Marine Policy 34 (2010) 340–348

Contents lists available at ScienceDirect

Marine Policy

journal homepage: www.elsevier.com/locate/marpol

The many faces of ecosystem-based management: Making the process work today in real places

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ARTICLE INFO

Article history:
Received 4 August 2009
Accepted 14 August 2009

Keywords:
Ecosystem-based management
Integrated ecosystem assessment
Marine
Puget Sound
Indonesia

ABSTRACT

Despite the widely accepted need for ecosystem-based management of coastal and marine systems, many managers struggle with how to put these principles into practice. Commonly voiced concerns include complicated and expensive implementation, prohibitive data requirements, and lack of testing with long-term applications. We address some of these perceived barriers by providing guidance on strategies and approaches that can be used for the steps of one ecosystem-based management process, the integrated ecosystem assessment framework, including scoping, defining indicators, setting thresholds, risk analysis, management strategy evaluation, monitoring and evaluation. Importantly, we demonstrate how an ecosystem-based management approach can be utilized in a variety of contexts which vary widely in data quality and availability, governance structure, and time frame. We then illustrate the suggested steps in the process by exploring two case studies that represent realistic ends of the data/governance/time frame spectrum: Puget Sound, Washington, USA and Raja Ampat, Indonesia. By providing concrete suggestions for how to move forward with key steps in an integrated management process, we show that ecosystem-based management is feasible from a range of starting points and that for any given starting point there are numerous productive paths forward.

1. Introduction

Management and conservation of natural resources have been plagued by two shortcomings: considering only single sectors or objectives and overlooking the value of ecosystem services in decision-making. Scientists and managers have argued for ecosystem-based management (EBM) as a means to address these challenges [1–4]. EBM recognizes that human and ecological well-being are tightly coupled such that sustainability only occurs when pursued in both arenas [2,4]. Although the importance of an ecosystem approach is widely accepted, it remains difficult to put these principles into practice.

Implementation of EBM is challenging in part due to perceptions that it is too complicated and has prohibitive information requirements. Compounding these perceptions is the scarcity of evidence of improvements in ecosystem outcomes as a result of long-term applications of EBM. The few examples of marine EBM worldwide tend to be small-scale, fishery-based, or in the incipient stages [5], leaving EBM proponents to base their arguments on principles rather than tangible proof.

Here, we dispel some of the perceived barriers to EBM implementation, demonstrating how this approach can be applied today in any context. We outline strategies using an EBM framework, the integrated ecosystem assessment (IEA), being developed by NOAA in the United States [6]. We have expanded the five step IEA approach to seven steps for discussion: scoping, defining indicators, setting thresholds, risk analysis, management strategy evaluation, monitoring and evaluation (Fig. 1). Ideally, this process is used iteratively, continually improving management and understanding of complex ecosystems.

2. Assessing the state of play for EBM

At each step in the IEA (or any) framework, many approaches and analytical methods can be used. The approaches taken are dictated to some degree by three common elements: data,

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doi:10.1016/j.marpol.2009.08.003

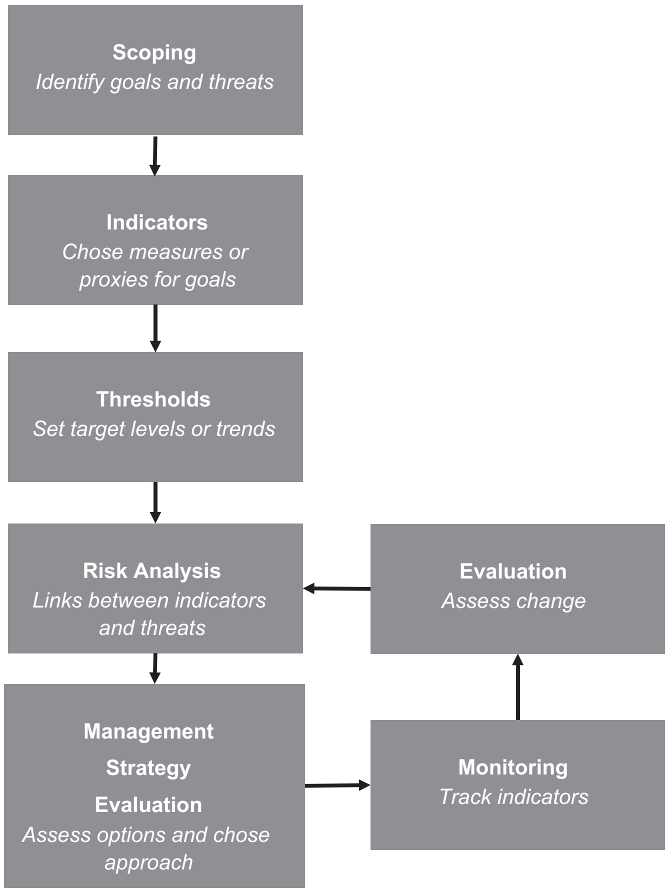

Fig. 1. The integrated ecosystem assessment (IEA) process. Adapted from Levin et al. [6], with permission.

governance and time frame. Here, we discuss the general significance of each of these elements for EBM. The IEA is a logical framework for EBM and thus the guidelines presented here are broadly applicable, regardless of the conceptual framework.

When managers contemplate the myriad species, ecological processes, interactions, cumulative effects, and drivers that could be considered in EBM, they face challenges with data acquisition. We consider data to be documented qualitative or quantitative information about the ecosystem of interest from published or unpublished research, experts, stakeholders, or local knowledge holders. Data availability may pose a challenge to EBM when data are few or existing knowledge is not documented in a traceable and accessible way. Even when data are ample, governance structures may obstruct data sharing and access. The timelines over which managers have to act can also inhibit the use of existing but scattered datasets because amassing and preparing data for use in analyses is time consuming.

Governance can also be seen as a factor inhibiting EBM. Characteristics of a governance system which can constrain or enhance EBM include the stability of the government, the level of cooperation and coordination among different government entities, the number of jurisdictions within the management region, and the ability of governments to enforce laws [7]. We define poor governance as a situation where: laws do not exist or are not reliably enforced, rule of law is not stable, property rights are not defined or enforced, decision processes are not transparent and inclusive, and/or stakeholders are in conflict over goals.

Finally, the length of time managers have to implement an EBM process influences which approaches are most appropriate. We assume that all EBM processes will have a long lifetime through iterative stages of planning and implementation, but the initiation or launch phase can be extremely short. Time constraints can alter the number of objectives that can be reasonably addressed, the rigor and complexity of analytical approaches, and the extent of monitoring programs. Importantly, even on short time frames of three years or less, there are critical first steps towards EBM that improve later outcomes.

In the next section, we detail how each step of the IEA process could be approached under different starting conditions. We then illustrate our suggestions with case examples representing two realistic ends of the management scenario spectrum; Indonesia is characterized by poor data and weak governance and Puget Sound, USA, represents ample data and strong governance.

3. Options for application of integrated ecosystem assessments

3.1. Scoping

In the initial step of an IEA, ecosystem objectives are identified, such as protection of species (e.g., killer whales, sea turtles), habitats (e.g., mangroves, coral reefs), processes (e.g., flood control, provision of water quality) or human well-being (e.g., human health, thriving resource-based communities) [6]. This step focuses management on critical components of the ecosystem and selects goals that will underpin the design of subsequent steps.

When data are poor, scoping can be informed by creating a qualitative conceptual model of the ecosystem through a stakeholder engagement process (Fig. 2). Data can be drawn from basic ecosystem understanding of participants, synthesis from disparate or informal sources, and understanding from similar ecosystems and societies. Ideally, a stakeholder process will engage a cross-section of all available perspectives including those of resource users, citizens, managers, and experts or specialized knowledge-holders. In situations with contentious relationships among stakeholder groups (e.g., weak governance), individual or sub-group engagements can replace a structured group consensus approach, referred to throughout as an "informal" stakeholder processes. Time may also limit the diversity of stakeholders who can be engaged, the amount of information that can be gathered and the type of forum that can be used. Individual, in-depth interviews of local knowledge-holders can be extremely valuable, but are very time consuming. Large, structured stakeholder discussions that seek to reach consensus can also take a long time, especially if the groups have a history of dissent. The right combination of stakeholders, process structure and depth of information will need to be identified for each situation. Importantly, although only discussed in detail for this step, stakeholder engagement is a good option for initial progress in low data situations for each IEA step.

In abundant data situations, in which there are data describing relationships between management targets and major system drivers or threats, sophisticated ecosystem simulation models and sensitivity analyses can reveal which connections in the system are strongest and most affected by management (Fig. 2). The species or processes involved in these connections would be ideal components on which to focus goals. When the time frame for scoping is short, an existing model could be applied quickly but if existing models are not available, a simpler approach will be necessary. Statistical analysis can quantitatively identify the most critical connections in the system in data rich situations with short time frames, or in relatively poor data systems (Fig. 2). Even statistical analyses can be time consuming, so conceptual modeling is a good option, while plans should include monitoring

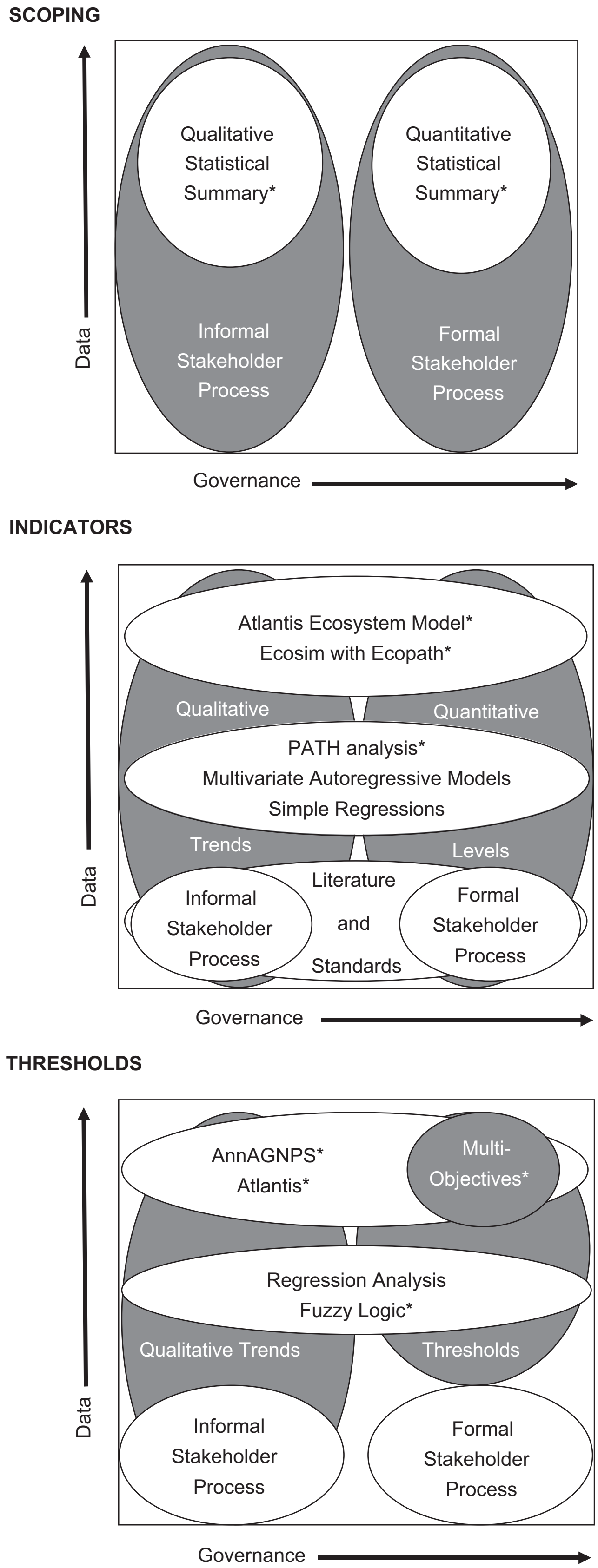

Fig. 2. Options for conducting the scoping, indicator and threshold steps of the Integrated Ecosystem Assessment process. These options present examples of approaches that can be used at each step, and are not an exhaustive list of all possible tools. Options presented for poor governance or poor data situations can also be used in good governance or high data situations, but not vice versa. An asterisk (*) indicates approaches that can be very time consuming. If the IEA process is on a short initiation timeframe, approaches at lower data or governance levels can be applied in the first iteration of planning and implementation.

and timing of future phases to allow more complex models and statistics in future iterations.

Regardless of the analytical approach used, scoping is largely a political step focused around policy discussions to select which objectives frame the EBM approach. Reaching agreement on common objectives is a major, time consuming hurdle. Given this, the level of governance may influence which analyses are used and how they are applied and discussed. In areas of relatively poor governance at the national level, it may still be possible to devise local area governance mechanisms that accomplish a shared objective agreed under a bottom up process (P. Christie, pers. comm.). In areas with relatively good governance there remain challenges to determine the appropriate scale of decision-making and how to mediate when stakeholder interests are in conflict [5].

3.2. *Defining indicators*

Once objectives are set, indicators are chosen to facilitate tracking of ecosystem status and trends relative to objectives [6] (Fig. 1). Indicators can relate to the condition of natural or human systems, and should encompass both. Examples of ecological indicators are population size of important species, acres of habitat, or toxin levels in water. Social indicators can include the number or types of jobs, amount of waterborne navigation, or level of livelihood for specific social groups (e.g., tribal nations, low/high income groups). Indicators should be relevant to management, informative to subsequent steps of the IEA process and trusted in the decision process.

When data availability is poor, generic indicators can be drawn from similar settings or guidance from the literature [8] (Fig. 2). Some work, largely for fisheries management, identifies useful indicators that show consistent behavior in diverse ecosystem settings [9]. Community-level ecological indicators, for example, have been shown to be the most reliable for detecting fishing effects [10]. Literature describing reference conditions or strong interactions among species, habitats, social and ecological drivers, or ecological processes can be used to help identify indicators. Although the use of historic data to set benchmarks or thresholds for restoration or management is highly contentious, such data can be used to identify key interactions. These types of information can be augmented with a stakeholder process to select a list of scientifically defensible indicators most relevant to management. Stakeholder processes to choose indicators in the absence of scientific guidance can lead to an overly long or irrelevant list, a challenge we discuss further in the case studies.

Even in poor data cases, multivariate statistics can be used to combine indicators and identify those that represent several characteristics of the system (e.g., [11,12]). In intermediate data situations, simple regressions, multivariate autoregressive models or path analysis could be used (in increasing order of complexity and data requirements) (Fig. 2). Again, the goal with these analyses is to identify the strong interactors in an ecosystem and use those as indicators.

Ecosystem simulation models require extensive data on ecosystem components and their interactions, but can be very useful for highlighting the most responsive indicators for a set of objectives (see Puget Sound case study). Sensitivity analyses of integrated management-ecosystem models can highlight the most important and effective indicators. Ecosystem simulation models can also be applied to components of the system to give quantitative guidance for some indicators. Extensive work in fisheries to use Ecopath with Ecosim models to assess food webs and identify critical biological indicators [13] is perhaps the best known application.

Indicator selection will also be determined by governance and timing. Weak governance can result in inappropriate selection of indicators and restrict the design of programs to monitor them. Furthermore, when the initiation phase of an IEA is short, thoroughly vetting a long list of possible indicators may not be feasible. As in the data-poor situation, existing guidelines can be used to identify an initial set of indicators that can be revisited in later rounds of adaptive management.

3.3. Setting thresholds

Thresholds need to be set for each ecosystem indicator (Fig. 1). In this step, we are moving from a general identification of which indicators best represent the system to setting actual targets for each indicator that represent a desired level of 'health' for the system. Setting thresholds addresses questions of "how much is enough" or "how little is too little" for indicator magnitudes. Under ideal circumstances, we would have ample time series data and sufficient time to use ecosystem simulation modeling to set quantitative thresholds for multiple objectives simultaneously. Models such as Ecopath with Ecosim or Atlantis [14] can help set thresholds for multiple criteria, but likely must be expanded or paired with other models to assess a wide set of objectives, including but not limited to fisheries (e.g., recreation and tourism, water quality, etc.) (Fig. 2). Fairly comprehensive hydrology models have been created to deal with hydrologic responses to management including the annualized agricultural non-point source pollution model (AnnAGNPS) (e.g., [15]). Combining models like this with models such as Atlantis to create a coupled terrestrial-marine and human-natural systems model will increase our ability to consider multiple objectives simultaneously over relevant ecosystem scales.

As a first step in data poor situations, knowledge of factors such as harvest rates, species composition and habitat condition based on local observation and stakeholder interviews can be a useful starting point (Fig. 2). When data are extremely sparse, important trends rather than thresholds can be identified for each indicator. Even in ample data settings existing thresholds can be used until better system-wide modeling can be completed. For example, thresholds that have been set to guide management of species (e.g., viability or rebuilding criteria established by state or federal management), habitats (e.g., no net loss or other state or federal targets), water quality (e.g., US Clean Water Act water quality standards), and human health (e.g., fish and shellfish consumption thresholds) for other programs can be used to guide initial decisions in other management contexts.

Additionally, when data are insufficient to run ecosystem simulation models, portions of the system can be modeled to gain quantitative guidance on a subset of indicators. Having a quantitative estimate of a threshold for even one indicator can help inform threshold setting for others. One such approach, used in fishery applications, is the development of minimum realistic models [16]. These contain the minimum essential pieces of the system to represent a specific set of interactions or indicators. Outside of a fisheries context, there are fewer simplified models of system components, although examples are emerging such as: The Natural Capital Project's models for water quality, flood mitigation, water supply and sediment transport, carbon sequestration, and tourism and recreation [17,18]. These can be used to help identify critical thresholds for some non-fisheries indicators.

In intermediate data cases, species indicators can be developed using single species models to derive the minimum viable population size, using this number as the indicator's threshold (Fig. 2). Indicator time series paired with disturbance data can also be analyzed by regression to identify thresholds. Alternatively, fuzzy logic can provide a rigorous framework for organizing literature values and coarse-scale or sparse primary data (e.g., [19]).

Regardless of data availability, poor governance may necessitate a focus on trends rather than thresholds if threshold values are contentious or cannot be monitored. Similarly, it may be difficult to formally assess multiple objectives if government agencies are not forthcoming with data, or if agencies or stakeholder groups are in conflict. In some cases, these challenges can be circumvented by using remotely sensed data or indirect data from other sectors.

3.4. Risk analysis

Each indicator will be affected by a range of threats (Fig. 1). The risk analysis step of IEA identifies these relationships and then assesses the current state of each indicator relative to the state of threats in the system [6]. Risk is described by the sensitivity of each indicator to human or natural disturbances in the system and the likelihood of each disturbance.

In the most sophisticated approach to risk analysis, ecosystem simulation modeling describes the resilience of indicators to the full range of exposure (Fig. 3). The likelihood of each risk can be derived from long time series data on risk occurrence. Resilience and exposure estimates can then be plotted against each other to derive an overall risk score. This approach is called productivity–susceptibility analysis (PSA) and has been used in ecosystem-based fisheries management [20]. PSA can also be applied in an intermediate data environment where literature values for resilience of simple indicators (e.g., species) can be combined with risk frequency estimates from the literature or local knowledge. Alternatives at this level of data availability include developing population viability analyses from count-based time series data [21] or using ecosystem viability analyses [22] (Fig. 3).

In the lowest data situations, an informal stakeholder process can be used to develop maps of threat intensity and frequency along with system resilience. As discussed, short time frames and poor governance can restrict the stakeholder process, so combinations of maps and conceptual models may be more appropriate. For example, Halpern et al. [23] have developed a global map of threat frequency for multiple impacts. These maps could be paired with locally developed conceptual models that link threats to indicators and that rank likely impacts of each threat in the system.

3.5. Management strategy evaluation

In this step, all of the information and decisions in previous steps are incorporated into a comprehensive assessment of how proposed management actions are likely to affect the chosen indicators [6] (Fig. 1). Projecting management impacts may sound like a daunting, complex process, but when necessary, strategies can be evaluated with simple, conceptual models that follow basic decision theory [24] and formalized expert opinion about the major linkages among objectives, drivers and management actions (Fig. 3).

Simple regression modeling or minimum realistic models can be combined with conceptual models to improve the representation of links between a subset of system components (see Puget Sound case study). The most formal process, called management strategy evaluation (MSE) [25,26], uses ecosystem simulation modeling to give sophisticated, ecosystem-wide projections of responses to management options. Although these models are very complex, they can be applied to specific questions in a short

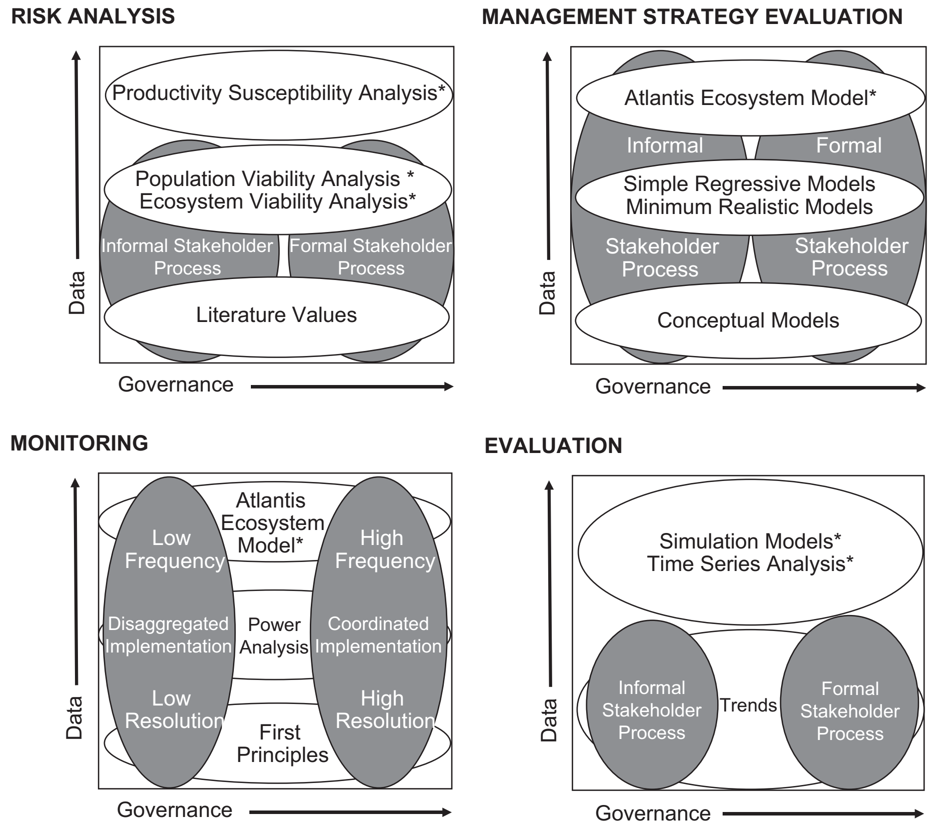

Fig. 3. Options for conducting the risk analysis, management strategy evaluation, monitoring and evaluation steps of the integrated ecosystem assessment process. These options present examples of approaches that can be used at each step, and are not an exhaustive list of all possible tools. Options presented for poor governance or poor data situations can also be used in good governance or high data situations, but not vice versa. An asterisk (*) indicates approaches that can be very time consuming. If the IEA process is on a short initiation timeframe, approaches at lower data or governance levels can be applied in the first iteration of planning and implementation.

window of time if the base models have already been developed for the system of interest.

Governance will affect this step of IEA by limiting the management strategies under consideration. Models of any level of sophistication can be constructed to help reveal which management options will be most robust to management uncertainty when governance is unstable or ineffective. It is also possible to use MSE to explore new or more effective governance structures themselves. Rather than assuming that governance will remain static, it may be useful to evaluate the potential for changing governance given various ecosystem effects.

3.6. Monitoring

Monitoring the outcomes of implementation is critical to document effectiveness of management strategies (Fig. 1). This stage of IEA involves designing and installing a monitoring program that identifies how the chosen management action(s) affects the chosen indicators [6]. Many of the data collected during monitoring can be used in future IEAs, allowing managers to move from data poor to data rich situations, improving the rigor and sophistication of their decisions with each iteration.

The simplest approach to designing a monitoring plan is to use general theories and stakeholder-based monitoring (Fig. 3). When historic data on indicators exist, we can use the variation in these measures to conduct a power analysis to inform the number of locations, replicates and sampling frequency for the monitoring program [27]. In cases where ecosystem models can be constructed, they can test the performance of monitoring programs. The model is used to generate "true" dynamics, and perturbations to the model are used to create time series of ecosystem dynamics. Various monitoring schemes, such as different sampling frequencies or spatial allocation of effort, can then be simulated. The results from the virtual monitoring program are compared to "true" dynamics, and a monitoring program can be designed to capture key dynamics with the least amount of sampling effort.

When governance is stable and multiple agencies cooperate, an integrated, coordinated and efficient monitoring program can be established across agencies. Under less ideal governance situations, where funding for monitoring is questionable or the maintenance of monitoring equipment or programs is unlikely, the monitoring program can be designed to target critical time frames or areas or to take advantage of remote sensing. Finally, third party rapid assessments may be ideal components of monitoring programs in these situations, providing high quality data in a short time frame from a reliable source [28].

3.7. Evaluation

The final step in an IEA is evaluation, when monitoring data are assessed for how well the management strategy is performing relative to objectives [6] (Fig. 1). In data rich regions, simulation models can be used (Fig. 3) to create a "null system" where the implemented management action was *not* taken. Monitoring data can then be compared to this prediction, allowing clear management assessments. This is especially helpful for new management programs because identifying trends related solely to management practices (not to climate or other drivers) is difficult until time-series are relatively long. When data are sparse, simple analyses of trends and relative measures can be informative, although it may be difficult to make direct associations between management practices and indicator responses.

Governance can influence how the evaluation step is conducted and who participates. Ideally, evaluation will be done with a multi-stakeholder group, using transparent and coordinated data and analyses and resulting in an efficient and widely accepted conclusion. Such processes must be bottom up and informal when governance is poor. Even for an informal stakeholder process, it will be critical to keep lines of communication as open as possible to ensure that analyses are trusted by most or all parties.

4. Case studies

Here we outline two case examples from different contexts, demonstrating how EBM is being implemented on the ground today. They show how some of the methods listed above have been combined into real approaches, with the aim of making our framework more tangible.

4.1. Raja Ampat, Indonesia

The Raja Ampat archipelago lies to the west of New Guinea in a region noted for its extraordinary biological diversity. Although human population density is low, the Raja Ampat marine ecosystem faces a number of pressures including overexploitation of natural resources, destructive fishing practices, land-based pollution and outbreaks of corallivores [29]. Although artisanal and commercial fisheries are the dominant economic sectors, pearl farming, agriculture, tourism, and logging contribute significantly to the economy [30], and interact with fisheries [31]. Other activities, such as mining, are currently minor contributors to the region's economy, but are considered as development options [31].

Since the late 1990s, Indonesia has been decentralizing its governance structure and delegating more authority to regency level authorities [32]. While devolution of the central authority is probably preferred by the inhabitants, the diffuse population over a large area results in challenges for resource management [30]. It is against this backdrop that several non-governmental organizations (NGOs) initiated a process with the Raja Ampat Regency Government to explore the utility of Marine Protected Areas as a means to achieve the ecosystem goal of protecting the livelihoods of the 24,000 fishers who depend on the marine environment while also allowing economic development. Local stakeholders, academia, NGOs, and the government have joined forces to develop and implement an EBM plan for coastal and marine resources in Raja Ampat. Thus, despite poor governance and the absence of significant institutional commitment, it has been possible to move EBM forward because of strong interest from other entities.

EBM most effectively begins with a clear statement of objectives. In this case, however, three NGOs (The Nature Conservancy, Conservation International and World Wildlife Fund) were the dominant participants in the process, and their organizational objectives preempted a formal scoping process. Scientific research was then conducted to understand possible EBM advances [33], work which is now the foundation for a multi-sector EBM plan focusing on fisheries and aquaculture.

While only meager scientific information was available a decade ago, an influx of funds has allowed the accumulation of knowledge. In 2002, a rapid assessment of the region's ecological and social systems was conducted [34]. Such work in combination with a disaggregated stakeholder engagement process helped identify indicators that had economic importance and were of interest to the NGOs (e.g., hawksbill turtles, groupers, Napoleon wrasse).

To establish management thresholds for fish biomass as well as ecosystem condition, researchers combed archives, museums and libraries to reconstruct the historical Raja Ampat ecosystem. Despite the relative isolation of this region, this work revealed declines in turtles and fish selected as indictors [35]. Social indicators, such as population density of coastal villages and the relative importance of subsistence fishing, suggest social drivers underlie ecosystem degradation. Additionally, Ainsworth and others [19] conducted extensive interviews with local fisherman to reconstruct time series of fish abundance, allowing managers to consider current information on indicators in the context of historic conditions. A formal risk assessment of the region has not been conducted. However, Raja Ampat's rich biodiversity along with existing and emerging threats were sufficient for NGOs to conclude that conservation action was needed [34].

The Raja Ampat EBM partners had the foresight to invest in primary data collection (e.g. dive transects, fish stomach sampling, community interviews, coastal and aerial surveys, oceanographic monitoring) for and development of an Ecopath with Ecosim model. Combined with existing data, this work allowed Ainsworth and colleagues [29] to evaluate multiple fisheries harvest strategies (e.g., restricted grouper fishery, increased tuna fishery), as well as fisheries gear changes (e.g., excluding net fisheries, increasing blast fishing). While Raja Ampat is data-poor by developed-nations standards, the targeted acquisition of key field data for a tuned ecosystem simulation model has enabled stakeholders to evaluate the likely ecosystem-wide effects of fisheries management options.

Although Raja Ampat lacks the capacity for comprehensive monitoring, the NGO partners monitor coral cover, coral bleaching, and invertebrate grazing as indicators of reef health. Censuses of commercially exploited groupers and snappers are conducted annually. Artisanal fishing effort is monitored via aerial surveys every two years. In addition, the Nature Conservancy has invested significant effort in monitoring illegal fishing activity. Thus, while a monitoring effort is not institutionalized in a government agency, the high biodiversity of the region has motivated NGOs to monitor the state of the ecosystem. The timing and targeted investments in data collection allowed relatively sophisticated approaches for several steps of the IEA process, even in a weak governance and poor data environment. However, future iterations of the approach need to expand the scope to include other sectors such as logging (which acts as a significant driver of marine systems) and other ecosystem services and associated indicators.

4.2. Puget Sound, Washington, USA

One of the most sophisticated EBM processes underway in the US is coordinated by the Puget Sound Partnership, a state agency whose task is to work with local, state, tribal and federal governments, businesses, and citizens to restore the natural and human components of the system by 2020. Initiated in 2005, a short (1 year) scoping stage did not provide enough time for any quantitative approaches to goal setting. Alternatively, extensive, structured stakeholder engagement led to formal creation of the state agency, its governance structure, and a legislative mandate to restore the ecosystem [36]. The primary scientific inputs in the scoping phase consisted of a multi-authored synthesis of existing scientific understanding of the upland, estuarine, marine, and human parts of the ecosystem [37], scientific workshops to discuss priority threats and potential strategies, and numerous discussions between the scientific and policy leadership groups of the Partnership. The process identified six overarching ecosystem goals: species and food webs, habitats, water quality, water quantity, human health and human well-being [38]. In 2008, the Partnership enlisted the help of the World Resources Institute to conduct a more comprehensive scoping process with stakeholder interviews and meetings to refine objectives by identifying the ecosystem services of greatest public interest and concern. This more detailed scoping highlighted the provision of water flows, recreation and ecotourism, and ethical and existence values as the 'most valued' ecosystem services across the most sectors [39].

A mix of analytical tools was used to identify indicators. First, the Partnership conducted a systematic review of all existing indicators currently being monitored in the Puget Sound ecosystem for the six goals. Conceptual models of the ecosystem and key processes for each goal were created through an expert judgment process and used to screen existing indicators. A total of 657 indicators were then classified based on criteria for properties of a "good" indicator [40–42], shortening the list to 73 indicators and identifying objectives for which no indicators currently are monitored. A policy focus group from the Partnership will select a subset of the provisional indicators to use in the first phase. Subsequent analytical phases of indicator selection are explicitly built into the work plan.

As with the previous steps, time constraints of the initiation phase led to threshold setting approaches appropriate for a low data situation. A discussion of existing scientific basis for thresholds or historical reference conditions associated with water quality, species, and habitats was conducted [38]. Most existing quantitatively established thresholds in the Puget Sound ecosystem have been identified for single species (e.g., salmon, orcas) or ecosystem components directly related to human health (e.g., shellfish consumption advisories for contaminants). In the next phase of the Partnership, approaches to threshold setting will include a thorough literature review and formal meta-analysis to inform thresholds for the ecosystem indicators not yet addressed. They will also apply quantitative models (e.g., Ecopath with Ecosim) to refine thresholds for select ecosystem components associated with marine food webs.

The first round of risk analysis consisted of two primary approaches: (1) regional summaries of existing status and threat assessments in watersheds and marine ecosystems, and (2) a demonstration project using spatial threat mapping, existing threshold information, and conceptual models to illustrate how a more complete ecosystem-scale analysis can inform prioritization of strategies. The regional summaries highlighted indicators whose current status is fairly well understood (e.g., salmon, fresh water flows) and those for which there is very little information and revealed a general lack of historic data for baselines. The demonstration project went a step closer to a quantitative risk analysis, focusing on a few examples of threats and their known impacts on specific indicators (i.e., land use effects on biodiversity and groundwater nitrate contamination) [43]. The spatial threat and status data will be used in the next phase of the risk analysis in which quantitative statistical or mechanistic models are being developed to estimate cumulative impacts of drivers and pressures on state and impact indicators.

The spatial threat data and assessment summaries from the risk analysis informed the next step of the IEA, management strategy evaluation (MSE). These summaries were combined with conceptual models to identify priority strategies for each of seven sub-regions. Although no new quantitative analyses were used in the first year, previous quantitative assessments for parts of the ecosystem were used. A major source of these assessments was watershed recovery plans for salmon, which include models evaluating climate, harvest, hatchery and habitat management strategy impacts on salmon populations [44–46]. These models informed adoption of specific management priorities for salmon and watershed recovery, including where habitat restoration and protection will occur and how hatcheries are to be managed to allow recovery of wild fish. The next round of MSE will use quantitative sub-modules (similar to minimum realistic models) that will allow evaluation of several management strategies and their impacts on multiple indicators. Ultimately, these sub-modules will be linked together to form the full ecosystem model for Puget Sound to conduct a formal MSE.

For the final steps of the IEA—monitoring and evaluation—the Partnership is producing an adaptive management framework that includes existing monitoring plans from major portions of the ecosystem. Monitoring and adaptive management plans from the salmon ecosystem plan [47], a Governor's statewide monitoring forum for freshwater systems and several more local plans will be integrated and efficiencies sought under the Partnership's approach. Importantly, a number of gaps in monitoring for ecosystem objectives, and strategies for addressing those gaps, have been identified. More formal treatment of monitoring and evaluation approaches will be addressed in subsequent iterations of the IEA as the ecosystem modules and full models are developed.

5. Moving forward with ecosystem-based management

By providing concrete examples of how an IEA process can be used to implement EBM under a range of starting conditions, we demonstrate that EBM is not a prohibitively demanding or complex management approach in any context.

While ecosystem-based management is widely seen as critical for conserving and restoring marine ecosystems, a number of barriers—real and perceived—have hindered widespread implementation of EBM. In all IEA steps, we provide a suite of options along the spectrum of data availability and governance—a stakeholder engagement process to formalize existing knowledge can be used when few data are documented or available, statistical approaches can be used at intermediate data levels, and ecosystem simulation modeling can be used in data rich situations. We emphasize that a stakeholder engagement process can be used at every step, even in poor governance and data situations (Figs. 2 and 3). Therefore, given minimal capacity and finances, there is always an opportunity to make progress towards EBM regardless of how challenging the context may seem. Obviously, stakeholder processes come with uncertainty and require simplifying assumptions, but they can be an extremely productive first step, continually improving the knowledge base and allowing increasingly sophisticated decision making in the future.

As the case studies demonstrate, it is possible to mix and match approaches at each step of an IEA to conduct the most robust and informative analyses possible. This will likely be true even in ideal high data and good governance settings because there will always be limitations on time, political momentum, and financial and personnel resources. Therefore, a crucial next step for informing the use of EBM frameworks is to provide guidance on which parts of the process provide the largest rewards when conducted with more sophisticated approaches. From examples to date, we have learned that scoping, threshold setting and management strategy evaluation are particularly critical steps in the IEA process. It is essential to spend sufficient time and resources on scoping to move past contentious issues among stakeholders and to reach a collectively supported set of objectives. Thresholds are similarly important given that without clear standards for acceptable levels of indicators, it is impossible to evaluate management success. Having quantitative thresholds substantially changes the management strategy evaluation step, giving much more concrete guidance to the types of actions needed to meet specific goals. Finally, it is very difficult to compare management strategies if their likely outcomes for indicators are unknown. For example, in Puget Sound, one specific objective is to recover orca (killer whale) populations. However, we do not know the order of magnitude of response in orca populations to expect from management strategies ranging from reducing toxic pollutants to recovering salmon populations to restricting interaction with vessels. Without this information, choosing a strategy is very challenging, and would be rapidly improved by qualitative information ranking the effectiveness of different approaches.

Additional guidelines such as these will continue to emerge and allow improvements in the application of EBM. There is no single correct path forward. Instead, EBM is a management approach with many faces that can (and should) evolve over time. The approaches outlined here are not prescriptive, but rather can be mixed and matched to best fit the needs of a particular location. Given this flexibility, it is time to embrace a culture of ecosystem based management that improves the likelihood that we can avoid management failures by using the best social and natural science available in a process that is inclusive and transparent.

Acknowledgments

This work was supported by the California Current Ecosystem-Based Management (CCEBM) initiative, a grant to the Institute of Marine Sciences, University of California, Santa Cruz, and the Communication Partnership for Science and the Sea (COMPASS) from the David and Lucile Packard Foundation and the Gordon and Betty Moore Foundation. C. Ainsworth helped extensively with the Raja Ampat case study. We thank the other members of the CCEBM Scientific Advisory Committee for their insights: J. Barth, F. Chavez, C. Costello, S. Gaines, B. McCay, J. Parrish, and C. Pomeroy.

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