, these models are mostly focused on sustaining fisheries, and not on preserving ecosystem health or biodiversity (which are stated goals of the MBNMS). The

CCIEA report states that more research into ecosystem-wide drivers and pressures and their relation to management strategies is needed (CCIEA 2012). It is possible that this may be achieved by developing models focused on system resilience rather than on controlling specific ecosystem components such as the presence of certain fish species.

Current work on the CCIEA is focused on adding ‘Habitat’ as an EBM component, which may prove beneficial both within the Sanctuary and throughout the CCLME. Once the current phase of ecosystem assessment is completed the knowledge base may be sufficient for developing an active EBM program in the region. A more holistic program of this nature could expand some of the protections offered within the MBNMS to the CCLME as a whole, with a greater focus on ecosystem health and resilience. This will afford myriad benefits to the preservation of biotic and abiotic resources—and to the sustainability of human communities which depend on those resources—both within the MBNMS and throughout the entire CCLME. A more detailed analysis of system resilience based on indicator and driver models could give MBNMS management greater clarity as they attempt to incorporate the results of the CCIEA more fully into their programs.

3.2. Florida Keys National Marine Sanctuary

The Florida Keys National Marine Sanctuary (FKNMS) was established in 1990 and was the ninth National Marine Sanctuary to be added to the system. It currently protects approximately 2,900 square miles of coastal and ocean waters surrounding the Florida Keys, and is bordered by Miami to the north and the Dry Tortugas to the west. The Sanctuary was founded with the passage of the Florida Keys National Marine Sanctuary and Protection Act, which combined and expanded existing protected areas such as the John Pennekamp Coral Reef State Park and Looe Key National Marine Sanctuary into one interconnected and diverse protected zone. The

FKNMS is currently managed by a partnership of the National Ocean Service and the Florida Department of Environmental Protection (DEP) under a comprehensive revised management plan adopted in 2007 (NOAA 2014).

The FKNMS was established in response to the rapid decline of coral reefs off the coast of the Florida Keys and is now a heavily zoned multi-use site with extensive protections, especially for corals, manatees, and other important marine species. The various zones are regulated under Subpart P of Title 15, Part 922 of the Code of Federal Regulations. Boating within the Sanctuary is restricted to no-wake speeds within 100 yards of coastline, reef markers, dive sites, and stationary vessels. Any disturbance to corals (including anchoring, cutting, moving, possessing, and any other damage) is prohibited throughout the sanctuary, as well as any discharge of sewage, garbage, or hazardous materials. Dredging, drilling, and development anywhere within the Sanctuary is forbidden as well—interestingly, the regulations define these activities collectively as “placing or abandoning any structure on the seabed” (Title 15, Section 922.163).

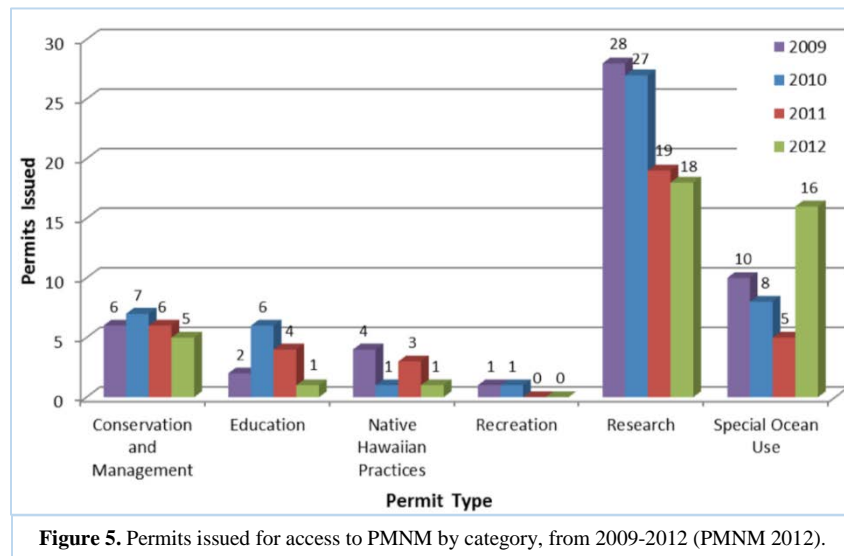
Site-specific management and spatial zoning are important components of the FKNMS management program (Ethridge 2010, NOAA 2007). The Sanctuary is currently zoned according to five categories: ecological reserves, existing management areas, sanctuary preservation areas, special-use areas, and wildlife management areas (NOAA 2014). The FKNMS contains 24 completely protected no-take zones, and a number of research areas in which entry itself is prohibited without a permit. These areas are restricted to recreational and scientific diving, ecosystem monitoring, and other areas of scientific research and archaeological exploration. There are also several wildlife preserves for specific species, managed by NOAA and DEP under guidance from the U.S. Fish and Wildlife Service. A 2003 report by the Pew Oceans Commission found that spatial zoning had significantly improved management of the FKNMS

(Ethrige 2010). The revised 2007 management plan does contain an assessment of the greater Florida Keys marine ecosystem, but restrictions and prohibited activities within the Sanctuary remain largely compartmentalized and managed individually rather than holistically (NOAA 2007).

Although the FKNMS management program has improved since the Sanctuary's founding in 1990, recent research in the fields of climate change, coral degradation, larvae dispersal, and adaptive cycles demonstrates that the resilience of reef ecosystems is dependent on cross-boundary recruitment of larvae as well as the ability of corals to resist the thermal and chemical stressors associated with greenhouse gas increases (Huelsenbeck 2012, Hoegh-Guldberg & Bruno 2010, Hughes et al. 2010, Donner 2009, Hoegh-Guldberg 2009, Kleypas & Yates 2009, Levin et al. 2009, McCook et al. 2009). This implies that managing ecologically significant zones individually may not result in long-term ecosystem preservation. NOAA is currently conducting an IEA for the Gulf of Mexico, and has plans to assess the Caribbean Sea at some point, but no IEA for the FKNMS and surrounding areas has been undertaken. A sanctuary-wide IEA similar to the CCIEA could help to develop scientifically accurate models for ecosystem stressors (including climate changes). This in turn will lead to recommendations for more holistic, integrated management programs. Such programs will not require an abandonment of the area's zoning policies, merely the addition of strategies for preserving the Sanctuary's coral reefs and other resources across spatial boundaries.

3.3. Papahānaumokuākea Marine National Monument

In 2006, the Papahānaumokuākea Marine National Monument (PMNM) was officially established by Presidential Proclamation 8021, which combined several existing MPAs and research areas in the northwestern Hawaiian Islands archipelago as well as surrounding waters. It



is currently the one of the largest marine protected areas in the world, covering 137,792 square miles, and was designated a UNESCO natural and cultural World Heritage Site in 2010 (PMNP 2012). The PMNM is intended to protect the

archipelago's coral reefs, which are home to over 7,000 species of marine animals, as well as the region's native Hawaiian cultural resources. The Monument is co-managed by a board of trustees comprised of NOAA's National Ocean Service, the U.S. Fish and Wildlife Service, and the State of Hawaii. NOAA is responsible for leading management of the Monument's marine areas, USFWS has jurisdiction over the area's wildlife refuges and the Battle of Midway National Memorial (the PMNM's most significant post-settlement cultural site), and the State of Hawaii helps to manage native Hawaiian practices in the region, while also maintaining primary responsibility for managing the Northwestern Hawaiian Islands Marine Refuge and State Seabird Sanctuary at Kure Atoll.

Habitat protection and ecosystem preservation are the top management priorities for the PMNM board of trustees (PMNM 2012). Access to the site is currently extremely limited, with virtually all activity besides uninterrupted passage by seagoing vessels requiring permits. The majority of permits are issued for the implementation of management programs, visitation for educational outreach, native Hawaiian activities such as sustenance fishing and traditional ceremonies, and scientific research. Some permits for non-extractive recreational and “special ocean use” purposes have been issued as well, although these activities are confined to those which specifically benefit the conservation and management initiatives of the PMNM (PMNM 2012). This can include documentary filmmaking, snorkeling, kayaking, and other forms of ecotourism; however, none of these activities may be carried out on a fee-for-use basis. All commercial fishing, development, drilling, diving, and other invasive or extractive activities are completely prohibited, making Papahānaumokuākea one of the most comprehensively protected areas within the U.S. EEZ (NOAA 2014, PMNM 2012, Jokiel et al. 2011). Nevertheless, challenges such as invasive species, pollution from passing vessels, impacts from research activities, coral disease, and climate changes (including acidification, sea level rise, and isolated warm-water events) remain for the PMNM and its management agencies (Selkoe et al. 2008).

Papahānaumokuākea is especially relevant to the study of marine ecosystem-based management due to the dichotomy of traditional Hawaiian management practices—which have been followed by native communities for centuries—and Western marine resource management policies which have been in place since Hawaii was settled in the 19th century. Under the traditional system, known as *ahapua’ā*, protection of the area’s reefs and their resources was achieved through an intuitive, adaptive knowledge of small changes to the weather patterns, watersheds, coral formations, and fish populations (Jokiel et al. 2011, Selkoe et al. 2008). This practice was

developed over many generations, and was maintained under the authority of tribal chieftains who enforced sustainable fishing and recreational practices within their localities. Take was limited to only what was necessary for supporting the tribe, and guidelines were dependent on the chief's perception of how various fish and coral species were responding to fishing practices. If the chief and his fisherman noticed that a particular area or species was being overused or not adequately recovering from takings, a *kapu* (forbidden take) could be imposed, with severe and immediate punishments for those who violated the ordinance. These practices, along with a strong culture of respect for the ocean and its resources, allowed Hawaii to sustain a population of over 250,000—even while utilizing primitive technology and a very limited range of food resources—for hundreds of years before Western contact (Jokiel et al. 2011).

The *ahapua'a* system, through its highly adaptive nature and respect for the balance between human needs and ecosystem health, resembles contemporary EBM goals and criteria. Although it was largely replaced by Western command-and-control practices following colonization, the management plan for the PMNM encompasses somewhat of a return to these traditional methods of viewing and interacting with the ocean (PMNM 2012, Jokiel et al. 2011, Selkoe et al. 2008). Traditional Hawaiian fishing practices are allowed to continue, and the Monument's 2012 management plan stresses evaluation of various ecosystem components (and subsequent adaptation of management strategies) as an objective (PMNM 2012). This reconciliation of traditional practice with a modern, Western management structure is a novel approach to EBM, and its potential for preserving the resilience of the Papahānaumokuākea social-ecological system is notable, if the past success of *ahapua'a* is any indication. However, new and unique challenges such as climate change, invasive species, and vessel pollution will require more extensive models of system components and drivers of change (Selkie et al. 2008). Simply

limiting human use of the area to a great degree will not protect against such impacts, and therefore active monitoring and adaptive management will be essential for long-term ecosystem preservation (this has been acknowledged in the 2012 management report). Developing models for drivers and indicators of system resilience in the PMNM could help to inform management actions in the future.

3.4. Comparison of EBM Achievement

A 2006 study by Arkema et al. identified 16 specific EBM criteria for marine environments and compared the relative frequency of adoption of these principles by various management agencies (Arkema et al. 2006). The table below adapts 8 of these criteria, followed by 2 additional criteria focused on resilience management, with comments on whether they have been adopted into management plans for the three MPAs examined previously.

Criteria	Description	MBNMS	FKNMS	PMNM
Ecological Health	Includes non-specific goals for maintenance of ecosystem integrity	Yes	Yes	Yes
Inclusion of Humans in Ecosystem	Considers the health and education of human communities an important part of management decisions	Yes	Yes	Yes
Complexity	Incorporates linkages between ecosystem components into management decisions	No	No	Yes
Spatial/Temporal Planning	Applies management plans to processes that occur over a variety of spatial and temporal scales	Somewhat [Spatial and temporal planning applied for fisheries; less so in other areas]	Somewhat [Area assessed as a whole as well as divided into zones; however most management actions are site-specific]	Yes
Adaptive Management	Attempts to improve management through systematic evaluation of programs	Somewhat [management strategy evaluations (MSEs) conducted every 5-7 years]	Yes	Yes

Co-Management	Multiple organizations and agencies share responsibility for management	Yes	Yes	Yes
Precautionary Approach	Manages conservatively where extent or nature of threats are uncertain	No	Yes	Yes
Monitoring	Tracks changes in human and natural ecosystem components	Yes	Yes	Yes
Resilience Models	Assesses effects of various drivers and pressures on system resilience through scientifically informative models	Somewhat [Drivers and pressures modeled extensively; not focused on system-wide resilience]	No	No [May be perceived as unnecessary due to heavy restrictions on activities]
Resilience Management	Actively pursues the preservation of system resilience as a management objective	No	No	Yes

Table 1. Attainment of EBM and resilience management goals by three U.S. marine sanctuaries.

These case studies demonstrate that management strategies for MPAs in the United States vary widely, even within the narrow context of National Marine Sanctuaries. However, all of the examined sites demonstrated a marked potential for management programs rooted in a deeper analysis of system resilience. The remainder of this paper is comprised of strategies and recommendations for developing a resilience management program for MPAs, based on insights gained from the above case studies and from the existing literature on resilience thinking and marine management.

4. Resilience Management: In a Nutshell

This is a brief synopsis of the practical implications of implementing a resilience management program at the agency level.

4.1. Program Management

Management programs focused on resilience and ecosystem preservation can be achieved through a variety of policy tools which need not detract from the goals, missions, or objectives of

the managing agency. In many respects, a resilience approach can be integrated into the existing management framework, especially where ecosystem assessments and monitoring for ecosystem health are already undertaken. A resilience management program is a continuous process of developing and monitoring scientific models of the drivers of system resilience, their relationships to one another, the indicators representing the drivers, and outside variables affecting them. It is also essential to consider political and economic realities (as with any management program); effective communication and stakeholder involvement can help to achieve this. See Section 5 for a detailed program outline for resilience management.

4.2. Resource Management

The resources necessary for an ecosystem-based approach to MPA management do not necessarily exceed those used in current management practices (Levin et al. 2009, Ruckelshaus et al. 2008, Leslie & McLeod 2007, Arkema et al. 2006, Sanchirico et al. 2002). Resilience management requires:

- A skilled environmental science staff for monitoring ecosystem components and developing models of resilience;
- Management staff for interpreting results, directing management actions with the goal of preserving resilience, budgeting, and developing management policy;
- Enforcement staff for upholding laws and site-specific rules;
- A communications staff consisting of at least one ombudsman, legislative liaison, and public information officer;
- Equipment and resources for all of these staff members;
- Miscellaneous expenses such as office equipment.

Co-management can help to alleviate or reduce many of these expenses. Many of these positions can be distributed between different agencies or contracted to outside organizations, as long as this does not compromise the goals and objectives of the resilience management program.

4.3. Political Management

Public outreach, education, stakeholder involvement, and pursuit of a favorable legislative framework are essential to a successful resilience management program. The concept of system resilience is not difficult to grasp compared to the variously defined and often disorganized principles of EBM (Levin et al. 2009, Ruckelshaus et al. 2008, Leslie & McLeod 2007, Arkema et al. 2006). Indeed, a workable understanding of EBM principles can easily follow from a solid knowledge base of SES dynamics and systems resilience. This may be conducive to a more consistent flow of information between scientists, managers, stakeholders, and the general public—within a resilience framework, management decisions can be understood as benefitting the ecosystem (and associated human communities) through the enhancement or restriction of certain relevant system components. It is important that this be communicated as the central strategy of resilience management, in order to cultivate support for what may otherwise be viewed as an untested or radical program. Correspondence with lawmakers on legislative issues relevant to marine management is also vital, as well as public education on the topics of resilience and management of social-ecological systems.

5. Towards a Resilience Approach: A Program Outline for Managers

Any MPA management plan ought to be uniquely tailored to the specific management area (especially with regards to the highly varied nature of U.S. MPAs), but there are a variety of unifying principles for achieving a resilience management framework within any plan. These strategies will allow managers to develop quantitative analyses of the drivers of system resilience

at various spatial and temporal scales. It will also contribute to a working knowledge of the human-generated variables affecting resilience drivers, and therefore will directly inform management decisions. The essential aspects of a resilience management program are modeling resilience indicators as part of an IEA, consistent monitoring of the drivers which affect these indicators, a synthesis of these fluid models from an ecosystem-wide perspective, and an adaptive management framework which incorporates changes in resilience components directly into management actions. For a successful resilience management program, resilience thinking ought to be applied to co-management between stakeholders and educational/public outreach initiatives as well.

5.1. Resilience Modeling as an IEA Component

The development of scientifically accurate, quantifiable models for system resilience can be easily incorporated into the existing IEA process as outlined by Levin et al. in 2009, and applied to NOAA's IEA program (NOAA 2014, Levin et al. 2009). In the example of the California Current Integrated Ecosystem Assessment, extremely thorough models for tradeoffs between fisheries management practices and the presence of various biological indicators were developed (CCIEA 2012). These models can inform models of system resilience, because they demonstrate the degree to which outside stressors (in this case, commercial fishing and pollution, among others) affect critical ecosystem components. Developing models which specifically address the drivers of resilience in an ecosystem, and the outside variables which affect them, can help managers to achieve a fluid, adaptable, and concrete program which can be easily communicated between stakeholders and to the public.

The fundamental questions to be answered through resilience modeling are thus:

-What are the drivers of system resilience?

-On what scales do they function?

-What indicators can be used to assess them?

-Which outside variables affect these indicators, and to what degree?

When managing a coral reef, for example, one well-established **driver** of reef resilience is the extent to which larvae are dispersed and recruited (Hughes et al. 2010, McCook et al. 2009). This process functions on a localized scale (within a patch of reef isolated by hardbottom or sand) and an ecosystem-wide scale (between various patches and reef zones of the greater MPA). The primary **indicators** of successful larval recruitment are coral growth (local) and the appearance of new corals on separated substrates (ecosystem). These indicators are affected by changes in sea surface temperature, pH, pollutant levels, and physical damage from human activities—these outside stressors are referred to here as **variables** because they are the root causes of changes to resilience components, as well as the eventual targets of management actions.

The development of models for how these variables affect the indicators of larva dispersal allow scientists and managers to monitor the extent of detrimental effects to dispersal. Therefore, it allows them to monitor system resilience through changes in larva dispersal (among other drivers), and provides a framework for determining *how* such changes may have occurred. This, when combined with data for other critical resilience drivers, informs management decisions.

Other drivers of resilience in the case of a coral reef MPA could include the presence of limestone substrate, as well as biodiversity indicators such as large predatory fish, marine mammals, and seabirds. A synthesis of models for all of the critical resilience drivers in a given

SES allows for the determination of a resilience ‘baseline’—the levels of resilience indicators when the models are first developed. From there, managers can use their newly-modeled knowledge of the outside variables affecting resilience drivers to develop management actions to improve resilience where possible, and also to deemphasize drivers which are relatively resistant to outside variables.

5.2. Monitoring Drivers and Indicators

Once models for the various drivers of resilience within a system, the scales on which they operate, and their indicators are developed, it is important that monitoring be undertaken.

Typically indicators will be affected by multiple outside variables, and oftentimes changes in one driver will affect changes in other drivers, so extensive monitoring and updating of models is beneficial. Therefore, it is useful to use the indicators of critical resilience drivers as the starting point for monitoring, and then assess which variables may have contributed to any observed changes. An example of a monitoring program for a particular resilience driver is as follows:

Step 1: Determine how each indicator changed. Are the driver’s indicators more present or less present in the area that they were when previously sampled?

Step 2: Determine how the variables affecting this indicator changed. The models for the driver demonstrate which outside variables affect the driver’s indicators. Have any of these variables increased or decreased? Is this consistent with the models’ predictions?

Step 3: Determine how the changes to this driver may affect other drivers. Oftentimes, one driver may function as a variable for another driver, or two drivers may contribute to each other in a feedback loop. For example, decreased larva dispersal in a coral reef (driver 1) results in a decrease in substrate production, which in turn decreases the available space for larval recruitment.

Step 4: Repeat this process for each indicator of critical resilience drivers.

Step 5: Assess the net change to overall resilience and the variables which caused this

change. The drivers of resilience collectively determine the resilience of the ecosystem. Did the indicators for these drivers as a whole increase or decrease? Which outside variables contributed to this net increase or decrease in resilience?

Optimally, monitoring should be as frequent and extensive as resources allow; however, an advantage of a resilience approach is that it allows managers to determine which drivers are most critical to system resilience and the extent to which they are affected by changes in outside factors.

5.3. Ecosystem Focus

A successful modeling and monitoring program will lead to the development of an ecosystem-wide “resilience web,” which displays the interconnectivity between the various resilience drivers and the variables which affect them. Because of the hugely complex nature of systems resilience, and its operation on multiple spatial and temporal scales, any ecosystem-wide model of resilience must inevitably be simplified. However, this still allows managers to view a lucid representation of the relationships which comprise system resilience within their management area. By synthesizing the myriad models established through resilience management, a picture of the ecosystem emerges wherein the relationships between various components—and their relative importance for overall system resilience—can be viewed and assessed.

These webs can be constructed on any spatial scale. For temporal analysis, it is important to determine the speed at which variables develop and cause changes to drivers—it is useful to categorize these as “fast” and “slow” variables (Walker & Salt 2006). Fast variables are often

considered as “shocks” such as hurricanes, warm-water hot spots, oil spills, et cetera. Slow variables include elements such as prolonged overfishing, acidification, sea level rise, etc.

Ecosystem webs can also be used to assess the system’s thresholds—although these are difficult to determine with precision, a conservative estimate for the amount of variables or combination of variables which will push the system into a new, fundamentally different *K* phase. Viewed holistically, this also includes long-term socio-economic changes which may occur due to ecosystem disruption. Because some variables, such as sea level rise, will affect both human and natural components of the SES, it is important to consider variables and thresholds in terms of the holistic system. This allows stakeholders to view the consequences of anthropogenic variables on various spatial scales and over various time periods.

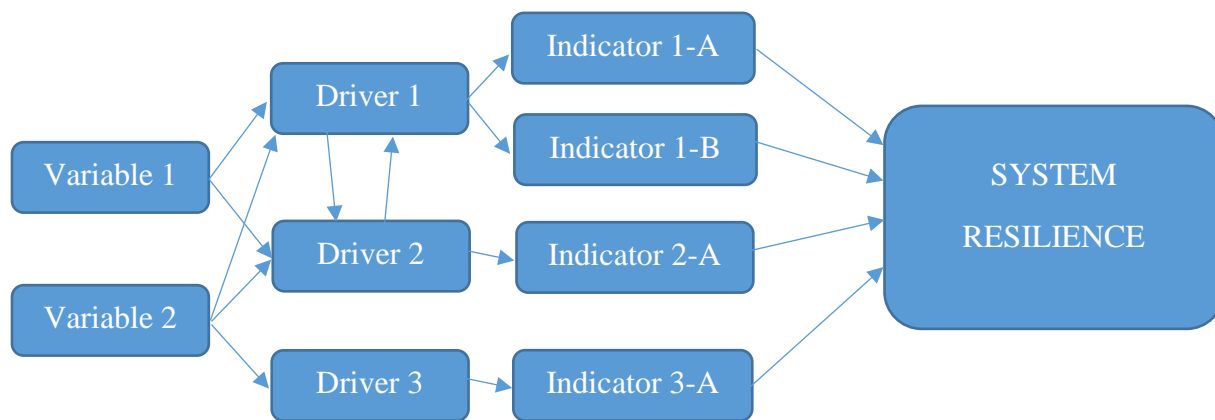


Figure 6. Simplified outline of a resilience web. Outside variables influence drivers, the stabilizing capacity of which are represented by indicators. Each relationship (represented here by arrows) can be modeled and any changes can be monitored and managed appropriately.

5.4. Adaptive Management

A successful resilience management program will be adjusted as frequently as possible in response to changes in system dynamics as expressed in the various models. Managers can tailor their programs to the specific dynamics of their management areas which contribute to resilient systems, placing limits on variables which significantly impact critical resilience drivers. The

ability to analyze scientific models for the development of agency policies and management actions is a crucial skill for anyone attempting to implement a resilience management program. As changes to resilience indicators are observed, management can reallocate resources to the driver(s) affecting those indicators as needed. Resilience monitoring with adaptive management also streamlines the program evaluation process by providing hard evidence of whether or not goals and objectives have been achieved.

Adaptive management can also provide a framework for achieving regulatory compliance—by accurately monitoring the outside variables affecting the system’s resilience, it can be determined whether or not regulations are being followed by the human components of the system. For example, if pollution from a coastal resort is affecting ecosystem health (which can be noted by observing changes in resilience indicators), managers can direct stakeholders to reduce discharges in order to comply with applicable laws and regulations. Continued monitoring will allow scientists and managers to determine if the variable (pollution) is being reduced, and whether the reduction is beneficial to system resilience as evidenced by indicator monitoring. The program can then be adjusted in order to find a balance between the resort’s economic goals and the continued resilience of the affected SES. This general adaptive process is already well-established in environmental management literature, though it is rarely utilized for practical application (Levin et al. 2009, Briske et al. 2008, Plummer & Armitage 2007, Salm & Clark 2002, Walker et al. 2002), and it fits well within the framework of resilience management.

5.5. Stakeholder Involvement

As previously mentioned, it is essential to involve as many affected stakeholders as possible into a resilience management program. Using the terminology of resilience thinking, management actions can be communicated to stakeholders clearly, and the outcomes of management actions

can be carefully monitored. Doing so will lead to a clearer and more open dialogue about marine management wherein programs can be constantly reevaluated, adjusted, and adapted in order to preserve system resilience in the long-term. This high level of oversight which includes quantifiable, easily understood representations of system components will likely prove attractive to stakeholders concerned about protecting their private economic interests as well as sustaining marine systems.

Most marine protected areas in the United States are already co-managed by multiple agencies which consult with stakeholders in the public, private, and nonprofit sectors (NOAA 2014). Maintaining and improving upon this high level of cooperation will streamline the process of developing a widely understood resilience lens for achieving management goals. Because resilience focuses on both human and natural components of the systems, it allows for an open dialogue on the tradeoffs between economic development and environmental protection. Compared to traditional methods of spatial zoning and command-and-control regulations, the resilience approach can help to foster better connections between stakeholders, improve regulatory compliance, and achieve more holistic strategies for the management of MPAs.

5.6. Educational Outreach

The final aspect of a resilience management program is the development of strategies for educating the general public about basic SES dynamics. Using resilience as the crux of the EBM process is less vague and more unified than the often-disparate EBM goals and criteria currently utilized in U.S. MPA's (Levin et al. 2009, Ruckelshaus et al. 2008, Leslie & McLeod 2007, Arkema et al. 2006). A public information program can be developed—optimally in cooperation with environmental advocacy groups—in order to convey resilience concepts and the importance of achieving sustainable SESs to voters, activists, and communities at large. This will generate

support for the diffusion of resilience thinking and associated innovative management strategies through a wide variety of channels. This could prove promising for the continuance of research in resilience concepts and ecosystem-based management strategies in the coming years.

6. Conclusion

The development of a social-ecological systems framework which views human and natural ecosystem components holistically holds promise for the future of environmental management and sustainable development. Marine systems, especially, can be readily conceptualized as complex adaptive systems with identifiable drivers of system resilience. These drivers are affected by outside variables—both direct human impacts such as pollution and overfishing and slower variables such as climate change. Recent research in ecosystem-based management for marine protected areas in the U.S. has led to the development of a variety of holistic management programs, but the goals and criteria for achieving EBM remains inconsistent in the literature and in practice. Focusing on resilience as the key component of marine environmental management can help to unify the disparities found in EBM, and may lead to more sustainable policies for MPAs. A resilience-based integrated ecosystem assessment and subsequent management plan grants managers the ability to determine which resilience drivers are in danger of decreasing, analyze which variables are contributing to this decrease, and formulate a strategic plan for managing these variables. After reviewing current research and practice for marine management, and studying three National Marine Sanctuaries in depth, I recommend that managers working with MPAs in the U.S. begin incorporating resilience management into their programs, as outlined in Section 5 of this paper. Evaluation of such programs, along with further research into SES dynamics and marine systems resilience, will provide guidance as to how specifically to pursue a resilience-based strategy for marine EBM in the future.

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