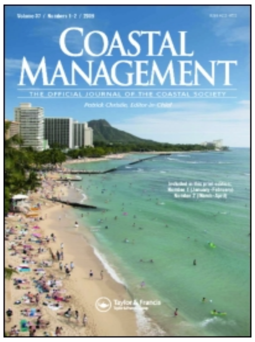

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Conceptualization of Social-Ecological Systems of the California Current: An Examination of Interdisciplinary Science Supporting Ecosystem-Based Management

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ABSTRACT
Improved understanding and management of social-ecological systems (SES) requires collaboration between biophysical and social scientists; however, issues related to research philosophy and approaches, the nature of data, and language hinder interdisciplinary science. Here, we discuss how we used conceptual models to promote interdisciplinary dialogue in support of integrated ecosystem assessments (IEAs) in the California Current ecosystem. Initial conceptualizations of the California Current IEA were based on the Driver-Pressure-State-Impact-Response framework. This initial framing was biophysically centered, with humans primarily incorporated as impacts on the system. We wished to move from a conceptualization that portrayed an antagonistic relationship between humans and nature to one that integrated humans and social systems into the IEA framework. We propose a new conceptualization of the California Current that functions across temporal and spatial scales, captures the diverse relationships that typify SESs, and highlights the need for interdisciplinary science. The development of this conceptualization reveals how our understanding of the place and role of people in the ecosystem changed over the course of the history of the California Current IEA. This conceptual model is adaptive and serves to ensure that interdisciplinarity will now be the standard for the California Current IEA and, perhaps, beyond.

KEYWORDS
integrated ecosystem assessment; interdisciplinary collaboration; social-ecological system; transdisciplinary science

Introduction

Recognition that humans and nature are deeply enmeshed has resulted in calls for a more multilayered, multidimensional, and integrative scientific approach to environmental management (Castree et al. 2014; Mace 2014). The notion that human and biophysical systems are coupled is not a new idea; however, operationalizing this concept has become a challenge for scientists and managers working in marine and coastal systems (Collins et al. 2011; Leslie et al. 2015). With more than half of the world's population within 100 kilometers of marine

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*Mark L. Plummer is deceased.

coastlines (Sale et al. 2014), policy makers, managers and researchers cannot afford to ignore linked human-biophysical systems in coastal regions.

The concept of social-ecological systems (SES) explicitly acknowledges linkages and feedbacks between human and biophysical systems (Binder et al. 2013) and has gained traction as a means to promote sustainability (Ostrom 2009). SES frameworks can enable the integration of knowledge from diverse natural and social science sources and provide a powerful means of testing ideas about the dynamics of social-ecological interactions. The most integrative SES frameworks describe interactions among people and living resource systems comprised of ecosystem types and biophysical processes, together with social and governance systems and processes (Armitage et al. 2008; Berkes 2012; Ommer et al. 2012). Social and biophysical interactions are mediated by social, economic, and political contexts and the ecosystems within which the SES is embedded.

Clearly, to better understand and effectively manage social-ecological systems, biophysical and social scientists must collaborate; however, issues related to disciplinary differences in research philosophy and approaches, the nature of what constitutes rigorous data, and language hinder interdisciplinary science and management (Heemskerk, Wilson, and Pavao-Zuckerman 2003; Sievanen, Campbell, and Leslie 2012). Conceptual models have proven useful tools for crossing such boundaries. They can be valuable for organizing diverse sets of values and goals (Jones et al. 2011), improving communication (Abel, Ross, and Walker 1998), increasing understanding of complex system dynamics (Ozesmi and Ozesmi 2004), and accommodating diverse types of knowledge (Ozesmi and Ozesmi 2004); thus, they have the potential to facilitate integrating information across multiple SES disciplines.

Over the last decade, the U.S. National Oceanic and Atmospheric Administration (NOAA) has been actively developing integrated ecosystem assessments (IEAs)— evaluations and syntheses of information on biophysical and human processes showing system trends and societal and ecological trade-offs between different management or policy options. By their very nature, IEAs are interdisciplinary, and, thus, must confront the challenges of transdisciplinary research (Plummer and Levin 2014; Samhouri et al. 2014). Our approach to meeting these challenges for the California Current IEA was fundamentally shaped by the creative, rigorous, and instrumental contributions of our late colleague, Mark Plummer. Here, we pay tribute to Mark's life and career by discussing the development, evolution, and use of the SES conceptual model of the California Current marine ecosystem. In doing so, we reveal how our understanding of the place and role of people in the ecosystem changed over the course of its conceptualization, and why we think this shift is foundational for the effective management of the ocean for nature and people.

Evolution of a social-ecological conceptual model for the California Current integrated ecosystem assessment

Recognizing the importance of human-biophysical connections, the initial conceptualization of IEAs focused on the Driver-Pressure-State-Impact-Response (DPSIR) framework (Levin et al. 2008). DPSIR was developed by the European Environmental Agency (Holten-Andersen et al. 1995; Kristensen 2004) and is now widely used as a framework for ecosystem assessments (Borja et al. 2006; Gari, Newton, and Icely 2015; Kelble et al. 2013). In its simplest form, *driving forces* (e.g., coastal development, per capita seafood demand, global climate patterns) exert *pressures* (e.g., habitat loss, fishing, ocean currents) on the environment. Consequently, the *state* (e.g., ecosystem integrity, habitat, protected species, fisheries) of the ecosystem shifts. This leads to *impacts* (e.g., changes in ecosystem function, changes in fishery yield) that may result in management *responses* (e.g., habitat restoration, altered fishing regulations).

Following the DPSIR mindset, the California Current IEA team worked with regional managers to develop a set of drivers, pressures, and states to examine in the initial phase of the California Current IEA (Levin and Schwing 2011). The IEA team opted not to separate drivers and pressures and binned them into twelve broad categories (Figure 1). These drivers and pressures affected four ecosystem states that were of primary interest to managers (Figure 1). Through the use of management activities, the team envisioned that drivers and pressures could be mitigated in order to reach the desired state of the ecosystem.

This initial framing of the California Current system was a biophysically centered view with human systems primarily incorporated as impacts on the system to be controlled or reduced. In order to represent more fully the SES that included linkages and feedback between human and biophysical systems, we moved away from a conceptualization of the ecosystem that portrayed an antagonistic relationship between humans and nature. Moving from an ecocentric to a more social-ecological view required that we integrate humans and our social systems more completely into the IEA framework (Plummer and Levin 2014). One approach might be to incorporate more fully ecosystem services and the benefits people derive from nature into a DPSIR framework (e.g., Kelble et al. 2013); however, this modification, while useful, does not fully include aspects of social systems that are central to social-ecological systems (e.g., institutions and governance). It also espouses a stance of "nature for people" (Mace 2014). While such a stance reduces the tendency to treat human and

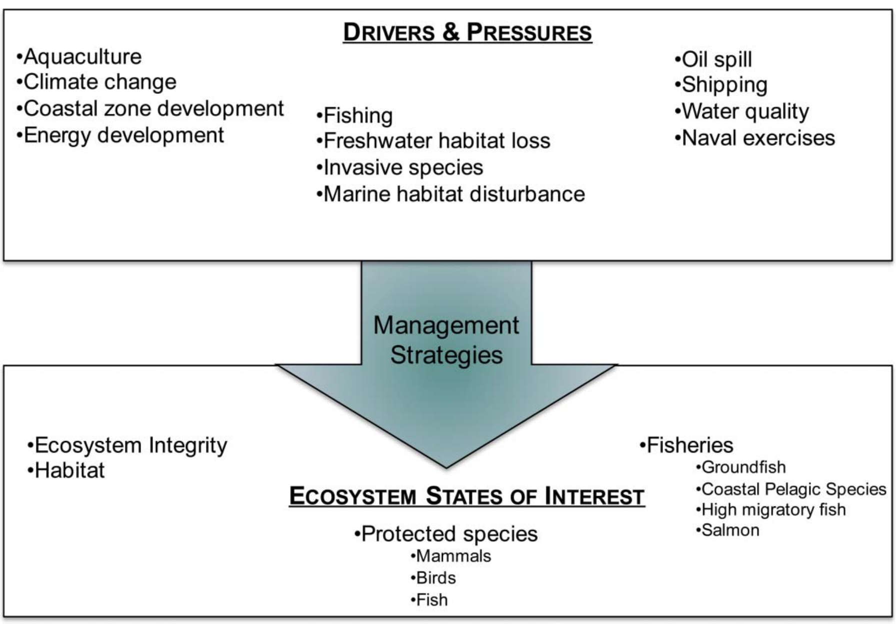

Figure 1. An adaptation of the Driver-Pressure-State-Impact-Response framework for use by the California Current Integrated Ecosystem Assessment. Key Ecosystem components and the drivers and pressures that impacted them were elicited from regional managers in the California Current.

biophysical systems as separate entities, some consider an ecosystem-services perspective that seeks to maximize a unidirectional flow of conditions for humans to be overly utilitarian and simplistic (Mace 2014; Norgaard 2010).

As a consequence, our present conceptualization of the California Current SES moves beyond the linear relationships characteristic of DPSIR and ecosystem service framings. We propose a new conceptualization of the California Current SES that can function across a diversity of temporal and spatial scales (Figure 2). This conceptualization is the result of an iterative process among dozens of natural and social scientists and managers involved with the California Current IEA. It is grounded in current SES theory (e.g., Ostrom 2009; Duraiappah et al. 2014; Díaz et al. 2015), but borne of practical experience. Our model attempts to capture the manifold and multidimensional relationships that typify SESs (*cf*. Díaz et al. 2015). It highlights the need for interdisciplinary social and natural sciences, connects to policy in multiple ocean-use sectors, and includes the social structures, institutions, and practices underlying large-scale drivers (Poe, Norman, and Levin 2014; Breslow 2015).

Our conceptualization organizes the biophysical environment into three major tiers: climate and ocean drivers, habitat, and focal components of ecological integrity (Figure 2). These three tiers were derived from initial scoping with California Current natural resource managers (Levin and Schwing 2011). At its base, *climate and ocean drivers* such as ocean

Figure 2. A conceptualization of the social-ecological system of the California Current showing broad biophysical and social drivers, the potential mediating effects of habitat and local social systems and the management endpoints of ecological integrity and human well-being. Human activities are placed at the center, suggesting they are the most tangible points of connection between the social and ecological systems, yet can only be understood in the context of broader drivers and local variability. Instead of arrows, the spherical matrix represents the multidirectional interconnections among all elements.

circulation, sea surface temperature, and upwelling patterns represent key bottom-up drivers in the California Current. In this framing, *habitat* is the stage upon which ecosystem dramas play out (Southwood 1977). As such, habitat occupies an intermediate tier where it mediates effects of climate and ocean drivers on biota; habitat serves as the matrix through which most ecosystem interactions occur. At the top level are specific focal components of *ecological integrity* such as seabirds, salmon, and diversity, which we care about and submit as important indicators of the system (Foley et al. 2013). Humans, through their activities, interact with and affect each of these tiers in different ways, not only as forces of change, but also as responsive members of a shared relationship that must adapt to the dynamics of the biophysical subsystem.

Like the biophysical environment, the human dimension of the California Current SES is comprised of multiple interrelated tiers, here organized as social drivers, local social systems, human activities, and human well-being (*cf.*, Díaz et al. 2015). Following McGregor and colleagues (McGregor 2008), we characterize human well-being as a state of being with others and the environment, where human needs are met, where individuals can enjoy a satisfactory quality of life, and where individuals can act meaningfully to pursue their goals. Human well-being—even those aspects related to environmental condition—is mediated by *broad social forces or drivers, local social systems*, and *human activities. Social drivers*—such as population growth and settlement patterns, national and global economic and political systems, historical legacies, dominant cultural values, and class systems—constrain or enable local social systems and human activities in ways that directly or indirectly affect human well-being. Likewise, *local social systems* that vary geographically and across different social groups—such as state and local laws and policies, regional economies, local institutions and infrastructure, social networks and social hierarchies, diverse cultural values and knowledge, and other particularities—affect human well-being directly or indirectly, and constrain or enable human activities related to the natural environment. Such *human activities* might include, for example, fishing, farming, mining, recreation, environmental research, education, activism, restoration, and resource management. These activities generate benefits for humans, and they are also ways by which humans affect the natural environment.

Making use of the California Current SES conceptualization

The co-construction of this framework by natural and social scientists in our team served to improve communication, expose prejudices about alien disciplines, and reveal hidden assumptions. Perhaps most useful, our conceptual model can guide and facilitate discussion about the California Current among managers, ecologists and social scientists, and user groups and other stakeholders. Below we present two vignettes that reveal how our conceptual framing can improve interdisciplinary collaboration on contentious topics, by enabling us to step back to observe the nuanced and changing role of people in the ecosystem over time, and ultimately improve communication that can aid management outcomes. Links to our conceptualization are emphasized in italics.

Management tradeoffs in the California Current: Whales as an ocean icon

Following centuries of commercial whaling (*human activities*), baleen whales (e.g., blue whale, *Balaenoptera musculus*; fin whale, *B. physalus*; humpback whale, *Megaptera* *novaeangliae*; gray whale, *Eschrichtius robustus*) are recovering in the Northeast Pacific Ocean. These growing populations connect to all elements of the California Current SES. They prey upon tremendous amounts of zooplankton, small pelagic fishes, and benthic invertebrates, while providing food for large predators and scavengers (Croll, Kudela, and Tershy 2006; Kareiva, Yuan-Farrell, and O'Connor 2006). Their habitats encompass the epipelagic zones over the shelf and slope; the extent of favorable habitat varies by year and season as a function of depth, productivity, oceanography, and long-term climate variability (Hazen et al. 2013; Redfern et al. 2013). On the human side of the SES, whales are protected at broad scales by federal legislation (the U.S. Endangered Species Act and Marine Mammal Protection Act) and international treaty organizations (*broad social drivers*) (e.g., the International Whaling Commission). Regional practices (*local social systems*) include regulation of shipping routes and ship speeds to minimize whale strikes (Redfern et al. 2013). Furthermore, baleen whales are iconic species with cultural value for many social groups in the United States (Kareiva, Yuan-Farrell, and O'Connor 2006). They are highly valued by taxpayers and donors to conservation organizations (e.g., Loomis and Larson 1994). They evoke awe, mysticism, and public appeal through their sheer size and compelling behaviors (Kareiva, Yuan-Farrell, and O'Connor 2006), and they form part of the cultural identity for some coastal communities (*local social systems*), particularly those indigenous peoples who once harvested them and wish to do so again as whales recover (Firestone and Lilley 2005; Lang et al. 2014; Sepez 2008).

Numerous human activities intersect with baleen whales in this SES. There are nonextractive activities such as a lucrative whale-watching industry (Pendleton 2005) and sighting whales during other leisure activities. There are potentially disruptive activities: shipping brings the risk of harmful or lethal collisions (Redfern et al. 2013); shipping, ocean exploration, and military activities may produce harmful noise levels (Tyack 2008); and fisheries can cause entanglements or depletion of prey resources (Barlow and Forney 2007). These activities bring considerable social benefits however, including revenue, jobs, food, trade, and national security.

A holistic conceptualization of the SES serves as valuable context for addressing difficult management questions, perceiving tradeoffs, and anticipating change related to these iconic species. This is best illustrated by recognizing that a change in one aspect of the SES likely will propagate to other aspects as well. For example, larger populations of baleen whales may attract predatory killer whales Orcinus orca and reduce predation on pinnipeds by killer whales (*ecological integrity and interactions*). In the SES, this ecological interaction carries tradeoffs on the human side: pinnipeds interact very strongly with fishes and human activities. For example, seals prey upon salmon that support important recreational and commercial fisheries and have high cultural importance to native peoples; they also consume herring, which indirectly support similar social and economic benefit via food web interactions. Thus, an indirect effect of baleen whales on pinnipeds could have considerable social consequences (Kareiva, Yuan-Farrell, and O'Connor 2006).

As another example, variation in climate will likely shift prey fields and preferred habitat for baleen whales; a change in their habitats could have considerable repercussions for a shipping industry driven by broad forces (trends in vessel size, global commerce, and widening of the Panama Canal) and local regulations (positioning of shipping channels related to regional air quality, ecological reserves, and military activity; e.g., Redfern et al. [2013]). These changes may adversely affect whale populations, through incidental ship-strike mortalities; or human well-being, through changes in coastal economies or redistribution of whale viewing opportunities. Any increase in human-caused whale mortalities might further entrench negative public opinion around petitions by coastal tribes to resume traditional and treaty-protected whale hunting. Viewing recovering baleen whale populations in the milieu of our SES framework, where their dynamic relationship to their environment and their strong degree of cultural affinity and legislative protection are juxtaposed against contested human activities, will help anticipate tradeoffs and promote dialogue among conflicting parties.

Shellfish harvest

Shellfish production on the Pacific coast of North America generates more than $100 million in revenue annually, making it an economic driver in many coastal communities (Northern Economics Inc. 2013). In addition to supporting jobs and livelihoods for coastal residents, shellfish hold cultural importance for many coastal communities, forming a sense of place tied to local ecological knowledge, identity and heritage (Poe, Donatuto, and Satterfield 2016). However, shellfish aquaculture also alters coastal ecosystems (Reum et al. 2015), leading to both positive and negative effects on *ecological integrity*. For example, the conversion of intertidal and subtidal *habitat* to shellfish farms forces shifts in ecological community structure and food webs (*species interactions*) (Feldman et al. 2000; Simenstad and Fresh 1995; Reusink et al. 2006). On the other hand, shellfish filter vast quantities of water, thus lowering turbidity, increasing water clarity, and enhancing growth conditions for seagrass (Newell 2004).

As food, shellfish provide a range of nutritional benefits to people, but their consumption may also pose risks under certain *ocean conditions*. These risks come from human exposure (consumption, inhalation, skin contact) to toxins or contaminants concentrated from marine waters in shellfish tissues, including biological toxins, from harmful algal blooms, as well as direct point and nonpoint sources of contamination from pollution and run-off (*human activities*) (Mallin et al. 2000). Importantly, the frequency, duration, and geographic scope of harmful algal blooms have increased in recent years, in part, due to large scale *climate drivers* (Moore, Mantua, and Salathé 2011). Toxins associated with these algal blooms lead to the closure of shellfish beds and a disruption of recreational, commercial, and subsistence harvesting. These blooms also negatively affect other marine biota, with potential effects across the food web (*ecological integrity*), further highlighting ways in which ecological health and human well-being are interrelated (Trainer et al. 2012).

A recent case involving oyster growers in Willapa Bay, Washington (USA) illustrates multidimensional aspects of the social-ecological system, and, in particular, it shows how *social forces* such as consumer demand at a national level, can have regional economic and ecosystem consequences by influencing local aquaculture practices. Oyster production in this region can be limited by a native burrowing shrimp, *Neotrypaea californiensis*, which affects oyster survival and growth. Historically pesticides were used to control shrimp populations, but environmental concerns and subsequent regulation resulted in its cessation (Feldman et al. 2000). In April 2015, growers were able to gain regulatory approval for the use of a new pesticide intended to be more ecologically benign. However, vocal public concern resulted in oyster growers pulling out of the pesticide plan (http://www.seattletimes.com/seattle-news/oyster-pesticide-issue-shows-who-really-wields-power/).

Viewed through the lens of our conceptualization, we see that shellfish harvest is a human activity driven by economic demand for safe food. The health of the shellfish industry and the people that depend on it are directly and indirectly related to large-scale climate forcing and the desire of governmental regulators and the marketplace to balance the benefits of associated shellfish harvest, with habitat and food web damage associated with its production.

Conclusions

Ocean ecosystems face a myriad of problems, and in the California Current, as in many regions, we are fortunate to have a great deal of high-quality science that has illuminated these issues (Lester et al. 2010). However, this science is often poorly organized and lacks interdisciplinary integration and synthesis that would place environmental problems in the appropriate economic, social, cultural, and political context (Levin et al. 2014). While disciplinary science has built our basic knowledge, there is a clear need for interdisciplinary, problem-oriented approaches. Indeed, solving the problems facing ocean ecosystems requires that we not only conduct research to generate new knowledge, but that ocean scientists and managers of all stripes need to think beyond the confines of their basic disciplines (Brewer 1999). Achieving this laudable goal, however, is challenging.

Within the rubric of the California Current Integrated Ecosystem Assessment, we have found simple conceptual models to be crucial for framing the tasks associated with holistic ecosystem management of the SES. The expansion of our framing means that the first step of the IEA–defining objectives–is necessarily broad. It requires us to consider both biophysical and human objectives equally, obliges us to develop the means to determine the status of both human and biophysical components of the system, and forces us to think carefully and broadly about the intended and unintended consequences of management actions. The evaluation of management alternatives becomes much more robust using this conceptualization. For example, fisheries managers might ask about the impact on ecological integrity of a fisheries management action, given a range of possible climate futures (e.g., Pacific Fisheries Management Council 2013). By using this conceptualization, we see that we also need to understand how fisheries management might affect ecological integrity under a range of global market scenarios. In predicting the potential success or failure of a management option, we need to consider how it impacts human well-being as well as ecological metrics. This requires us to consider aspects of equity—how might the benefits and costs derived from a management action be distributed among communities and sectors? A greater focus on human well-being also compels us to consider how management strategies influence the sense of self-determination and distribution of decision making power in fisheries systems (in this case). For instance, given two management actions that are equivalent ecologically, the action that increases well-being by improving ability of individuals to determine their own future, may be preferred.

Our conceptualization of the California Current SES highlights the notion that sustainability is multidimensional. It not only requires that we consider extractive goals (e.g., sustainable fishing to meet food and economic objectives), but it also requires that we conduct human activities at a level that ensures ecological sustainability (e.g., ecologically sustainable yield; Zabel et al. 2003). Moreover, the notion of sustainability implicit in our model includes specific attributes of human well-being such as food security, equity, environmental justice and governance. Thus, the conceptual model that underlies the California Current IEA posits that for any policy or management action to be considered sustainable, it must attend to biophysical and human endpoints (Elkington 1997).

Importantly, even with this conceptualization, interdisciplinary research is difficult. Throughout the development of this model, for example, we saw that the conceptualization frustrated some biophysical scientists in our team who preferred more mechanistic representations of systems. It similarly upset some social scientist team members because they felt it oversimplified the human condition. Additionally, while this model is useful in highlighting difficult trade-offs, in some instances, additional decision-support tools will be necessary for the decision-making process.

Mark Plummer started our journey from rigid, disciplinary thinking to a more nonlinear, multifarious, and nuanced perspective. The road to interdisciplinarity is challenging, yet necessary. Our conceptual model, like science itself, is certainly not an end, but rather a point along a dynamic process. As noted by Peart (1987): "The point of the journey is not to arrive, the point of departure is not to return." Thus, we expect our conceptualization to evolve as the dialogue between natural and social scientists, managers and policy makers continues. However, we trust that moving forward, interdisciplinarity will now be the standard for the integrated ecosystem assessment of the California Current and beyond.

Acknowledgments

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