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Lessons learned from an ecosystem-based management approach to restoration of a California estuary

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A B S T R A C T

Ecosystem-based management (EBM) is the dominant paradigm, at least in theory, for coastal resource management. However, there are still relatively few case studies illustrating thorough application of principles of EBM by stakeholders and decision-makers. At Elkhorn Slough, a California estuary, we launched an EBM initiative in 2004. Stakeholders collaboratively developed and evaluated large-scale restoration alternatives designed to decrease two types of rapid habitat change occurring in the estuary, erosion of channels and dieback of salt marsh. In the end, decision-makers rejected large-scale alternatives altering the mouth of the estuary, and instead opted for small- to medium-scale restoration projects and recommended an added emphasis on reduction of nutrient-loading. We describe seven challenges encountered during the application of EBM principles: (1) interdisciplinary collaboration is difficult due to differences in professional culture and values, (2) roles and responsibilities of different participants are often not sufficiently clear, (3) implementing EBM is very costly in time and human resources, (4) an ecosystem services framework may not resonate with stakeholders already committed to biodiversity conservation, (5) conflicts arise from differences in desired restoration targets, (6) multiple geographic and jurisdictional scales cannot be simultaneously addressed, and (7) understanding of ecosystem drivers and processes may change rapidly. We recommend approaches to overcoming each of these challenges so that our experiences implementing EBM at one estuary can inform collaborative decision-making initiatives elsewhere.

1. Introduction

> *"Ecosystem-based management is fundamentally about perceiving the big picture, recognizing connections, and striving to maintain the elements of ecosystems and the processes that link them."* [1]

Ecosystem management emerged in the 1980s as an alternative to traditional resource management approaches that focused on limited species or narrow political boundaries. Environmentalists and scientists advocated for broader landscape-scale planning, collaboration with stakeholders, and flexible adaptive management. The term 'ecosystem-*based* management' (EBM) was later adopted to convey that management efforts are focused on human activities affecting the ecosystem; the ecosystem itself is not being managed [2]. Many different definitions of EBM have been developed [3]. A recent review identified 17 different criteria that are commonly used to define ecosystem-based management [4]. These fall broadly into the general categories of sustainability, ecological health, and inclusion of human uses within the ecosystem framework.

Many natural resources agencies began to apply principles of EBM. However, by the mid 1990s, EBM fell out of favor with many land managers and terrestrial environmentalists, because political interests

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dominated some EBM processes, resulting in human resource uses being favored over ecological integrity and sustainability [2]. While EBM was declining in popularity in terrestrial systems, it gained momentum in marine systems: EBM became a major focus of marine conservation efforts, after being endorsed by various prestigious scientific panels [5–7]. By the early 2000s, EBM was the dominant paradigm, at least in theory, for managing natural resources around the world, in both marine and terrestrial systems [8].

Despite the ubiquity of the concept of EBM, there are still relatively few case studies of successful implementation, and the extent to which the EBM principles advocated by scientists have been adopted by managers and concretely applied to local projects is unclear [4]. Indeed, a review of recent management plans suggests that there is still a gap between the academic framework for EBM and its on-the-ground implementation, with many key tenets of EBM failing to be translated into management [4]. Furthermore, in some instances the original goals of ecosystem sustainability and resilience are not achieved due to dominance of political interests supporting human uses [2]. Thus, case studies have been valuable for elucidating tactics for successfully applying EBM to local management [1,9,10].

The majority of case studies of marine EBM are focused on open coast fisheries management and/or marine protected areas e.g. [10,11]. However, estuarine ecosystems also provide rich model systems for implementation of EBM – indeed, given the obvious linkages between watersheds and estuaries, and the multiplicity of human uses of estuaries, some principles of EBM were already being applied to estuaries before the term was invented. For instance, on the US Atlantic coast, resource managers in Chesapeake Bay began an initiative to restore multiple targets including water quality, vegetation, and oysters decades ago, at a broad geographic scale, although it has not made all the environmental gains that had been hoped for initially [12]. At another estuary, on the US Pacific coast, the Puget Sound Partnership is considered a model in the application of EBM [13].

The goal of this paper is to describe our application of the principles of EBM to Elkhorn Slough, an estuary in central California. While this estuary is small, the management issues there are comparably complex to many other coastal systems. We will characterize the framework and process used to generate, evaluate and select restoration alternatives for the estuary. We will then share broader lessons learned from our challenges and successes, so they can inform resource managers and stakeholders developing nascent EBM projects in other places, and so they can contribute to the on-going academic evolution of the concept and framework for EBM.

2. Case study: EBM at a California estuary

2.1. Elkhorn Slough: a rich but highly altered ecosystem

Estuarine habitat is rare along California's topographically rugged coast. In central California, there are only two large estuaries, Morro Bay and Elkhorn Slough, and both are relatively small. Elkhorn Slough thus provides regionally important representation of estuarine habitat types, including some of the most extensive salt marshes in the state, after San Francisco Bay. The estuary has been highly impacted over the past century by human activities, especially by hydrological alterations [14]. Today about half of the original estuarine wetlands are behind water control structures, and there has been extensive loss of salt marsh and degradation of water quality in these areas. In contrast, the portion of the estuary that has not been diked has been subject to a dramatic increase in tidal energy following the 1946 creation, and subsequent maintenance, of the Moss Landing Harbor. The artificially deep mouth to the estuary increased tidal amplitude and current speeds in the estuary, leading to substantial tidal scour of the main channel and contributing to salt marsh loss (Fig. 1) [14,15]. Channel banks erode at a rate of 0.3–0.6 m/year, with sediment export from the estuary estimated at $>50{,}000\ m^3$/year; about 50% of salt marsh in the estuary has been lost since 1870 [14].

In addition to these hydrological alterations that have greatly affected habitats at Elkhorn Slough, degraded water quality has strongly affected environmental conditions for organisms dwelling in the estuary. Elkhorn Slough is surrounded by some of the most intensely cultivated and productive farmlands in the nation. Nearly 6% of the world's strawberry production occurs within the watershed. The estuary receives substantial agricultural run-off, and nitrate concentrations observed in the estuary are high [16].

Despite the many human alterations, hundreds of species of plants, algae, invertebrates, fish, birds and mammals use these estuarine habitats, including over a dozen "estuarine endemics", found only in estuarine or brackish coastal ecosystems [17]. Tens of thousands of people visit the estuary each year to experience these estuarine landscapes and the species that inhabit them (Fig. 2).

2.2. Formation and structure of EBM initiative

For many decades, conservation initiatives have grown and expanded in the Elkhorn Slough watershed, with wetlands and adjacent lands in the watershed protected by The Nature Conservancy, the California Department of Fish and Wildlife (CDFW), the Elkhorn Slough National Estuarine Research Reserve (ESNERR), a partnership between CDFW and NOAA, and the Elkhorn Slough Foundation. One of the challenges to decision-making about the estuary itself was the diversity of jurisdictions, regulatory authorities, landowners and community interests involved. In 2004, we launched the Elkhorn Slough Tidal Wetland Project in order to

Fig. 1. Elkhorn Slough estuary. *Top*: View to West, of lower main channel and surrounding marshes. *Bottom*: View to Northeast, showing Moss Landing Harbor and the artificial mouth to the estuary constructed and maintained to support it. (Photos by K. Ellenbogen.)

Fig. 2. Diverse considerations in Elkhorn Slough strategic planning. *Top left*: degrading salt marshes, and *Top right*: bank erosion were major concerns motivating the initiation of the EBM project (photos by K. Wasson). Supporting populations of organisms coexisting with the marsh loss and erosion, such as migratory shorebirds (bottom left) was an important component of the process (photo by P. Zaretsky), as was continued access for kayakers (bottom right), who list shorebird and otter viewing (note otter on marsh in background) as main reasons for visiting the estuary (photo by R. Eby).

meet the critical need for scientific, coordinated, and collaborative management of the estuary.

Over a hundred coastal stakeholders have engaged in this EBM initiative [14,18], playing different roles (Fig. 3). The Strategic Planning Team has decision-making authority for estuary-wide strategic planning and is supported by the Science Panel, which is tasked with providing expertise to support the process. Smaller working groups with Strategic Planning Team and Science Panel membership, as well as paid consultants and ESNERR staff, have been engaged as needed to provide targeted expertise. The local community has been engaged through numerous public meetings, electronic updates, and comment periods. The Tidal Wetland Project is coordinated by ESNERR, which has invested significant resources in the initiative.

2.3. *Development and evaluation of large-scale alternatives*

The emphasis of the first decade of the EBM initiative was on finding solutions to rapid erosion of tidal channels and recent extensive dieback of salt marshes, which represented the most dramatic and rapid habitat changes in the ecosystem. Tidal erosion and marsh dieback were prioritized both because of their urgency (no other threat was so rapidly altering the ecosystem) and because no other organization or effort was addressing these key issues. Large-scale alternatives comprised the initial focus for strategic planning because if there were a single large project that could improve conditions in the entire estuary, then this would be the most effective approach and should be explored prior to consideration of small- or medium-scale projects. Alternatives were generated by stakeholders in 2005 and winnowed to four finalists in 2006. These were strategies to reduce tidal prism in the estuary and thereby slow current velocities and reduce tidal scour, three of which involved alterations to the mouth of the estuary by constructing submerged sills or damming the current mouth and creating a new one in another location (See more detail in Supplementary material).

From 2006 to 2011, interdisciplinary evaluations of the large-scale restoration alternatives were conducted, with high involvement of stakeholder on evaluation approach and findings (see Supplementary material for detail on timeline, accomplishments and roles of different groups involved in this process). Evaluations included assessment of hydrodynamics and geomorphology [19], marsh sustainability [20–22], water quality [23,24], key estuarine species [25–32], and socioeconomics [33]. At the end of the evaluation period, the results from the different investigations were summarized into consistent "report cards" ranking the alternatives from the perspective of different criteria (Tables 1–4 in [18]), an approach which readily revealed significant contrasts among criteria – which alternative was optimal differed depending whether hydrodynamic, water quality, biological or socio-economic criteria were applied.

2.4. *Decision-making process and outcome*

Decision-makers approved 10 recommendations regarding the large-scale alternatives, in meetings following a period of open comment and modifications. None of the large-scale alternatives at the mouth of the estuary were considered viable management options for Elkhorn Slough. These alternatives would have reduced tidal scour, but it was not clear that they would have supported long-term marsh sustainability, and they involved a risk of water quality degradation which could negatively impact biodiversity and ecosystem services important to recreational visitors and fishers.

Thus while the decision-makers began by considering large-scale alternatives, as a result of this EBM process they instead chose investment in small- to medium-scale restoration projects, which

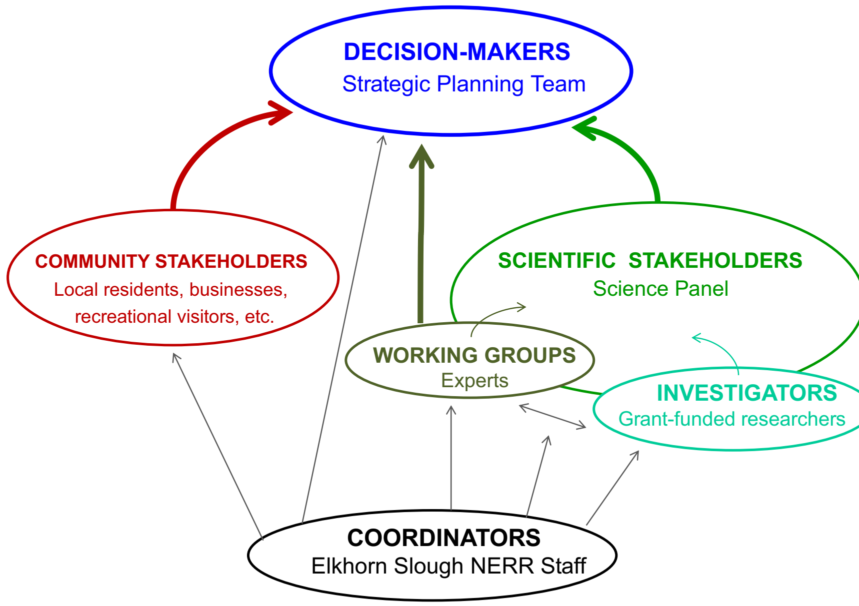

Fig. 3. Decision-making for the Elkhorn Slough EBM initiative, the Tidal Wetland Project. Conceptual diagram showing how different participant groups support decision-making by the Strategic Planning Team, both for selection of large-scale restoration alternatives and for other strategic planning for the estuary.

involved lower risk to the ecology of the estuary and greater confidence of benefits to the ecosystem than any of the large-scale alternatives. One recommendation, which has already been partially implemented involved reduction of tidal velocities in the large Parsons Slough complex of the estuary with a submerged sill. Another recommendation was to directly restore salt marshes through sediment addition to subsided areas (adjusting local marsh plain elevation rather than water levels in the whole estuary); work has begun on one such restoration project. A related recommendation indicated the importance of further research to address causes of marsh dieback, which are more complex than originally recognized, and to explore additional options for enhancing marsh sustainability in the future. New research has been initiated as a result of this recommendation.

While the original focus of the large-scale alternatives was on reduction of tidal exchange, one of the final recommendations of the EBM process was, ironically, to increase tidal exchange to portions of the estuary. Investigations conducted as a part of this process revealed that water quality and biodiversity are extremely degraded in the approximately 50% of the estuary with restricted tidal exchange. Decision-makers recommended increasing exchange to some of these wetlands, where it would not contribute significantly to tidal scour or conflict with other local management goals or landowner values. ESNERR has restored tidal exchange to one small managed wetland following this recommendation, and has applied for funding to restore a much larger tidally restricted wetland in the estuary.

Water quality assessments and modeling undertaken as a part of the characterization of large scale alternatives led to a new recognition that the estuary overall is moderately eutrophic, and that many of the more peripheral, and often tidally restricted, wetlands in the estuarine complex are highly eutrophic. One recommendation resulting from this EBM process was thus for regional organizations to support initiatives to decrease nutrient inputs, and to foster further research on the sources, consequences, and potential mitigation of nutrient-loading to the estuary. Thus while the original focus was on ecosystem degradation resulting from the artificial harbor mouth to the estuary, the flexibility of the EBM process allowed for a new emphasis on other threats to ecosystem integrity.

A final recommendation was that stakeholders in this EBM initiative explore the potential for jointly setting specific goals for habitats and conditions in Elkhorn Slough watershed, so that multiple organizations can implement projects under a shared conservation plan. In the course of evaluating the trade-offs associated with each of the large-scale restoration alternatives proposed for Elkhorn Slough, it became clear that there is no broadly agreed upon consensus for habitat goals or ecological conditions for the estuary. Currently, several conservation organizations are managing different portions of the current and historical estuarine wetlands of the Elkhorn Slough watershed, some with contrasting goals. A future phase of the EBM initiative could build consensus on future targets, for instance by choreographing a collaborative process to create maps that illustrate the desired mosaic of marine vs. brackish vs. freshwater habitats, and/or target areas for different valued biodiversity elements (e.g. salt marsh, intertidal mudflats, native oysters, snowy plovers) or ecosystem services (e.g. recreational activities, water filtration).

3. Application of EBM criteria

We considered the 17 criteria for EBM developed by Arkema et al. [4], and present evidence (Table 1) indicating that we have thoroughly applied each of them to this process at Elkhorn Slough. Arkema et al. [4] noted that very few if any projects comprehensively apply all of these tenets of EBM, so perhaps our project is unusual in doing so. However, it is possible that self-evaluation by coordinating staff and lead investigators, such as we have done here (Table 1) yields different perspectives from outside evaluation – if an external researcher had only searched the broadly disseminated public documents available for this project, s/he might not have so readily generated examples as we, who were intimately familiar with the project, were able to do. Nevertheless, even the public documents (e.g. [14,18]) provide fairly clear evidence for implementation of these 17 criteria. Our case study thus demonstrates that it is quite feasible for EBM initiatives to successfully apply all of these varied and broad criteria to their projects.

4. Lessons learned from implementing EBM

Ecosystem-based management is challenging, time-consuming, and costly for the same reasons that it is powerful and effective:

Table 1
Application of EBM criteria by Elkhorn Slough Tidal Wetland Project. Criteria and explanation in first two columns are taken from Arkema et al. [4]. The third column provides an example of how this criterion was applied by the Elkhorn Slough Tidal Wetland Project (TWP) in strategic planning decisions about wetland restoration alternatives.

EBM criteria	*Explanation of criteria*	Concrete examples of application at Elkhorn Slough
General criteria		
Sustainability	*Emphasizes maintenance of one or more aspects of the ecosystem*	The vision statement of TWP, drafted and approved by the Strategic Planning Team, is “We envision a mosaic of estuarine communities of historic precedence that are sustained by natural tidal, fluvial, sedimentary, and biological processes in the Elkhorn Slough Watershed as a legacy for future generations.” [14]
Ecological health	*Includes non-specific goals for ecosystem health or integrity*	TWP objectives are broad and non-specific [14]. While specific concerns about tidal erosion and marsh loss motivated the development and consideration of large-scale engineered fixes, these were ultimately rejected because of concerns about negative impacts to overall ecological health of the estuary. [18]
Inclusion of humans	*Recognizes that humans are elements in an ecosystem and their education and well-being are important components of management decisions*	Engagement of diverse stakeholders and public outreach has been a key component of TWP [14]. The creation and maintenance of the Moss Landing Harbor was recognized as playing a major and permanent role in the estuarine ecosystem, and a representative of the Harbor District participated on the Strategic Planning Team [18]. Increased engagement with farmers to address nutrient loading was one approved recommendation by TWP decision-makers [18].
Ecological criteria		
Complexity	*Acknowledges that linkages between ecosystem criteria components, such as food web structure predator–prey relationships, habitat associations, and other biotic and abiotic interactions, should be incorporated into management decisions*	Salt marsh dieback was a main motivation for consideration of large-scale engineered alternatives, because the artificial harbor mouth was initially identified as the likely driver of marsh loss. New science generated by this initiative revealed that causes of marsh loss are more complicated and involve linkages to other human alterations, and some factors, such as sediment starvation and eutrophication, might worsen under large-scale mouth fixes. This influenced some decision-makers to reject large-scale mouth alternatives. [18,20,22]
Temporal	*Incorporates temporal scale and the dynamic character of ecosystems*	A new paleoecological analysis suggested that marsh extent has been dynamic over the past thousands of years at Elkhorn Slough, and that the loss documented over the past century was preceded by a gain in marsh extent, perhaps related to European colonization, so current marsh extent falls within the natural range for the estuary. Understanding of ancient dynamics of marsh gain led to recognition that 1850 marsh extent is not desirable or even feasible as a restoration target. Modeling of future sea-level rise impacts to marshes also led to recognition that most of the marshes in the system will not be sustainable [22,43]
Spatial	*Recognizes that ecosystem processes operate over a wide range of spatial scales*	Analysis of eutrophication indicators at 18 wetlands in Elkhorn Slough revealed high spatial variation in eutrophication. While the estuary as a whole is highly nutrient loaded, those areas with strong tidal exchange are only moderately eutrophic, but those with limited tidal exchange are highly eutrophic. This finding suggested that decreasing tidal exchange might have negative effects on water quality [18,24]. Spatial scale was also explicitly considered when modeling marsh migration in the face of sea level rise, recognizing that tomorrow's marshes may be outside today's footprint [22].
Human dimension criteria		
Ecosystem goods and services	*Recognizes that humans use and value natural resources, such as water quality, harvested products, tourism, and public recreation*	The socioeconomic analysis highlighted the importance of kayaking as an ecosystem service, and safe and accessible kayaking was a major consideration in rejection of two of the management alternatives by the Strategic Planning Team. Harbor access and channel navigability was also a major consideration considered when developing and evaluating alternatives [18,33].
Economic	*Integrates economic factors into the vision for the ecosystem*	An economic analysis was conducted to identify the dominant economic activities in the estuary, and to characterize linkages between them and estuarine conditions. The economic analysis also included cost of the restoration alternatives, and this was an important consideration for Strategic Planning Team decision-making. [18,33]
Stakeholder	*Engages interested parties in the management planning processes to find common solutions*	Over one hundred stakeholders were engaged in the evaluation of restoration alternatives, with representation by resource managers, conservation organizations, regulatory agencies, scientists, and community-members (residents, businesses, recreational users). Dozens of meetings were held to engage these stakeholders [18, Table S1]
Management criteria		
Science-based	*Incorporates management decisions based on tested hypotheses*	The final decision and recommendations were based heavily on the interdisciplinary science evaluations. A large, active Science Panel of regional

Table 1 (*continued*)

EBM criteria	Explanation of criteria	Concrete examples of application at Elkhorn Slough
		experts met frequently to deliberate the evidence, and 12 scientific working groups contributed significantly to the project. [18]
Boundaries	*Recognizes that management plans must be spatially defined*	The focus of consideration was explicitly defined as the current and historic estuarine habitats of the Elkhorn Slough watershed, although larger areas were included in consideration of marsh migration and of sources of nutrient inputs. [14]
Technological	*Uses scientific and industrial technology as tools needed to monitor the ecosystem and evaluate management actions*	Bathymetric change was quantified with multibeam technology and GIS change analysis, revealing high erosion rates and motivating the development of alternatives [14]. A sophisticated network of in-situ nutrient and water quality sensors provided critical data on source and transport of nitrates in the estuary; the Land Ocean Biogeochemical Observatory revealed how delicately poised water quality in the estuary is, which led to concerns about reduction in tidal exchange associated with mouth-shrinking alternatives [18,23].
Adaptive	*Continue to improve management actions through systematic evaluation*	One recommendation approved by the Strategic Planning Team was to use monitoring data from a smaller scale sill [the Parsons Sill project] to inform future consideration of a larger sill at the mouth of the estuary; a comprehensive monitoring program, with advisory input from interdisciplinary working groups, has implemented this monitoring. [18]
Co-management	*Promotes shared responsibility for management between multiple levels of government and stakeholders*	The Strategic Planning Team, tasked with making strategic planning decisions for the estuary, is comprised of managers with regulatory or jurisdictional authority over Elkhorn Slough, as well as representatives from regional conservation non-profits and estuarine conservation scientists. [14,18]
Pre-cautionary approach	*Manages conservatively when threats to the ecosystem are uncertain*	The high degree of uncertainty and risk associated with large-scale engineering of the mouth of the estuary was the major reason why the Strategic Planning Team rejected the mouth alternatives; the precautionary principle was applied with regard to protecting species such as sea otters and migratory shorebirds that currently thrive in the estuary. [18]
Interdisciplinary	*Bases management on scientific understanding from several disciplines [ecology, economics, sociology]*	The approved recommendations were developed directly in response to the interdisciplinary evaluations (hydrodynamics, geomorphology, water quality, biological indicators, and socioeconomics); the complex trade-offs revealed by these interdisciplinary perspectives resulted in selection of the “no action” alternative for the mouth of the estuary. [18]
Monitoring	*Tracks changes in biotic, abiotic, and human ecosystem components for management purposes*	Extensive monitoring datasets on habitat change, water quality, and biological communities were used to determine likely trends under no action alternative and to make projections about consequences of different alternatives; interpretation of these data shaped the outcome of management decisions. [18]

because it offers a voice to all stakeholders and obtains information and insights from many different perspectives. Often there are divergent views; but in our experience, working together through these differences and ensuring that stakeholders have a voice results in a common vision shared by most participants and successful projects with community support behind them.

There has been a gap between academic advocacy for EBM and actual management implementation [4]. Case studies of EBM implementation are thus valuable to determine whether the approach can feasibly be applied on the ground, which is critical for gaining popularity with local managers as well as conservation theorists. Furthermore, examination of challenges encountered during implementation of EBM principles can help to refine approaches and build future successes.

We summarize below lessons that grew directly out of our experience implementing EBM at Elkhorn Slough. For each, we describe challenges we faced and recommendations for overcoming them, based both on what we did do, and what we wish we had done, in hindsight. Our goal is to share these lessons learned in a manner that is specific enough to explain their genesis, but general enough to be broadly applicable to other systems.

4.1. Interdisciplinary collaboration

Challenge: differences in professional culture, paradigms and values can hamper productive interdisciplinary collaboration.

Recommendation: choreograph a process for communication among partners with different expertise, and develop syntheses that capture multiple perspectives.

It is still relatively rare to commit to a thoroughly interdisciplinary approach to environmental management. We implemented this critical principle of EBM [34], engaging an interdisciplinary team of investigators and stakeholders to evaluate restoration alternatives from a diversity of perspectives. This pathway was neither fast nor easy. Indeed, one of the most challenging aspects of EBM implementation at Elkhorn Slough was reconciling the pronounced differences in perspectives between highly engaged participants representing different disciplines. Conflicts arose because of differences in professional culture that resulted in contrasting values. Participants were often comfortable with the methodologies and constraints in accuracy of their own discipline, but concerned about the rigor of other disciplines, or frustrated with the limitations to predictions they could provide. Moreover, there were stark contrasts between professional cultures in desired restoration outcomes resulting from differences in currencies used to evaluate them. For instance, participating hydrologists and geomorphologists were extremely concerned about the fast currents, sediment export, and tidal erosion caused by the harbor mouth, while the water quality scientists highlighted the benefits of strong tidal flushing for mitigating eutrophication, and were more concerned about decreased tidal exchange resulting from proposed restoration projects or already occurring behind water control structures. Conservation biologists focused on supporting populations of key estuarine species, including those that have coexisted well with extensive tidal erosion (sea otters, shorebirds, etc.) and tended to view highly managed systems with skepticism. Social scientists focusing on human values, while using very different currencies and approaches, came to similar conclusions as the conservation biologists. In contrast, proponents of ecological engineering favored construction projects to actively manage physical processes.

What enabled us to work through these challenges was communication at different scales. We held many small meetings to share perspectives among disciplines, increasing trust and understanding. Despite differences in professional currencies and paradigms, in the end the investigators and stakeholders found it valuable and productive to work together, questioning each others' assumptions and learning from each other. At a larger scale, for the big stakeholder meetings, we implemented communication strategies designed to fairly represent multiple perspectives. Presenters from different disciplines were given similar, consecutive speaking and discussion slots on the agenda, and contributions from each discipline were synthesized in a consistent summary table evaluating alternatives. Obtaining and integrating interdisciplinary perspectives took a lot of time and resources, but led to more balanced decisions. For instance, taking only a hydrological and ecological engineering perspective to slowing erosion might point to one extreme solution (constructing a high sill to the mouth of the estuary), while taking only a water quality or biological diversity perspective might point to another (taking out all water quality structures in the system to improve water quality and enhance biodiversity), but incorporating both of these led the decision-makers to choose a middle path that recognizes trade-offs between different currencies and values.

Based on our experiences, we thus highly recommend an interdisciplinary approach to investigations and decision-making in EBM. The challenges of such an approach can be mitigated through frequent communication. The process requires a technically savvy but neutral coordinator. The coordinator must be intimately familiar with the ecosystem and the approaches and perspectives of different disciplines, so s/he can synthesize findings and choreograph group discussions. This coordinator can also be charged with developing communication tools that fairly capture multiple perspectives and make them available to stakeholders and decision-makers, so different currencies can be incorporated into collaborative decision-making.

4.2. Participant roles

Challenge: providing sufficient clarity about roles and responsibilities of different participants in the collaborative decision-making process.

Recommendation: coordinate a robust, transparent process for participation and interactions among stakeholders.

Coordinating the involvement of many different stakeholders, who varied from light to intense engagement, or from continuous participation to joining in for limited periods, proved to be very difficult. During the launch phase for our EBM process (Supplementary Table S1), we invested heavily in working with stakeholders to develop clear roles and responsibilities (Fig. 3). Overall, the early design of these roles and subsequent implementation was successful, and we recommend this sort of approach to other EBM processes. We found it effective to have a small panel of decision-makers (the Strategic Planning Team) ultimately selecting restoration alternatives, supported by a diverse Science Panel and informed by public input. The work of the Science Panel was in turn supported by numerous ad hoc working groups that included local and national experts, and by grant-funded investigations. All of the above was supported by high investment by ESNERR, the coordinating organization, in preparing heavily for each meeting, following guidelines for effective collaborative decision-making (e.g. [35]). We found it critical to clearly define roles and responsibilities of different participants, and to develop a roadmap to the process. As a result of this very heavy investment, most stakeholders indicated that they trusted the rigor and transparency of the process, and remained engaged for almost a decade in strategic planning and subsequently in support for on-going implementation of the plans.

4.3. Cost

Challenge: implementing an ecosystem-based management approach is very costly in time and human resources.

Recommendation: identify dedicated long-term funds that can support a robust stakeholder engagement process and syntheses of relevant science.

While it was hugely rewarding to take an interdisciplinary approach and heavily involve stakeholders in a clear process, we want to be transparent about the high cost of this type of environmental decision-making. Just this first phase of our EBM process, in which large-scale management alternatives for the estuary were developed, assessed, and selected, took seven years, millions of dollars, and thousands of person-hours. Participation by stakeholders and decision-makers was made possible by contribution of their hours to numerous meetings and review of documents (Supplementary Table S1). Significant ESNERR staff resources were dedicated to the process. Coordination of the EBM process and funding of new scientific investigations to evaluate management alternative was only possible because of generous funding from a variety of sources, in particular, a large grant jointly from the David and Lucile Packard and Resources Legacy Fund Foundations.

Before initiating a comparable EBM process, we recommend that coordinators identify a secure source of funding with a long time horizon. Building trust among stakeholders and implementing a collaborative decision-making framework takes years, as does the integration of ecology and economics [36]. Conservation funders could greatly support EBM by providing long-term grants that support collaborative decision-making and the science required to inform it. It is relatively easy to obtain large grants that provide short-term funding for restoration projects with concrete, on-the-ground outcomes. But it is rare to find funding sources to conduct the thoughtful collaborative decision-making needed first, to set the restoration targets for such projects. The Packard Foundation provided a welcome exception, from 2004–2009, when it pioneered an EBM program funding regional initiatives, including the one at Elkhorn Slough. Unfortunately, this program has ceased, so nascent EBM initiatives will need to seek elsewhere for sources of long-term funding to implement collaborative decision-making. Alternatively, they can attempt to move a continuous EBM process forward spanning multiple separate grants, earmarking some funds from each grant towards consistent coordination of the stakeholder process.

Once the initial phase (e.g. first 5–10 years) of a regional EBM initiative has been completed, developing a robust collaborative framework and setting a vision for future action, the cost of continuing to coordinate and implement an EBM approach to management decreases dramatically. We can now more easily build funding for stakeholder meetings and continued coordination into restoration action grants that implement the decisions reached in the initial phase.

4.4. Ecosystem services

Challenge: recent academic literature emphasizes the importance of ecosystem services in an EBM approach, and while benefits to humans played a role in decision-making at this California estuary, the primary focus of most active participants and decision-makers was on ecosystem integrity.

Recommendation: recognize that for ecosystems where most stakeholders are already committed to ecosystem sustainability, EBM can include ecosystem services concepts but be successfully implemented without relying primarily on an ecosystem services framework.

Early definitions of EBM recognized the role of humans in the ecosystem, but emphasized ecological sustainability [3,34]. However in the past decade, the importance of human benefits from the environment has played an increasingly dominant role in conservation, and sustainable delivery of "ecosystem services" (values of nature to humans) has become a prominent part of newer conceptions of EBM [4,37]. Proponents argue that measuring benefits to humans, ideally using monetary metrics, provides a common currency that improves collaborative decision-making [13]. However, alternate views suggest that some of the failures of EBM to increase ecological sustainability have been due to attempts to find win-win solutions that support multiple human uses, and to put this goal above protection of environmental integrity [2].

Consideration of ecosystem services certainly informed the selection of management alternatives for Elkhorn Slough. For instance, the decision-making team included the Moss Landing Harbormaster, who ensured that no alternative would be chosen that endangered safe and economical harbor operation and vessel navigation – a vital ecosystem service provided by the estuary. Other ecosystem services, such as kayaking, birdwatching and fishing were characterized by the socioeconomic analysis, and incorporated into decision-making. A major reason for some decision-makers rejecting large-scale projects altering the mouth of the estuary was concern for negative effects on kayaker access and safety. Nevertheless, the socioeconomic analyses conducted as a part of this EBM process did not reveal many clear or direct linkages between ecosystem services and environmental contrasts associated with different management alternatives. It was not apparent how changes in tidal erosion of channels, in salt marsh extent, or in water quality would affect ecosystem services such as birdwatching, kayaking, harbor operation or power plant functioning.

While human uses of the estuary were included in decision-making, most of the decision-makers were primarily motivated by concern about ecological sustainability and resilience of the estuarine ecosystem. Beyond the small decision-making team, the most heavily engaged members of the larger stakeholder group were conservation scientists, land managers, and environmentalists, who came to the initiative with a belief in the intrinsic value of nature. This EBM initiative thus focused on attributes of estuarine ecosystem integrity and function, such as hydrological and sedimentary processes, water quality, and biodiversity. These ecosystem attributes of importance to our decision-makers and stakeholders could be considered cultural ecosystem services, and thus be captured within an ecosystem services framework [8]. But the concept of ecosystem services largely did not resonate with our conservation-minded stakeholders, whose participation in the process was inspired by a commitment to nature rather than to human benefits – they were motivated by their hearts not their wallets [38]. These stakeholders were broadly aware of the concept of EBM and committed to its application to Elkhorn Slough, but were largely unaware of the academic evolution of this term (with the addition of "-based" intended to convey a focus on human activities). Our conclusion is that, despite the recent emphasis on an ecosystem service framework [13,39], EBM can be successfully implemented with explicit objectives focused more on ecosystem integrity than human benefits, at least in systems where stakeholders are already strongly committed to conservation principles, and/or where human uses are not strongly affected by ecosystem changes.

4.5. Restoration targets

Challenge: conflicts arise from differences in desired restoration targets.

Recommendation: develop a detailed, shared vision for restoration targets, so that specific management actions can be evaluated with respect to how well they achieve this consensus plan.

Participants in this EBM process were generally committed to conserving and restoring ecological functions and working to enhance sustainability and resilience of the ecosystem. There are no major consumptive services within the boundaries of the estuary. This is very different from EBM in forest planning, where logging and biodiversity conservation are in apparent conflict, or EBM in marine spatial planning, where fishers and proponents of marine reserves are pitted against each other. In our process, the biggest conflicts arose because of differences in perspectives about specific restoration targets. Perhaps more than many other ecosystems, estuaries are extremely dynamic in space and time, with variation in physical conditions (driven by variation in freshwater and tidal influence) resulting in variation in habitat extent (brackish marsh, salt marsh, mudflats, channels) and consequent variation in abundance and distribution of different communities. Participants in the EBM process differed in where along the spectrum of a more vs. less marine-influenced system they felt Elkhorn should fall, and how much salt marsh should be restored.

For many participants, historical and pre-historical conditions provided important guidance for restoration trajectories. However, there were disagreements about which period to use for guidance – some participants favored recent historical conditions, such as the 1930s, when major hydrological alterations to the system had already occurred, others pointed to conditions documented by earliest European maps and records from the 1800s, while still others relied on the paleoecological record of the past thousands of years, which documents a system dynamic in salinity and marsh extent across long time periods. Other participants advocated for the importance of managing estuarine habitats for important regional needs, even if these differed from historical functions. For instance, a portion of the estuary is managed to exclude tidal influence and remove marsh vegetation in order to provide nesting habitat for threatened Snowy Plovers. Also, various former estuarine habitats are currently managed as freshwater impoundments, because so much freshwater habitat has been lost in the region and endangered species such as Santa Cruz long-toed salamanders depend on freshwater breeding sites.

The stakeholders thus concurred on science-based restoration of the estuary, but nevertheless differed quite dramatically in restoration targets for the estuary. In the nearby San Francisco Bay-Delta, there have also been conflicts in values underlying differences in stakeholder interpretation of scientific recommendations [40]. In hindsight, it would perhaps have been wise – although time-consuming and challenging – to have collaboratively set shared objectives for restoration targets for the estuary: how much estuarine vs. brackish vs. freshwater habitat is appropriate, how much vegetated wetland vs. mudflat vs. channel, and what water quality standards should be met. Such a joint vision would likely involve a spatial mosaic, so that multiple, contrasting objectives can be accomplished in different places (some representation of historical conditions, some areas managed for threatened species, some areas where water quality is maximized, etc.). Setting explicit thresholds for indicators is now considered a critical step in the EBM process [9]. Prior consensus on restoration targets would have made this phase of the EBM process, as well as future management decisions, much smoother, because management alternatives could have been evaluated in light of how effectively they met the consensus objectives. We recommend setting explicit, specific objectives for new EBM initiatives. Nevertheless, our case study demonstrates that collaborative decisions about management alternatives can be made in the absence of a detailed consensus on restoration targets. Rather than reaching consensus, multiple views were represented by different stakeholders, and were incorporated in the decision-making by the evaluation process (where all stakeholders were invited to score options) and by the final vote (where decision-makers with different perspectives were represented). And indeed, while we have highlighted the conflicts above, many of the decision-makers were not advocating for particular restoration targets but instead were attempting to optimize between multiple contrasting targets, using the interdisciplinary evaluations and resulting summary score cards prepared for stakeholders to seek middle ground.

4.6. Multiple scales

Challenge: no single geographic or jurisdictional scale for an EBM initiative can engage the right stakeholders to address all ecosystem functions and threats simultaneously.

Recommendation: keep the scope of an EBM initiative limited enough to allow for a good pace of progress and engagement of a relatively small group of decision-makers, but be transparent about which ecosystem components comprise the focus, and form clear bridges to related processes operating at different scales.

Guidelines to the implementation of EBM imply that it is desirable to address many possible ecosystem functions and threats to them in a single process. However, there is no single appropriate scale for management [34]. Realistically, the number of different types of stakeholders that would need to be engaged would be logistically impossible to coordinate in meetings, and the cost of obtaining scientific analyses of all components simultaneously would be prohibitive. So most EBM initiatives focus on particular ecosystem components; for instance, many coastal EBM projects focus on ecosystem services related to fishing and marine reserves e.g. [10,11]. The Elkhorn project was very focused: the current and historical estuarine ecosystems of the Elkhorn watershed was our geographic focus, decision-makers were primarily those with jurisdictional and regulatory authority over these, and stakeholders were those who care about some aspect of the estuary [14]. The emphasis for this phase of the EBM project was evaluation of management alternatives designed to address major habitat changes resulting from the artificial harbor mouth to the estuary. This tight focus was key to our ability to make significant progress understanding estuarine processes, building trust among stakeholders, and enabling decision-makers to map out a future for the estuary. Nevertheless, some participants were dissatisfied or confused about the limited focus, and we recognize that it would have been valuable to jointly develop and then frequently refer to a conceptual model mapping out the focus of the current phase.

Trying to address other threats to this ecosystem would have involved very different geographic and jurisdictional scales, stakeholders, and scientists. For instance, invertebrate invasions have led to whole-scale changes in estuarine communities and function at Elkhorn Slough. Many exotic species in the estuary arrived via international shipping to large harbors in California, then traveled to Elkhorn Slough via small boats [41]. Addressing this threat to the ecosystem would thus require a much larger geographic scale, with emphasis on stakeholders and decision-makers involved in international shipping and in regional boating.

Regional agriculture also has strong influences on the ecological sustainability of the estuary, and yet was not directly incorporated into this phase of the Elkhorn Slough EBM project. Agriculture has impacted the estuary in a variety of ways, ranging from historic and current dikes built to “reclaim” estuarine wetlands as pastures or fields [42], water control structures that decrease tidal inundation and water quality [24], diversion of the Salinas River, decreasing sediment supply and freshwater to the estuary, groundwater overdraft, which altered salinities and marsh community structure [43], and inputs of nutrients, contaminants and sediments [17]. These latter impacts, in particular pollution resulting in eutrophication, were an important part of the evaluation of management alternatives for the estuary. However, actually addressing the source of these impacts was not a component of the current EBM phase, not because we failed to understand its importance, but because we needed to focus our efforts and resources. To engage agricultural stakeholders who impact the estuary, a much larger geographic scope would be required (because agricultural drainage from other watersheds, including the lower Salinas River watershed, empties into the Elkhorn Slough estuary). Decision-makers would be very different, including organizations that represent, regulate, or assist farmers. The types of expertise would be very different as well – scientists who understand marsh sustainability or tidal hydrodynamics are not the same as those who study best management practices for agricultural run-off. Stakeholders would differ too – the people who care about setting marsh restoration targets are different from those who care about farm management practices. Thus, it is effective to have separate stakeholder engagement and management processes for the estuary and for the surrounding agricultural watersheds. However, the decision-makers in our EBM initiative recommended forming tighter, more explicit linkages between such processes. For instance, the estuarine stakeholders and decision-makers could identify key thresholds for water quality, which would inform regional initiatives to reduce nutrient-loading and contamination. Based on our experience, we recommend keeping the scope of EBM projects focused, while ensuring that this focus is transparent to stakeholders. The ecosystem services or threats that are not directly addressed should be at a minimum represented in conceptual models, and clear bridges should be formed between nested or related stakeholder processes operating at different geographic or jurisdictional scales.

4.7. Evolving understanding

Challenge: science-based management decisions should be premised on an understanding of key ecosystem drivers, but this understanding may undergo rapid evolution as new studies are conducted.

Recommendation: take a precautionary approach and allow for flexibility in adaptive management, particularly in systems where understanding of ecosystem processes is still undergoing frequent paradigm shifts.

Scientists have at times been chastised for their unwillingness to rapidly complete syntheses and for their propensity to highlight uncertainty. At the beginning of our EBM initiative, some stakeholders expressed impatience with the new interdisciplinary studies that would take years to complete, urging decision-makers to move forward with one alternative (construction of a sill at the entrance to the estuary) since it clearly would address the most urgent threat to the ecosystem. However, the new science that was conducted during the course of this EBM project fundamentally changed the management perspectives of key decision-makers. The paradigm shifts were hard won and not universally experienced, with some stakeholders holding tight to their original positions even in the face of new data. However, the majority of stakeholders were open to changing perspectives, and the outcome of the management decision-making was very different in 2012, when voting occurred, than it would have been in 2004, when the process was begun.

One major paradigm shift that occurred during this period was that eutrophication is probably impacting biodiversity and associated ecosystem services at least as much as tidal erosion resulting from the artificial harbor mouth, and large-scale restoration alternatives directed at the latter might worsen the former. Investigations that highlighted nutrient-loading and eutrophication (www.mbari.org/lobo; [24]) were one major reason why construction of a sill at the mouth of the estuary was rejected by decision-makers. A second paradigm shift during this period occurred with regard to causes of marsh die-back. At the inception of the EBM initiative, the harbor mouth was considered the primary cause of extensive salt marsh die-back observed along the main channel of the estuary. Marsh loss was a major impetus for the initiation of the EBM process, and construction of a sill at the mouth was considered a viable method of increasing marsh sustainability. Studies that occurred during the EBM process [19,21,22,43] revealed that causes of marsh die-back are complex, and that decreases in riverine sediments and subsidence related to eutrophication may be major contributors. These latter two factors would be worsened, not improved, by construction of a sill at the mouth of the estuary, and so there is high uncertainty about whether a sill would increase or decrease marsh sustainability. The new information of potential ecological costs to the sill (in terms of possible worsened eutrophication) and higher uncertainty about benefits (in terms of marsh sustainability) played an important role in the ultimate rejection of the sill as a currently viable management alternative for the estuary.

Major surprises are inevitable in studies of ecological dynamics, even when top experts have thoroughly studied a system for many years [44]. It is thus important to recognize the limits of our understanding of ecological systems, so we avoid hubris in management [1]. At Elkhorn Slough, where new science led to fundamental shifts in understanding of ecosystem processes, it was clearly premature to pursue major, irreversible management actions that were premised on an understanding of ecosystem processes. We concur with the recommendation [44] to take a precautionary approach and allow for flexibility in adaptive management, given the frequency of ecological surprises.

5. Conclusions

The EBM framework and process provided a flexible, adaptive approach to collaborative decision-making at Elkhorn Slough. The final decisions and recommendations were very different from the focus at the initiation of the process. Understanding and perspectives of stakeholders evolved over the course of the initiative, informed by the new interdisciplinary investigations and consideration of broad linkages and geographic scales.

The ten final recommendations, strongly supported by the majority of stakeholders and overwhelmingly approved by the decision-makers, provide a roadmap for the next decades of restoration in the estuary. Indeed, in the time since their approval, they have already provided guidance to implementation projects and facilitated project permitting and funding. The stakeholders and decision-makers who shared in the generation, evaluation, and selection of restoration alternatives are now committed to working towards their implementation. This joint implementation of collaborative decisions is one important measure of the success of application of EBM to this estuarine ecosystem. The ultimate measure of success – long-term sustainability of ecosystem functions and services – can, by definition, only be evaluated decades into the future.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.marpol.2015.04.002.

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