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Review

Science in support of ecosystem-based management for the US West Coast and beyond

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ABSTRACT

Declining ocean health, increasing human demands on marine ecosystems, and a history of management focused on individual activities, species or sectors has led to calls for more comprehensive, integrated management that considers entire coupled social-ecological systems. This transition to ecosystem-based management (EBM) for the oceans will certainly face a number of hurdles, and many practitioners struggle with how to move forward with EBM. In this paper, we assess whether the necessary science exists to support EBM. Specifically, we evaluate the state of the social and natural sciences for three research areas that are critical to EBM: (1) ecosystem services, (2) cumulative impacts, and (3) ecosystem variability and change. For each of the three research areas, we describe its importance to EBM and assess existing and emerging information and application of this knowledge, focusing on the US West Coast. We conclude that available science is not the bottleneck for moving forward with comprehensive EBM for this region, although we highlight important remaining knowledge gaps, particularly within the social sciences. Given imperfect and uncertain knowledge, EBM calls for an adaptive management approach, starting with readily available information, and continuously adapting as new information emerges. This synthesis can serve as a basis for comparison for other regions; it provides guidance for organizing information in support of EBM and outlines many novel and broadly applicable scientific approaches.

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1. Introduction

Coastal and marine systems are affected by numerous existing human uses (from recreation to fishing to oil extraction) and emerging uses (offshore aquaculture and alternative energy such as wind or waves), as well as impacts from atmospheric and land-based pollution, habitat degradation and destruction, and climate change (Gewin, 2004; Harley et al., 2006; UNEP, 2006; Halpern et al., 2008b). Acting in concert, these impacts can decrease the continued ability of marine ecosystems to provide the ecosystem services that sustain our lives. Furthermore, there is a historical legacy of piecemeal management that has largely focused on single sectors of activity and failed to consider marine ecosystems as interconnected wholes (POC, 2003; USCOP, 2004; Crowder et al., 2006). As a result, local, state, regional, and national bodies around the world are seeking to improve ocean management by implementing more integrated ecosystem-based approaches.

Ecosystem-based management (EBM) is place-based, considers connections within and among ecosystems (including a balanced and integrated view of social and natural components), and focuses on maintaining the long-term ability of ecosystems to deliver a range of services (Grumbine, 1994; McLeod et al., 2005; Rosenberg and McLeod, 2005). A shift to EBM requires management actions across a range of spatial scales and attention to connections among spatial as well as governance units. Notably, there is no single correct scale at which to employ this approach (McLeod and Leslie, 2009). In some cases, the greatest momentum for change will be generated by local-scale, bottom-up endeavors. Such efforts offer great promise, but larger-scale plans with political and legal backing can enhance both consistency and accountability (Rosenberg and Sandifer, 2009). On the US West Coast, there is an emerging network of local-scale EBM efforts (www.westcoastebm.org: San Juan County, Washington; Port Orford, Oregon; Humboldt Bay, Elkhorn Slough, Morro Bay, and Ventura, California). These local-scale efforts benefit from being able to effectively engage local communities, yet they lack the purview to cope with larger scale issues or to manage for ecosystem services that are produced over larger scales. Thus, in addition to supporting local-scale initiatives, there is a need to implement larger-scale EBM across California, Oregon and Washington (the US states within the California Current Large Marine Ecosystem) with an explicit consideration of connections among scales. The creation of bio-regional, state, or interstate programs would both build upon and benefit local initiatives, recognizing that ecological and social systems occur across multiple, interconnected scales.

EBM represents a departure from single species or single sector management, focusing on the full range of benefits provided by coasts and oceans (i.e., ecosystem services) and the inherent trade-offs in our management of the many activities that affect these systems. Many of the tenets of EBM are not new, but rather build upon other approaches to natural resource management such as integrated coastal management (Cairns and Crawford, 1991; Cicin-Sain and Knecht, 1998). Furthermore, the transition to EBM may often be through incremental progress, for example, the trend within fisheries management to move from single species management to multi-species or ecosystem-based fisheries management (EBFM), with these gradual steps offering guidance for more comprehensive EBM (Field and Francis, 2006; Marasco et al., 2007; Murawski, 2007; Levin et al., 2009). Regardless, a shift to EBM will face political, legal, social, and scientific hurdles (Leslie and McLeod, 2007; Ruckelshaus et al., 2008). For the purposes of this paper, we set aside all non-scientific hurdles in order to assess the availability of scientific information and understanding and in turn the degree to which science is a limiting factor to moving forward with EBM along the US West Coast.

We assess the state of the science for three critical research areas, with particular attention paid to science specific or relevant to the California Current region: (1) ecosystem services, (2) cumulative impacts, and (3) ecosystem variability and change. While other scientific topics are certainly relevant, these three research areas are particularly central to an EBM approach (Table 1). Given that EBM considers the ecological and human systems as inextricably linked, our key themes all include important human and natural science dimensions. Thus, we deliberately take an integrated look at the natural and social sciences, but draw particular attention to future research needs in the social sciences because these fields tends to lag those of the natural sciences. We focus our assessment on recent and emerging scientific advances, describing the relevance of each of the research areas to EBM and assessing existing information and application of this knowledge along the US West Coast.

2. Ecosystem services

The core goal of EBM is to maintain healthy ecosystems capable of providing a range of benefits (McLeod et al., 2005). Collectively referred to as ecosystem services, these benefits, including food, recreational opportunities, and shoreline protection, are declining or seriously compromised in coastal and ocean ecosystems around the world (UNEP, 2006). Managing for the long-term delivery of a range of ecosystem services, rather than single services, requires assessing: (1) What services does society want and need? (2) How are they distributed in space? (3) What are the economic val-

Table 1
Three key scientific research areas and their relevance to ecosystem-based management.

Research area	Relationship to EBM
Ecosystem services	EBM is a means of achieving the long-term delivery of a suite of ecosystem services, rather than single services. Services provide a critical currency to link human and natural systems, and enable socially desired (or valued) outcomes
Cumulative impacts	EBM focuses on the collective impacts of all key human activities and environmental change on ecosystem health, requiring means for assessing and understanding interactions among various impacts over space and time
Ecosystem variability and change	Managing with a long-term view requires an understanding of the range of variability in the ecological and human systems, in addition to the potential for directional changes, such as climate change

Note: Throughout this paper, we use “ecosystem” to mean a coupled natural–human system.

ues of those services? and (4) How can we explicitly assess trade-offs among them?

2.1. Identifying and quantifying key services

Identifying key services in a region provides a clearer picture of which sectors need to be included in an EBM approach and where existing management may be overlooking important interactions among sectors. For the California Current ecosystem, key services include fisheries (commercial, recreational and subsistence), aquaculture, shoreline protection and other regulating services, supporting services such as spawning and nursery habitat for fishery species, energy (wind, wave and tidal), recreation, tourism, cultural significance, and aesthetic value.

Once key services have been identified, it is helpful to assess the biophysical quantities and spatial distribution of services. Some services can be quantified directly if imperfectly (e.g., fisheries), while others require more indirect measurements (e.g., shoreline protection, for which one would measure aspects of the ecosystem that affect wave condition and consequently shoreline erosion). Spatially explicit data on the distribution or value of these services across the US West Coast are typically scarce or difficult to access and interpret. There are extensive sources of biophysical data that estimate the production of some services, such as fisheries, but in most cases these examples do not incorporate aspects of delivery, such as demand or the availability of local markets, much less the well-being of associated human communities.

We tend to have extensive records of the distribution of fish or larvae from programs like CalCOFI and NOAA Fisheries surveys or state fishery agencies (e.g., Bellman et al., 2005). In contrast, commercial fishery landings data, which include information on the volume and ex-vessel value of the catch, are recorded at relatively coarse and ecologically inappropriate spatial scales for reasons that range from concerns for confidentiality of fishing locations to constraints on agency data quality and management. The contrast in insight gained from high resolution landings data that are located by vessel monitoring systems (e.g., Murawski et al., 2005) versus coarse management block data is striking. However, these data are but useful starting points that require additional information and analysis to be translated into economic and social value to people and thus be relevant to management decisions. For example, NOAA’s Northwest Fisheries Science Center has been developing community profiles that characterize US West Coast coastal communities’ engagement in and reliance on fisheries (Norman et al., 2007), data which begin to address this critical link.

2.2. Mapping services

A few recent studies have started to make the connection between ecological and social systems to actually map ecosystem services for the US West Coast, including the California Ocean Uses Atlas Project, which is working to map significant human uses of state and federal marine waters throughout California (http://mpa.gov/science_analysis/atlas.html). The most highly resolved data come from a global map of human impacts to marine ecosystems (Halpern et al., 2008b) and a similar, higher-resolution version (although a higher resolution map does not necessarily mean higher resolution datasets) for the California Current, discussed in more detail in the following section (Halpern et al., 2009). Many of the activities included in this impact assessment are also directly connected to service provisioning. For example, the database provides estimates of the intensity and distribution of subsistence, recreational and several commercial fisheries for the entire California Current system. These data are not landings by species, nor are they economic values associated with landings, and many of the datasets used for these maps are of insufficient spatial resolution to inform management, but they do give a relative sense of the intensity of fish production services in the region. Furthermore, it may be straightforward to connect these spatial maps with non-spatial data on landings and value to map service provision. For example, Leeworthy and Wiley (2002) conducted spatially explicit analyses of commercial and recreational fisheries to evaluate the potential social and economic impacts of marine protected areas at the Channel Islands. In another effort, Ecotrust has combined trawl logbook (indicating fishing locations) and fish ticket data (documenting landings and their ex-vessel value) to create spatially explicit maps of groundfish trawl activity annually from 1987 through 2000 (Scholz, 2003). Although imperfect, such data are a useful start toward assessing the associated social systems and how social well-being is affected by changes in service provision, or how changes in well-being and other factors may translate into changes in service use.

Comprehensive data for services beyond fisheries are only available as coarse spatial estimates at the state or county level, or at higher resolutions for small sub-regions of the California Current. Annual state-level estimates of economic value are available for beach-going, recreational fishing, marine bird life viewing, and (for California only) scuba diving and snorkeling (Pendleton, 2008). These values combine activity estimates from the 2001 National Survey of Recreation and the Environment with economic value estimates from the literature for each appropriate region. This report also references many site-based estimates for individual services that may be useful at smaller scales. NOAA has also assessed the value of total aquaculture sales in 2005 at the state level (Forster and Nash, 2008), although these estimates include values for freshwater farmed species (e.g., catfish) along with marine species (e.g., oysters, salmon). The National Ocean Economics Program (http://noep.mbari.org) compiled data from Bureau of Labor Statistics into a database that allows users to search for annual contributions of ocean or coastal-based activities, including tourism, recreation, fisheries and transportation, to the economy at county and state scales. These estimates have important flaws, including underestimating fisheries employment and accruing value to land-based counties rather than showing where in the ocean these services are derived, but they provide useful starting points for some services. Lastly, there are some more regional efforts, such as documentation of social, cultural and economic baselines for fisheries and non-consumptive uses for sections of the California coast as part of the Marine Life Protection Act process (e.g., Petterson, J. and Glazier, E., unpublished data).

Collectively, mapping exercises for the California Current have focused primarily on fisheries, with some useful information for tourism and aquaculture. These maps suggest locations where multiple ecosystem services are delivered and thus where conflicts in management are likely to arise and where addressing multiple objectives is most critical. They can also identify which sectors overlap in space most often, and as a result, need to be engaged in coordinated management at the regional scale (Ekstrom et al., 2009). However, these data are not at a high enough spatial resolution to inform many of the decisions made by state or local managers or to evaluate interactions among ecosystems services at the sub-regional scale. For example, most existing fishery data were designed to inform single sector management and are difficult to apply to an EBM context, as demonstrated by interactions between shoreline protection by kelp beds and rockfish fisheries, a pair of services with the potential for positive interactions. Some juvenile rockfish use kelp beds as nursery habitat, but the majority of data on rockfish relate to adult landings further offshore. In addition, the role of kelp forests in protecting coastal communities from storm surge has not been documented across the region. Information at the scale of key ecosystem service interactions is essential for state and local managers to identify areas of most intensive conflict or synergy at the scale of their jurisdiction.

2.3. Service valuation

In order to connect information on the supply and spatial distribution of ecosystem services to management decisions, it is important to be able to assign socio-cultural and economic value to services. Both market and non-market based methodologies can be used to determine the economic value of services, and there is an extensive literature addressing valuation methodologies (e.g., Grafton et al., 2001; Freeman, 2003; Mäler and Vincent, 2005). There has been some progress on this front for the US West Coast. Market valuation has been used most commonly, particularly for fisheries production. Examples include the Ecotrust mapping of commercial fishing grounds in central and northern California to inform the placement of Marine Protected Areas (Scholz et al., 2006), the NOAA aquaculture report reviewing the production and value of aquaculture in the United States (Forster and Nash, 2008), and the National Ocean Economics Program database offering market data for a variety of services including tourism, shipping, and fisheries (http://noep.mbari.org/Market; note caveats cited above).

Examples of non-market data sources for the West Coast can also be found in the National Ocean Economics Program database, including value estimates for clean beaches, wildlife viewing, recreational fishing, and snorkeling. Benefit transfer analysis, whereby information on monetary benefits is extrapolated from other cases, has been widely used in this region to value services, including several small-scale ecosystem service valuation exercises (Troy and Wilson, 2006) and the only West Coast-wide valuation of non-fisheries services (Pendleton, 2008). However, this method is controversial (Wilson and Hoehn, 2006; Plummer, 2009). Although there tends to be mistrust of non-monetary value metrics (e.g. measures of human well-being or social welfare), they may prove more useful than economic values derived from benefit transfer approaches and represent an important future research avenue for the California Current region.

One approach that can be applied to both economic valuation and making strategic decisions is production theory. Production functions show the relationship between inputs, such as fertilizer and labor, and outputs, such as crop production. The same types of relationships also exist between natural inputs, such as the extent of wetlands, and ecosystem services, such as water filtration (NRC, 2004). In cases of natural ecosystem services, production functions are essentially dynamic models that translate the structure and functioning of ecosystems into the provision of ecosystem services (Daily and Matson, 2008). In many cases, we have a limited understanding of the ecological production functions of ecosystem services and thus how much natural capital will be gained or lost as the condition of land or seascapes change. We often know how ecological processes change in response to human actions, but we still need to make the link to human well-being (Tallis and Kareiva, 2006), better recognizing that humans are an integral part of ecosystems (NOAA, 2005). A clear framework for how such production function models can be developed, even in data-poor situations, is described elsewhere (Tallis and Polasky, 2009).

2.4. Evaluating trade-offs among services

EBM ultimately must strive to balance the delivery of multiple services because it is not possible to simultaneously maximize the delivery of all services (Barbier et al., 2008; Halpern et al., 2008a; Tallis et al., 2008b). Identifying and evaluating trade-offs among management options provides a direct link between ecosystem services and decision-making and has the potential to reveal the benefits of an EBM approach for the full suite of services provided by the ecosystem. One means to visualize the relationships among services and make decisions about trade-offs is to apply economic decision theory in an ecosystem services context (Lester et al., in preparation). Considering two (or more) services, one can create a graph with the axes corresponding to levels of ecosystem services and each point representing a given set of management actions that are known (or estimated) to produce the amount of each service indicated by that point on the graph. The outer bound of all the points is the “efficiency frontier” and represents the optimal delivery of the two or more services, given a set cost of management (for terrestrial applications, see Nelson et al., 2008; Polasky et al., 2008). For example, in response to deliberations over California’s Marine Life Protection Act, one can apply this visual approach to explore trade-offs between fishery yield and system-wide fish biomass (i.e. conservation) under any given fishing scenario (including or not including a network of marine protected areas). Each point on the graph in Fig. 1 corresponds to a spatially explicit fishing policy; the efficiency frontier is the outermost envelope of those proposals.

The relationship between services (i.e., the shape of the frontier) can narrow the scope of potential policy decisions and reveal when single sector management may be adequate and when it is likely to fall short. For instance, trade-off analysis may show that there is no interaction between the two services of interest, meaning that one can be managed with no impact on the other. When trade-offs do exist, this approach can reveal the severity of the trade-offs and critical threshold points. In addition to identifying the services likely to be most contentious and difficult to manage jointly, trade-off analysis can demonstrate the long-term benefits of employing a comprehensive EBM approach. Examining management options in the trade-off space reveals which management options are suboptimal (interior to the frontier), suggesting where changes to management may provide society with similar or even greater gains with lower costs and less conflict. For example, increased forage fish biomass left in the ocean for higher trophic levels may be achievable with no cost to fishery profit, an outcome which is unlikely to be realized in a single sector management context.

The primary obstacle to applying ecosystem service trade-off analysis in real management situations and populating the trade-off graphs is the availability of models capable of predicting service

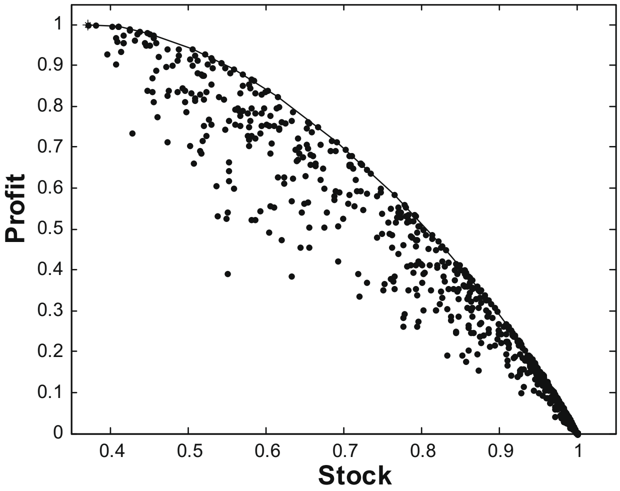

Fig. 1. The trade-off between system-wide fish biomass (horizontal axis) and system-wide fishery profit (vertical axis) for a harvested, spatially-explicit metapopulation. Fishery management is composed of patch-specific harvest levels, including the possibility of marine reserves in some patches. The solid line indicates the efficiency frontier and points represent biomass-profit combinations from randomly designed marine reserve networks. Modified with the authors' permission from Lester et al. (in preparation).

delivery now and into the future. The Natural Capital Project is developing a tool, Integrated Valuation of Ecosystem Services and Trade-offs (InVEST), that uses a production function approach to model and map the delivery, distribution and economic value of ecosystem services, both under current and future management scenarios (http://www.naturalcapitalproject.org/InVEST.html). InVEST was explicitly designed to handle different levels of data and output complexity, resulting in a tiered approach that is adaptable to a wide range of situations and end users. Thus far, InVEST has been developed exclusively for terrestrial settings (Nelson et al., 2009), but development of marine models is underway, focusing on fish production, coastal protection and recreation (Ruckelshaus and Guerry, 2009).

Finally, ecosystem services represent a dynamic connection between social and ecological systems. It is important to understand how humans respond to changes in the price of commodities derived from ecosystem services (e.g., the price of fish), changes in access (e.g., beach closures due to polluting events), or changes in aesthetics (e.g., loss of coral cover at a dive destination) and how these responses are mediated by social and cultural values. Furthermore, human responses in turn affect the ecosystem, creating the potential for complex feedbacks and dynamic social-ecological interactions. Unfortunately, knowledge of social responses to changes in services is sparse compared to data on people as drivers of change. However, there are a few well documented cases for the US West Coast. For example, the sharp cuts in allowable catches of West Coast groundfish led to $5 million in federal disaster relief allocated to California, Oregon and Washington. While this is not a direct measure of the full range of social effects of declining groundfish fisheries, it provides a starting point for understanding the effects of changes in fisheries on coastal communities (Conway and Shaw, 2008). As another example, California market squid became very scarce during the 1997–1998 El Niño, effectively undercutting the viability of squid, then the state's top fishery, in international markets. When squid rebounded strongly in late 1999, the fishery was very productive. However, demand for California product had weakened significantly when the fishery could not supply established markets, creating considerable upheaval in the fishery, including excessive competition for buyers and social conflict (Pomeroy et al., 2002). Cuts in allowable catches, combined with legislative changes that reflect changing societal values, have also contributed to efforts to reform governance institutions, including steps toward "fishery ecosystem plans," as exemplified in a pilot project for the Aleutian Islands (NPFMC, 2008). As an example of social responses to changes in a non-fishery service, the Puget Sound Partnership was formed in 2005 to address multiple issues including pollution and habitat degradation (Ruckelshaus et al., 2008), and numerous other groups and initiatives have formed to restore coastal and marine environments in response to declining services.

2.5. Future research directions

The information described here regarding ecosystem services suggests we have a considerable body of scientific knowledge for the California Current and beyond that can be applied to improve or facilitate the implementation of EBM, but also points to useful future research directions. For one, we need more information on the distribution, flow and value of services beyond fisheries, and indeed beyond the value and volume of fisheries production. Additionally, for all types of services, we have relatively little data on how the state of the system relates to ecosystem services, or production functions. Information about the range of factors affecting service delivery is particularly important if we are to apply the trade-off framework described in this section. Trade-off analyses would also be improved if we were able to develop robust means for assessing and valuing non-market services. Monetary valuation methods are often the approaches most trusted by the general public and decision-makers, but there are many non-market services that are better assessed with non-monetary metrics. Indeed, monetary valuation methodologies tend to be imprecise and inappropriate for capturing the broader range of non-market social and cultural values, perceptions and beliefs that affect behavior and thus the ultimate value of services. Finally, our understanding of how changes and fluctuations in ecosystem services affect the social components of the ecosystem is relatively poor compared to our understanding of humans as drivers of change in ecosystems. If we are to manage the California Current or any ecosystem as a linked social-ecological system, we need to understand all aspects of this linkage.

3. Cumulative impacts

Multiple human activities affect the marine environment and its associated human systems in complex ways, yet current management tends to consider each activity separately (POC, 2003; USCOP, 2004; Crowder et al., 2006; Halpern et al., 2008a). For example, fisheries, water quality, coastal development, land use, shipping, and oil and gas extraction are each managed as individual sectors despite obvious potential interactions among them (Crowder et al., 2006). Assessing the potential for cumulative impacts of multiple activities on the oceans produces a picture of the world quite different than that which emerges from single-sector assessments (Halpern et al., 2008b). Therefore, EBM seeks to manage for the cumulative impacts of all key activities on ecosystem health in a specific place.

Management efforts to address cumulative impacts require assessing: (1) What is the spatial distribution and variability of important ecosystems and their key services? (2) Where do impacts occur and what is the intensity or magnitude of these impacts? and (3) How do human and non-human ecosystem components respond to the combined effect of these impacts? We addressed the first question in the previous section. Data to address the second question are often widely available but rarely assembled in a common format or database to allow for easy analysis and comparison. Recent efforts have assembled these data globally (Halpern et al. 2008b) and for regions such as British Columbia (Ban and Alder, 2008) and the California Current (Halpern et al., 2009). However, information to conduct the third question, impact assessment (for both ecological and human systems), is much rarer, although there are methods using expert opinion that can estimate relative ecosystem impacts (Halpern et al., 2007; Teck et al., 2010). Only after those impacts ((2) above) are identified can social and economic impact assessments (3) take place. We briefly outline existing information and applications to the US West Coast for both steps below.

3.1. Mapping and quantifying ecosystem impacts

Climate change, commercial fishing, and invasive species are presently the key sources of potential or realized change (based on current prevalence and ecosystem vulnerability) to California Current ecosystems across many scales (Halpern et al., 2008b, 2009; Teck et al., 2010). In nearshore areas, land-based sources of pollution and habitat modification also top the list in terms of their overall magnitude, i.e. the summed intensity of the impact across all locations in the region. Not surprisingly, the greatest magnitude of and overlap in impacts occur in coastal areas near large urban centers, primarily in southern California, San Francisco Bay, and Puget Sound. There are also spots of very high impact in southern Oregon where land-based stressors, fishing, and climate change combine to heavily impact coastal ecosystems (Halpern et al., 2009).

Maps of the intensity of stressors provide baseline information about where, for example, areas of low and high stressor input occur and where and to what extent particular combinations of stressors co-occur. If species and ecosystem vulnerability are also included, these maps of intensity can be translated into maps of predicted impact (which could then be verified with ground-truthing surveys). As an example, there is an uneven distribution of pollution inputs into the seascape – different patterns of agricultural, animal farm, and urban land use lead to highly patchy distributions of nutrient, organic, and inorganic pollutants into watersheds along the West Coast – and there are key differences and similarities in the input of these different land-based pollutants (Fig. 2). With such a map, a manager honing priority protection strategies could target specific coastal marine areas for protection. One strategy could be to target areas for protection that are relatively unaffected by land-based stressors. Another might direct mitigation towards upland pollutant sources for important coastal regions with existing or imminent threats. The former uses the intensity maps to identify the remaining healthy settings. The latter requires a more functional knowledge of the connections between locations and the nature of actual impact from pollutants (i.e. ground-truthed estimates of ecosystem change) to reduce the impact status of key places.

Another use of impact distribution maps is to examine the number of overlapping impacts in an area given that interactions among multiple activities or impacts may be complex and thus should not be ignored within an EBM context. Recent synthetic research showed pairwise combinations of impacts lead to additive responses, synergisms (the whole is greater than the sum of the parts), and mitigative responses (the whole is less than the sum of the parts) in approximately equal proportions (Crain et al., 2008). Importantly, adding a third stressor made the interactions 'worse,' suggesting that synergisms likely predominate in nature. Consequently, management needs to account for these synergisms,

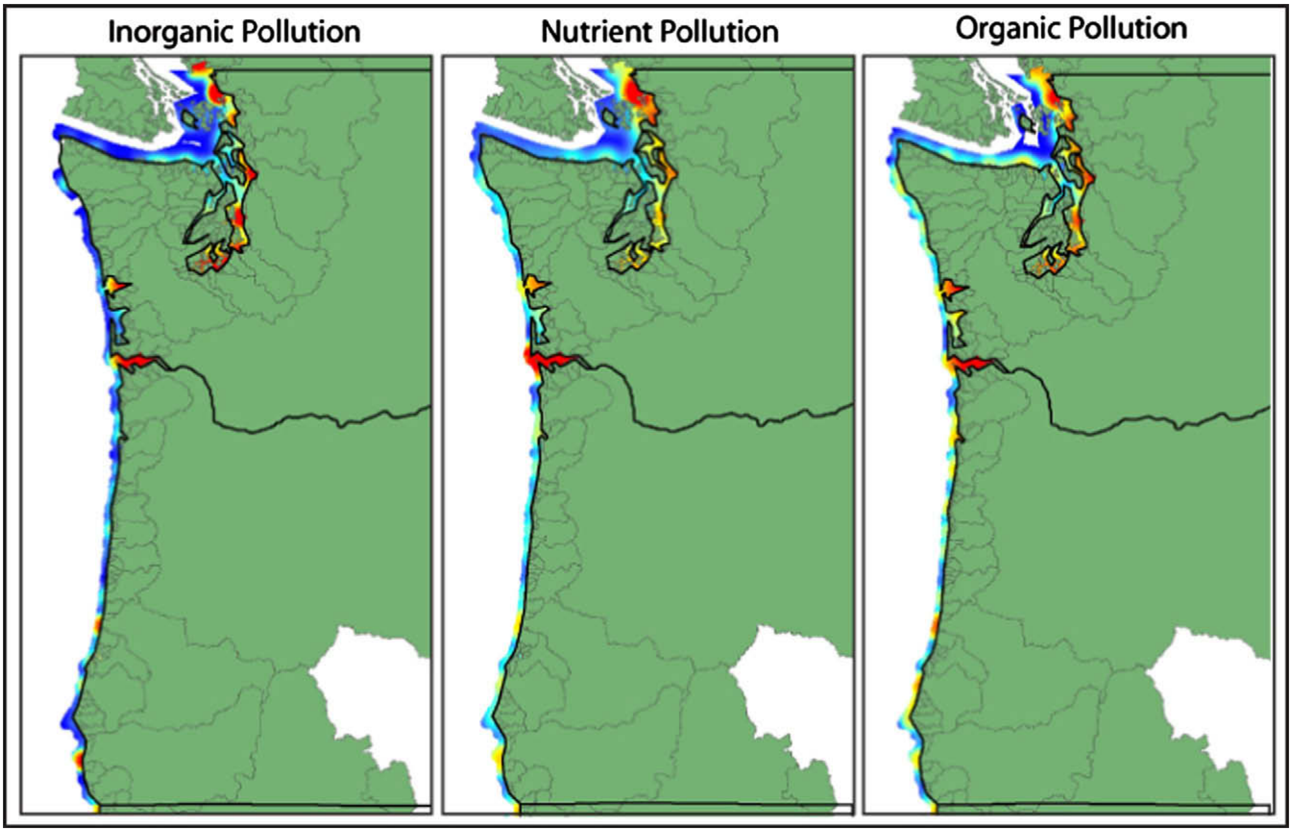

Fig. 2. The footprint (location and intensity) of three different types of land-based pollution in coastal marine waters of Washington and Oregon. Colors represent highest (red) to lowest (blue) amounts of pollution plumed into the water. Green areas on land are watershed boundaries. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

perhaps by limiting the number of co-occurring activities. The presence of synergies also suggests that efforts to mitigate threats may lead to greater than expected returns from removing a threat and thus its synergistic interactions with other impacts, although in some cases threat mitigation could have unintended and even negative consequences (e.g., removing low levels of nutrient input can decrease productivity and make a system more susceptible to other impacts).

In the California Current ecosystem, we can use impact distribution maps to examine these issues. For example, in San Francisco Bay, coastal development, polluted runoff from land, invasive species, noise and light pollution, recreational fishing, decreased sediment input, marine debris (trash), and port-based pollution all have relatively high intensities and overlap in space, and thus have the potential to produce synergistic effects. Collaborative exercises in mapping impacts, such as participatory modeling, can also be beneficial for managers and stakeholders, as shown with water management in the San Francisco Bay area (Van Eeten et al., 2002). Impact maps suggest which management sectors are important to engage in coordinated place-based management strategies or recovery plans for imperiled ecosystem elements.

3.2. Ecosystem consequences of cumulative impacts

After considering the spatial overlap of impacts, the next step is to evaluate their consequences for ecosystem health and the subsequent delivery of services. Such an analysis involves assessing how a suite of potential threats and drivers collectively affects the delivery of ecosystem services. Information for estimating impacts of activities and other stressors is scarce for the US West Coast at the spatial scales appropriate for management decisions. For instance, in order to ascertain whether high nutrient loadings in San Francisco Bay or the Columbia River mouth are worth priority attention, information is needed on the vulnerability of the ecosystem (e.g., phytoplankton species present, degree of nutrient limitation in the system, stratification and other mixing dynamics of nearshore oceanography) and observed impacts (e.g., low dissolved oxygen events, fish or invertebrate die-offs, shellfish bed closures to protect human health). One of the challenges in estimating ecosystem vulnerability is that different ecosystems or habitats may be uniquely vulnerable (or insensitive) to each human stressor, creating thousands of possible combinations for which little empirical information exists. For example, two nearshore kelp forest sites receiving the same nutrient loadings could have very different ecosystem responses because of a variety of biophysical and social characteristics. Priority actions should focus on areas of greatest cumulative impact, rather than threat magnitude alone. Some of these differences can be ascertained through simple rules-of-thumb – kelp forests in upwelling zones will be more resilient to nutrient input than those in more oligotrophic waters – while others may require some preliminary surveys of kelp vulnerability to help develop a predictive spatial model.

A key component of understanding, managing for, and ultimately mitigating cumulative impacts is identifying the underlying causes of ecosystem impacts. These causes include both general “drivers” such as climate change or increased demand for seafood, and specific ‘‘pressures” such as the effect of sea surface temperature change on biota or the effect of seafood harvesting on fish populations and ecological communities (Carr et al., 2007). Based on census, economic, and other data sets, it is feasible to develop assessments of anthropogenic drivers and pressures, although the data are rarely collected for the purpose of EBM and thus often are not available at the most appropriate scales or resolution. It is even more challenging to capture the more fundamental causes of human activity, including the social, political, cultural, and ethical dimensions that shape human motivations, patterns and levels of demand, and the distribution of power and wealth.

Location-specific case studies can help discern the actual linkages, synergies, and feedbacks among drivers and pressures that ultimately affect the state of ecological systems. For example, in 2000, 77% of California’s population lived in coastal counties, which represent 25% of the land. But this trend may be changing. Between 1990 and 2000, California’s coastal population grew more slowly than the overall state population (11.3% and 13.7% population growth, respectively). Areas of highest population growth were the inland areas immediately adjacent to the coast, where land was more available and less expensive (Kildow and Colgan, 2005). These changes in population density can potentially have important effects on the environment, including changing patterns of pollution events and increasing the demand for numerous marine ecosystem services. Ultimately, however, knowledge of the social drivers and pressures on ecosystems must be paired with an understanding of the effects, in turn, of environmental changes on the social system. These effects can be assessed using social impact assessment (SIA), the systematic appraisal of impacts on the day-to-day quality of life of persons and communities whose environment is affected by change (Burdge, 2008). Unfortunately, many regions, including the California Current ecosystem, lack such studies.

3.3. Implications for marine spatial planning

Taken together, information about the location, intensity, and cumulative impact of multiple human activities and an understanding of the social drivers of these impacts can inform marine spatial planning. Some activities are simply incompatible, as with military zones and fishing and shipping (for security and safety reasons), while many others lead to high cumulative impact when they co-occur (Halpern et al., 2009). Spatially separating such activities is one tool for minimizing negative interactions among activities while still allowing them to occur to the greatest extent possible. Although there is not currently a legislative mechanism or executive mandate for comprehensive spatial management along the West Coast, it is increasingly advocated by some (Sivas and Caldwell, 2008). Indeed, spatial management is already occurring (albeit piecemeal) in the California Current and elsewhere (Crowder et al., 2006).

3.4. Future research directions

There are remaining gaps in efforts to understand cumulative impacts that, when filled, will help inform spatial management and EBM more generally. Most notably, long-term ocean health requires planning for future levels of human activities as well as better predictions about how different management options will affect these levels. Such forecasting and management scenario analyses have been done for (1) single human activities, such as spatial planning for land-based pollution (Tallis et al., 2008a) or management strategy evaluation for fisheries (forecasting population dynamics under different harvest strategies; www.psmfc.org), (2) single issues, such as the International Panel on Climate Change (IPCC) forecasting (IPCC, 2007), and (3) climate change impacts and restoration efforts interacting to affect a key service like salmon production (Battin et al., 2007). These efforts provide a useful foundation to proceed with cumulative impact forecasting for multiple activities and ecosystems. Extending this foundation into more comprehensive forecasting of cumulative impacts will require the following combination of scientific advances, many of which are underway: (1) better single-issue forecasting models for all human activities that affect ocean health, (2) fully integrated and dynamic models for coupled ecological-socioeconomic systems, and (3) better understanding of how different stressors interact with each other. Furthermore, forecasting efforts need to better incorporate assessments of impacts to the human system. Understanding human motivations and responses, individually and cumulatively, is equally important to understanding ecological responses. Filling these knowledge gaps will greatly improve our ability to predict the ecological and social outcomes of different management and zoning scenarios.

4. Ecosystem variability and change

Ecosystem-based management not only aims to maintain the current delivery of a suite of ecosystem services, but also to ensure the long-term sustainability of the underlying system and its services. Managing with this long-term view requires understanding the natural variability within ecosystems and the potential for directional ecosystem changes, such as those resulting from climate change. Some changes will be predictable or gradual, while others will be abrupt and unexpected, requiring EBM to be adaptive as well as precautionary. From a scientific perspective, we need to better understand the range and variability of large-scale and long-term changes, whether physical, biological, or socioeconomic, in order to successfully manage human interactions within ecological systems into the future.

4.1. Environmental variability

There is growing awareness that environmental variability plays a dominant role in the structure and functioning of marine ecosystems and that this variability is much greater than previously thought. Here we define the term climate variability to include variations in the earth's natural rhythms and the term global change to include anthropogenic inputs to climate (global warming and associated climate) as well as the cumulative and global effects of other activities. Examining environmental variability for the California Current ecosystem reveals a coastal ocean that continuously fluctuates between warmer than the mean to colder than the mean and back. In other words, it is seldom average and interannual variability is as strong or stronger than seasonal variability (Parrish et al., 1981). The region is often partitioned into three domains: a) the Pacific Northwest (including northern California) with strong storms and high runoff in the winter and summer upwelling, b) central California with spring and summer upwelling and typically dry conditions, and c) the Southern California Bight, a large and relatively stable "upwelling shadow". Coastal topography strongly modifies oceanographic processes along the US West Coast and in fact these domains roughly correspond to the major capes along the coast (Cape Blanco, Cape Mendocino, Point Conception; see Francis et al., 2008). In the coastal upwelling region, the existence of smaller scale capes and bays results in significant alongshore variations in physics, chemistry and biology. Stronger vertical and horizontal motions occur at capes, and in the lee of these capes, water motion is less active. As a result of the slower physical dynamics, biological processes are enhanced and dense phytoplankton blooms are observed in these upwelling shadows. Strong gradients are formed between freshly upwelled waters and the sluggish waters in the shadow. These fronts attract a diverse community of predators.

On a seasonal basis upwelling of cool, nutrient-rich waters results in high biological productivity that supports a diverse food web. Every 3–8 years this high biological productivity is interrupted by El Niño, a large scale ocean disruption initiated by atmospheric perturbations in the western equatorial Pacific (Philander, 1990). El Niño events result in perturbations to the California Current system – tropical waters are advected poleward and onshore and cold, nutrient-rich waters are found deeper – that lead to lower nutrient supply and productivity for about 6–18 months, depending on the intensity of the event. During normal and cool periods, the California Current ecosystem has high biological productivity and relatively low diversity; during El Niño and other warm phenomena, productivity is reduced and biodiversity increases (Barber and Chavez, 1983).

Longer term and more subtle changes in the environment can have even stronger and more profound changes on living marine resources, leading to "regime-shifts" (Lluch-Belda et al., 1992; Chavez et al., 2003). Two prominent examples for the West Coast are the Pacific Decadal Oscillation (PDO; Mantua et al., 1997) and the North Pacific Gyre Oscillation (NPGO; Di Lorenzo et al., 2008). The PDO has a period of about 50 years and has similar dynamics as El Niño; hence, the warm phase of the PDO has been named El Viejo (Chavez et al., 2003). The NPGO has more of a "decadal" period and is related to changes in the strength of the North Pacific oceanic gyres driven by local winds rather than by remote, equatorial forcing. The NPGO impact may be greater during the cool PDO (La Vieja) phase. These longer period fluctuations seem to have considerable impact on upper trophic levels, and thus transitions from one phase to the other are considered "regime shifts" (Mantua et al., 1997). On the US West Coast, fish such as anchovy, salmon and sardine are particularly impacted, but the entire ecosystem changes character (Chavez et al., 2003).

Finally, even longer period fluctuations are being discovered for the US West Coast by analyzing time series from sediments preserved under anoxic conditions. For example, analyses of time series from the Santa Barbara basin off California are uncovering the impact of either longer period phenomena or global change (Field et al., 2006). The most recent period of these time series show the appearance of warm water species in concentrations never observed for the prior 500 years. Similarly, recent time series from marine sediments cores underlying the Peru oxygen minimum zone have uncovered dramatic shifts – during the Little Ice Age (LIA) the eastern Pacific was an ecosystem of high subsurface oxygen and low biological productivity (including fish). At the end of the LIA around 1820, it shifted to the present day low oxygen, high biological productivity system (Gutiérrez et al., 2008). Will similar "tipping-points" be reached in the future? If so, when will they occur, will they be predictable, and will human induced climate change alter their timing or characteristics? Managing ecosystems within this shifting environmental baseline will be difficult; climate variability and change must be accounted for in EBM as well as our degree of certainty in the paths it will take (e.g., Costello et al., 1998).

4.2. Directional change

In addition to the inherent variability in the system described above, there are also numerous sources of directional change and associated impacts. These impacts can be separated into two general classes for the California Current system: (1) nearshore local impacts driven by agriculture and coastal development and (2) large-scale impacts driven by warming and the slow diffusion of anthropogenic atmospheric carbon dioxide. The first class is linked directly to human population levels, and thus is more evident in the Southern California Bight where population growth and density are higher than in more northerly parts of the region. In the central and northern California region, agricultural impacts are more notable, but with population impacts enhanced in the San Francisco Bay area. Although population sizes are smallest in the Pacific Northwest (with Portland, Oregon and Puget Sound, Washington as noteworthy exceptions), high annual rainfall and resultant runoff enhances transport of anthropogenic elements from the watershed to the ocean. These impacts in turn affect human use of and access to key ecosystem services, such as beach closures and seafood advisories or bans due to contamination.

Large-scale, atmospherically driven warming impacts are less straightforward for the California Current system. Although coastal upwelling winds may be enhanced (Bakun, 1990), trade winds may weaken (Vecchi et al., 2006) and stratification may be enhanced (Freon et al., 2009). This combination of changes in the physical system means that biological productivity may be enhanced for nearshore areas (due to increases in upwelling-favorable winds), but the general size of productive habitat may shrink, creating strong frontal gradients. Under this scenario, it is unclear what type of ecosystem may be favored. What does seem clear is that there will be decreasing oxygen and lower pH (more acidic) conditions in the California Current system, trends which have already been documented over the past several decades (Bograd et al., 2008; Feely et al., 2008). These changes may be partly driven by long term cycles in climate but also have a clear anthropogenic component, at least for pH (Feely et al., 2008). Large scale stratification by global warming and increases in mean ocean temperature will also drive decreases in subsurface oxygen by limiting ventilation (the process that brings oxygen from the atmosphere to the deep ocean) and decreasing solubility.

4.3. Social variability and change

Variability in the biophysical components of the ecosystem must be considered in the context of variability and change in social components of the system, with an understanding of the complex feedbacks between the two systems. For example, the 1982–1983 El Niño had a number of impacts on the human and ecological systems, many of them linked. Specifically, changes in the natural system led to changes in fishery participants' behavior intra- and inter-seasonally (Pomeroy et al., 2002). In the case of Crescent City, California, fishery participants reported that pink shrimp, targeted by an expanding trawl fleet, disappeared from the traditional fishing grounds. To adapt, trawlers re-directed their effort to the groundfish fishery. This shift, in turn, led to changes in local infrastructure and markets to support an expanding groundfish fishery and a contracting shrimp fishery (FFITC, 1999). In 2009, despite an increase in the abundance and market demand (and price) for shrimp, the fishery is constrained by limited receiving capacity and the absence of shrimp processors at the port. As a result, the five boats equipped and licensed for the fishery are on rotation with one buyer, each boat fishing 1 day per week and limited to about 15 tons per trip (20–25% of capacity for these boats). The shrimp landed is trucked south to Eureka or north into Oregon for processing, so that the fuller economic and social value of production is exported, rather than being realized by the local community.

There have also been changes to the human system which are not necessarily linked to biophysical variability or change. For example, Washington, Oregon and California have shown an increase in ocean-dependent economic sectors over a recent 10 year period (1994–2004; noep.mbari.org), with a 47% average increase in gross domestic product (GDP) for the tourism and recreation sector and a 28% increase for the living resources component (fisheries, aquaculture, and seafood processing and trade). These aggregate figures mask significant sectoral and state-level events that appear to reflect structural shifts away from natural resource dependency toward tourism and recreation. The tourism and recreation sector in California experienced a huge increase in employment (75%) and wages (about 105%), although this entire increase may not be directly attributable to ocean uses. In contrast, the state of Oregon experienced a 23% decline in the number of living resources-related jobs, and the three states combined saw a 38% decline in the number of business establishments involved in the use of living resources. (These estimates do not account for changes in non-employer establishments which better reflect the number of commercial fishing operations.) Whether these economic changes reflect changes in the natural system and hence the availability of ecosystem services, or merely reflect changes driven by the social system itself (e.g., changing preferences for living along the coast or engaging in ocean-dependent jobs) or other external factors requires additional study.

4.4. Implications for management

Regardless of how the social system responds to variability in the natural system, effective management needs to consider the consequences of this variability to the services being managed. As an example of a management success in accounting for variability in the climate system, the California sardine fishery is managed under an innovative harvest control rule based on the 3 year running average of the sea surface temperature measured in San Diego, CA – higher harvest rates are permitted during more favorable environmental conditions (Jacobson and MacCall, 1995; PFMC, 1998). However, such an approach requires at least some knowledge of the association between environmental conditions and an ecosystem service. In many cases, even these simple correlative relationships are fraught with uncertainty. For example, for many fisheries species, the recruitment of young fish in the future is often poorly predicted by the stock of adults today (Myers and Barrowman, 1996). Climate-driven variation in egg production (Trippell, 1999; Kraus et al., 2005), larval feeding success (Wooster and Bailey, 1989), and larval transport (Roughgarden et al., 1988) can dominate the success of year classes and generate large uncertainty in forecasts that were based solely on population size, estimates which are themselves uncertain.

There are two broad classes of management approaches for addressing this uncertainty. One makes precautionary choices in the face of inherent uncertainty. The other tries to reduce the uncertainty by gaining a better mechanistic understanding of the underlying causes. California's Marine Life Management Act (CaDFG, 2001) is an example of the former approach for the California Current. It specifies more precautionary management measures for fisheries that have limited data and knowledge of their population dynamics. The cost of such precaution in the face of large uncertainty can be reduced yields, with consequences for businesses and communities. If we had a better mechanistic understanding of the population dynamics, yields could likely increase. The value of this added ecosystem insight would be the greater services that the system would provide. The question that must continually be addressed is whether the value of added information offsets the costs of obtaining it. If not, management precaution in the face of large uncertainty may provide better value to society.

The connections between climate variability and ecosystem services are emerging for a growing number of components of the California Current ecosystem. As examples, studies of fish and invertebrate recruitment show strong ties to ocean circulation (Parrish et al., 1981; Roughgarden et al., 1988; Gaines and Bertness, 1992; Connolly et al., 2001) and coastal erosion is coupled to El Niño cycles (Storlazzi and Griggs, 2000; Sallenger et al., 2002). These advances all offer significant opportunities for management that anticipates ecosystem changes driven by climate rather than that which responds after the fact.

5. Conclusions

Despite general consensus within the scientific community that we have the scientific information needed to improve existing management practices, an explicit assessment of the state of knowledge and advice on how to apply this information to policy and practice has been lacking. The emerging science presented in this paper, organized around three general concepts (Table 1), provides the basis for more comprehensive, ecosystem-based management of coastal and marine resources within the California Current.

Specifically, we have an improved understanding of the spatial distribution of cumulative impacts to marine ecosystems and have begun to work towards understanding their social drivers and impacts. We can also identify the region's key ecosystem services, and in some cases have mapped their spatial distribution, assessed their value, and determined factors underlying their production and delivery. This information will ultimately allow us to apply new methods to explicitly assess trade-offs among services under different management scenarios. We are increasingly able to document, and in some cases understand, the underlying drivers of variability in the biophysical components of the California Current ecosystem, allowing us to better manage with a long-term view. Importantly, there remains a need to further develop and advance the science, particularly that directed toward understanding the social components of the California Current ecosystem and its variability. Despite limitations in the social sciences, our assessment suggests that science is not a significant bottleneck in working toward EBM on the West Coast. An examination of non-scientific hurdles is beyond the scope of this paper, so we will not speculate on the most important factors limiting EBM progress for this region. Regardless of what these hurdles may be, there is growing interest and opportunity along the US West Coast for implementing EBM that will allow us to put our scientific understanding to practice (www.westcoastebm.org; WCGA, 2008).

Although focused on the US West Coast, the assessment presented here is broadly applicable. We assess key scientific needs and recent advances relevant to EBM and demonstrate how that knowledge can be applied to advance management. Many of the approaches described here can be effectively applied to other regions. Additionally, progress described for the California Current ecosystem can be used as a basis for comparison for other regions. We predict that in many places, existing management can be improved with readily available science (although admittedly in some cases available science is still inadequate for EBM) and that many of the lessons learned are relevant to locations around the world. Indeed, in many places we are not taking full advantage of available information to allow management to use ecosystem-based approaches or account for the range of services that ecosystems provide.

One major qualification concerns social science. Social science research related to the implementation of EBM in the California Current and elsewhere is less developed than its natural science counterparts. More social science research is urgently needed, as is greater attention to the integration of social science data and approaches with those of the natural and physical sciences. With a greater investment in social sciences, we will be better equipped to move forward with implementation of EBM under a broad range of starting points, including variation in data availability, government structures, and time-frames (Tallis et al., 2010).

Complete information will never exist for physical, biological or economic and socio-cultural datasets that is relevant to ocean matters, particularly at appropriate scales and resolutions. Rather than being an impediment to EBM, this underscores the need for more adaptive approaches to management, which start with readily available information, acknowledging gaps and uncertainties, but continuously adapt as new information and understanding emerges. By recognizing that science is often not the bottleneck, we can work to better apply existing information to management, gather information to fill key knowledge gaps, and address other key hurdles to realizing EBM.

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