A practical approach to implementation of ecosystem-based management: a case study using the Gulf of Maine marine ecosystem

Irit Altman[1*], April MH Blakeslee[2], Giacomo C Osio[3], Christopher B Rillahan[4], Sarah J Teck[5], John J Meyer[6], James E Byers[1], and Andrew A Rosenberg[3]

The application of ecosystem-based management (EBM) in marine environments has been widely supported by scientists, managers, and policy makers, yet implementation of this approach is difficult for various scientific, political, and social reasons. A key, but often overlooked, challenge is how to account for multiple and varied human activities and ecosystem services and incorporate ecosystem-level thinking into EBM planning. We developed methods to systematically identify the natural and human components of a specific ecosystem and to qualitatively evaluate the strength of their interactions. Using the Gulf of Maine marine ecosystem as a case study, we show how these methods may be applied, in order to identify and prioritize the most important components to be included in an EBM plan – particularly the human activities that are the strongest drivers of ecosystem change and the ecosystem services most threatened by cumulative and indirect effects of these activities.

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Increases in human activity in coastal and marine environments have led to substantial degradation in the ecological health of these systems. As a result, their continued production of ecosystem services is currently threatened (Lotze *et al.* 2006; Worm *et al.* 2006). These problems have led to widespread support by both scientists and policy makers for ecosystem-level approaches, such as ecosystem-based management (EBM; POC 2003; USCOP 2004; Hughes *et al.* 2005; McLeod *et al.* 2005). Several key features distinguish EBM from conventional management (McLeod *et al.* 2005), including the recognition that: (1) human communities rely on and benefit from properly functioning ecosystems; (2) ecosystems are composed of many interacting natural and human components; (3) ecosystem services are impacted by multiple human activities; and (4) human activities may have both strong direct and indirect impacts on ecosystem services.

In a nutshell:

- A conceptual framework and step-by-step methods for developing an ecosystem-based management (EBM) plan are presented, involving an approach that fosters collaboration and encourages an ecosystem perspective
- Key features include a qualitative evaluation of direct and indirect interactions between ecosystem services and human activities
- Tangible results will help users prioritize what should be the focus of an EBM plan, including which ecosystem services are most threatened by cumulative and indirect impacts of human activities

Important advances in EBM application include the development of a core set of principles to help guide its practitioners (de la Mare 2005; Guerry 2005; Leslie and McLeod 2007). Policy makers and resource managers are also beginning to incorporate ecosystem-based language into management plans (Arkema *et al.* 2006; Gregoire *et al.* 2006; HR 21 2009). While these examples represent important steps forward, most plans do not fully meet the criteria for comprehensive EBM (Brodziak and Link 2002; Arkema *et al.* 2006; but see also Hildebrand *et al.* 2002; Misund and Skjoldal 2005).

Given the substantial and widespread support for applying EBM in marine systems, what is preventing the implementation of this approach? Many challenges hinder the advance of EBM, including institutional barriers, limited scientific information, and lack of political will. A more subtle issue is the need for a shift in perspective regarding management goals and actions (Lotze 2004; Guerry 2005). Essentially, EBM requires a recognition that ecosystem function depends on the complex interconnections that exist among many species, habitat types, and human activities. While it is neither practical nor desirable for humans to attempt to manage all aspects of an ecosystem, it is critical to find ways to prioritize which are the key elements to

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[1] *Department of Biological Sciences, University of New Hampshire, Durham, NH *(irit.altman@unh.edu);* [2] *Marine Invasions Laboratory, Smithsonian Environmental Research Center, Edgewater, MD;* [3] *Institute for the Study of Earth, Oceans, and Space, University of New Hampshire, Durham, NH;* [4] *War in the Pacific National Historical Park, Hagåtña, Guam;* [5] *Department of Ecology, Evolution, and Marine Biology, University of California Santa Barbara, Santa Barbara, CA;* [6] *Department of Zoology, Oregon State University, Corvallis, OR*

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focus on within an EBM context. Here, we present a conceptual framework and methodology to help practitioners move forward, from thinking about EBM to applying this approach within a target ecosystem.

Background and study system

This work was developed as part of a seminar at the University of New Hampshire focused on EBM and organized by the National Center for Ecological Analysis and Synthesis (Santa Barbara, CA). Participants included graduate students and faculty in the fields of fisheries science, community ecology, natural resource management, and maritime history (see WebTable 1 for detailed information regarding seminar participants). The goal of our work was to develop a conceptual framework to guide the development of EBM in any target ecosystem. In addition, we sought to apply our methods to a specific case study in order to demonstrate their effectiveness. Because seminar participants conduct research in the Gulf of Maine (GOM), we selected this area for our case study.

The GOM is a semi-enclosed sea, bounded on its western edge by Canadian and US lands and to the south and east by shallow underwater landmasses. Historically, the ecosystem supported abundant populations of economically important species, including cod (*Gadus morhua*), haddock (*Melanogrammus aeglefinus*), and American lobster (*Homarus americanus*; German 1987; Rosenberg *et al.* 2005). Over the past century, however, the effects of human activity and population growth have led to an impaired state of ecological function, including overexploitation of marine species and decline of coastal habitat and water quality (Fogarty and Murawski 1998; US EPA 2004). High productivity and a diversity of human activities in the GOM make it a compelling example of the challenges associated with developing EBM. In addition, given that no EBM plan currently exists for the GOM, our results serve as a starting point from which future plans may be developed.

Identifying ecosystem services and human activities

To develop a conceptual model of the GOM, we first defined the specific ecosystem services (including provisioning, regulating, and supporting services) and human activities in this ecosystem; taken together, we refer to these as "ecosystem components". We consulted generalized published lists of ecosystem components (de Groot *et al.* 2002; MA 2003), management plans, and other relevant literature, as well as local experts, and refined definitions of ecosystem components to reflect the distinctive character of the GOM.

Evaluating how ecosystem components affect one another

We evaluated human impacts in the GOM ecosystem by constructing a matrix with i rows of human activities and j columns of ecosystem services, which we refer to as the human impact matrix (HIM; WebFigure 1a):

$$A = \begin{pmatrix} a_{11} & \cdots & a_{1j} \\ \vdots & \ddots & \vdots \\ a_{i1} & \cdots & a_{ij} \end{pmatrix}, \quad \text{(Matrix 1)}$$

where each cell represents the effect of a specific human activity on a specific ecosystem service.

To assess the strength of interactions among natural ecosystem components, we constructed a symmetrical matrix with both i rows and j columns of ecosystem services, which we refer to as the ecosystem service matrix (ESM; WebFigure 1b):

$$B = \begin{pmatrix} b_{11} & \cdots & b_{1j} \\ \vdots & \ddots & \vdots \\ b_{i1} & \cdots & b_{ij} \end{pmatrix}, \quad \text{(Matrix 2)}$$

where each cell represents the effect of one ecosystem service on another.

To evaluate how strongly one ecosystem component affects another, we developed a qualitative scoring system. Partial scores associated with several hierarchical criteria were summed to determine the total effect score (Figure 1). Scoring criteria were hierarchical, because their influence on the total effect score varied. Resilience – defined by Walker *et al.* (2004) as "the capacity of a system to absorb disturbance and re-organize while undergoing change, so as to still retain essentially the same function, structure, identity, and feedbacks" – was deemed to be the most important scoring criterion in the context of EBM. The largest scores were associated with effects that currently compromise the resilience of the ecosystem component (Figure 1). Scores were lower for effects likely to compromise a component's resilience in the future, because of the uncertainty associated with the outcome of future events. The lowest non-zero score was associated with effects that did not compromise the resilience of the ecosystem service. We considered the spatial and temporal scale over which the effect occurred as additional scoring criteria. Although less important than questions of resilience in the scoring hierarchy, designation of scale provided information about the relative importance of the effect across the ecosystem. Two levels of scale were identified: effects were considered large if they occurred throughout the ecosystem or across multiple habitats, whereas small effects occurred within a limited portion of the ecosystem or a single habitat type. Effects were considered chronic if they occurred during multiple seasons and/or with consistency on an annual basis. Acute effects occurred ephemerally.

Total effect scores fell into the following categories: no effect (0 score), weak effect (1 score), intermediate effect (2–3 score), and strong effect (4–5 score; Figure 1). Weak effects indicate that the resilience of a component is not compromised. Intermediate effects will likely compromise the resilience of an ecosystem service in the future, whereas strong effects do so now. For the latter two categories, a score at the higher end of the range indicates that the effect occurs on a greater temporal and/or spatial scale.

Effect scores for the GOM were determined by group-wide discussion and consensus. When knowledge within the group was limited, we sought additional information by reviewing relevant scientific literature and/or soliciting opinions from local experts. We elected to use this group scoring approach (as opposed to independent scoring by each participant) because our pooled knowledge was stronger than any individual's expertise alone.

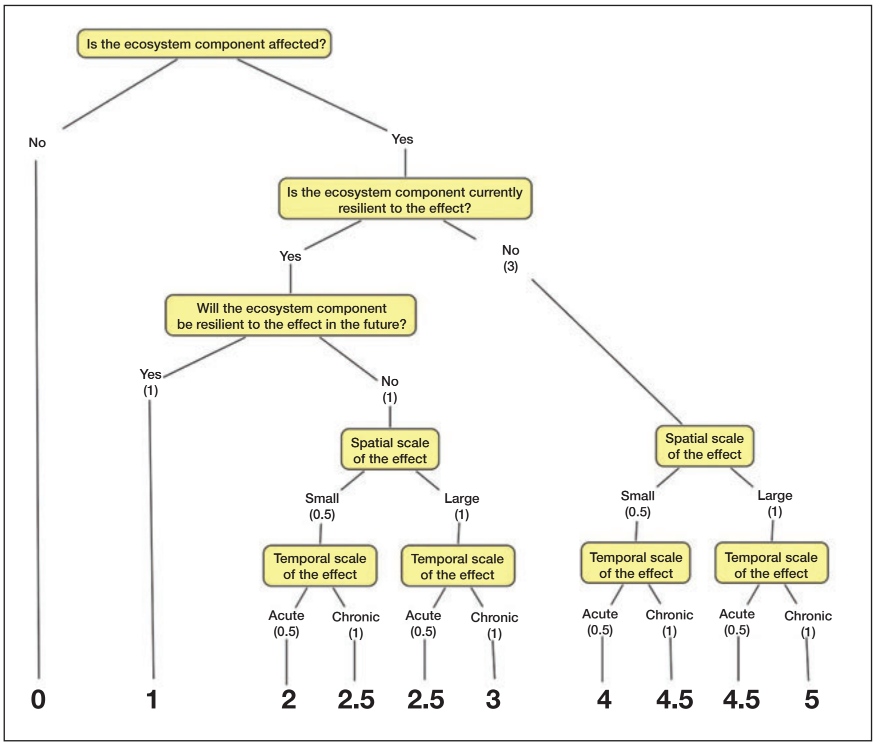

Figure 1. *Schematic of hierarchical scoring methods used to evaluate effect strength among ecosystem components. Responses to questions outlined in boxes provide partial scores (in parentheses), which are summed to obtain a final effect score (outlined in bold text at bottom). The higher the final score, the more strongly the resilience of the affected ecosystem is compromised over large spatial and long temporal scales. Total effect scores fall into four categories: no effect (0 score), weak effect (1 score), intermediate effect (2–3 score), and strong effect (4–5 score).*

■ Matrix analyses

Matrix scores were analyzed to identify the components that were the strongest drivers of ecosystem change and the ecosystem services that were most threatened as a result of the cumulative and indirect effects of human activities.

Human and natural drivers

Ecosystem change may be the result of direct drivers of human or natural origin that unequivocally influence ecosystem processes (MA 2003). To examine which human activities were the strongest direct drivers in the GOM, we summed effect scores for each human activity across the columns of the HIM (WebFigure 1a):

$$a_{m\bullet} = \sum_{k=1}^{j} a_{mk} \text{ , (Equation 1)}$$

where $m = 1, 2, \ldots i$ and $a_{m\bullet}$ represents the human driver score for a specific human activity – that is, the sum of all the effect scores $k = 1, 2, \ldots j$ of that human activity on all ecosystem services. Human activities may be strong drivers if they have strong effects on individual ecosystem services, affect many different ecosystem services, or both.

To examine which ecosystem services were the strongest natural drivers in this system, we summed effect scores for each ecosystem service across the columns of the ESM (WebFigure 1b):

$$b_{m\bullet} = \sum_{k=1}^{j} b_{mk} \text{ , (Equation 2)}$$

where $m = 1, 2, \ldots i$ and $b_{m\bullet}$ represents the natural driver score for a specific ecosystem service – that is, the sum of all the effect scores $k = 1, 2, \ldots j$ of that ecosystem service on all other ecosystem services. Ecosystem services may be strong drivers because they have strong effects on individual ecosystem services, affect many ecosystem services, or both.

Cumulative impacts

Multiple human activities collectively affect ecosystem services (Halpern *et al.* 2008). Cumulative impacts may be additive if their effects are predicted by individual impacts. Non-additive impacts are also possible and can be either synergistic (increased impact as compared to additive effects) or antagonistic (decreased impact as compared to additive effects; Crain *et al.* 2008). Difficulties predicting how numerous impacts combine restricted us from classifying non-additive effects. We therefore only assessed additive cumulative impacts in the GOM. Effect scores were summed for each ecosystem service down the rows of the HIM (WebFigure 1a):

$$a_{\bullet m} = \sum_{k=1}^{i} a_{km} \text{ , (Equation 3)}$$

where $m = 1, 2, \ldots j$ and $a_{\bullet m}$ represents the cumulative impact score for a specific ecosystem service, or the sum of effect scores $k = 1, 2, \ldots i$ of all human activities associ-

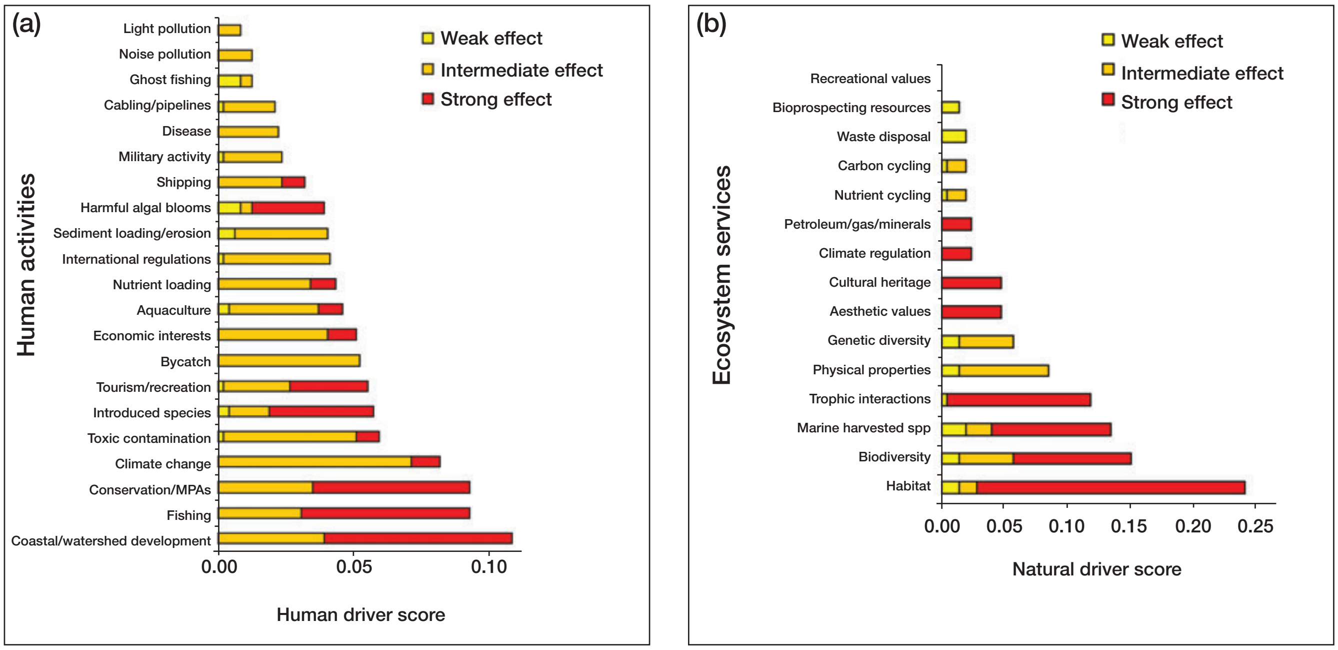

Figure 2. *Rank of ecosystem components in the GOM as drivers of ecosystem change. Colors within bars reflect the three different scoring categories. (a) Strength of human activities as drivers of ecosystem change in the GOM. (b) Strength of ecosystem services as natural drivers of ecosystem change in the GOM. Human activities (in [a]) and ecosystem services (in [b]) with higher relative scores have stronger effects on other ecosystem services, affect many ecosystem services, or both.*

ated with that ecosystem service. Cumulative impact scores thus integrate the number and strength of effects caused by multiple human activities.

Indirect effects

Indirect effects result when a human activity strongly affects an ecosystem service that is also a natural driver and therefore has subsequent effects on other ecosystem services. While indirect effects may be classified as linear or non-linear, limited information restricted us from predicting non-linearities. To assess the linear indirect effects of human drivers on ecosystem services, we constructed a third matrix, which we refer to as the weighted ecosystem service matrix (WESM; WebFigure 1c). Using the ESM as a starting point, we multiplied each cell by the cumulative impact score associated with the ecosystem service that causes the effect:

$$C = \begin{pmatrix} c_{11} = (b_{11} * a_{\bullet 1}) & \cdots & c_{1j} = (b_{1j} * a_{\bullet 1}) \\ \vdots & \ddots & \vdots \\ c_{i1} = (b_{i1} * a_{\bullet j}) & \cdots & c_{ij} = (b_{ij} * a_{\bullet j}) \end{pmatrix}, \text{ (Matrix 3)}$$

where each cell represents the effect of one ecosystem service on another, weighted by the cumulative impact score associated with the ecosystem service that causes the effect (Equation 3). To assess which ecosystem services are most at risk as a result of indirect effects, we summed effect scores for each ecosystem service down the rows of the WESM (WebFigure 1c):

$$c_{\bullet m} = \sum_{k=1}^{i} c_{km} \ , \quad \text{(Equation 4)}$$

where $m = 1, 2, \ldots j$ and $c_{\bullet m}$ represents the indirect effect score for a specific ecosystem service, or the sum of all the weighted effects $k = 1, 2, \ldots i$ for that ecosystem service. Ecosystem services have higher indirect effect scores when they are strongly affected by natural drivers that receive high cumulative impacts.

■ Results

We identified 21 human activities and 15 ecosystem services for inclusion in our conceptual model of the GOM ecosystem and determined 525 effect scores (see WebPanel 1 for our comprehensive list and definitions of ecosystem components). Qualitative methods make absolute scores difficult to interpret. We therefore present results in terms of relative strength of effect scores, which provides insight into which ecosystem components are most important with respect to this GOM case study.

Human drivers

The five strongest direct human drivers (Equation 1) in the GOM were coastal and watershed development, fishing, conservation/marine protected areas (MPAs), climate change, and toxic contamination. Human activities that were the weakest drivers of ecosystem change were light pollution, noise pollution, and ghost fishing (Figure 2a).

Natural drivers

The five strongest natural drivers (Equation 2) were habitat, biodiversity, marine harvested species, trophic interactions, and physical properties. The weakest natural drivers were recreational values, bioprospecting resources, and waste disposal (Figure 2b).

Cumulative impacts

The five ecosystem services most strongly affected by cumulative human impacts (Equation 3) were biodiversity, marine harvested species, aesthetic values, habitat, and recreational values. Ecosystem services least affected by cumulative impacts were climate regulation, physical properties, and the provision of petroleum/gas/minerals (Figure 3).

Indirect effects

Indirect effect scores (Equation 4) indicate which ecosystem services experienced the greatest indirect impacts as a result of human activities throughout the ecosystem. The five ecosystem services that experienced the strongest indirect effects were cultural heritage, trophic interactions, biodiversity, recreational activities, and genetic diversity (Figure 3). Note that biodiversity and recreational values were two of the most strongly affected ecosystem services through cumulative impacts, ie without considering indirect effects.

■ Discussion

Our results suggest that although many human activities occur in the GOM, a few of these are the most important drivers of ecosystem change. Specifically, of the 21 human drivers considered, the six strongest accounted for more than 50% of the total impact on ecosystem services (Figure 2a). An EBM plan for the GOM should specifically target these strong drivers. Several human activities may be considered low priority for inclusion because they are weak drivers that generate relatively low impacts, confined to only a few ecosystem services. These include light pollution, noise pollution, and ghost fishing. More targeted management approaches may be effective in dealing with these weak human drivers.

A similar suite of ecosystem services was found to be *both* strong direct natural drivers *and* the most at risk from human activities, including habitat, biodiversity, and marine harvested species (Figure 2b, natural driver scores, and Figure 3, cumulative impact scores; red bars). Because these ecosystem services are essential to the maintenance of ecosystem integrity and are strongly threatened by cumulative impacts, they should be the cornerstone of an EBM plan for the GOM.

Many ecosystem services were found to be at high risk from cumulative impacts and indirect effects of human activities, including biodiversity, aesthetic values, and recreational activities (Figure 3). This finding underscores the need for integrative approaches like EBM that manage across numerous activities and at the intersection of ecosystem processes. Moreover, an EBM plan that focuses on the impacts affecting this key group of ecosystem services should reap multiple benefits.

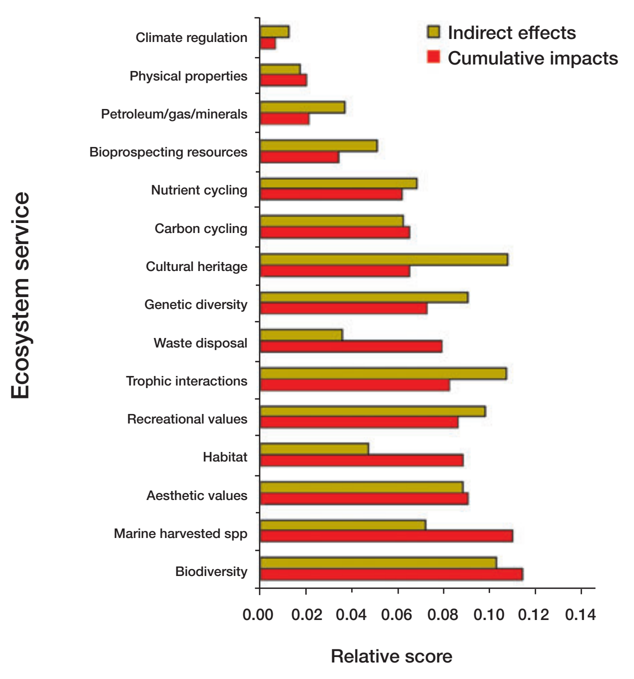

Figure 3. *Relative scores of the effect of human activities on ecosystem services in the GOM. Red bars are the relative cumulative impact score of human activities on ecosystem services. Yellow bars are the relative indirect effect score of human activities on ecosystem services (where the effects of human activity are mediated through natural drivers). Relative scores are presented for comparison, since the calculation of indirect effect scores (Equation 4) results in values that are on a higher scale as compared with cumulative impact scores (Equation 3).*

While many ecosystem services were at high risk from both cumulative impacts and indirect effects, some were found to be more strongly affected via one pathway. For example, the ecosystem service "cultural heritage" was impacted to an intermediate degree by cumulative effects (it was ranked nine of 15); nonetheless, it was found to be the ecosystem service most at risk from indirect effects (Figure 3). This information helps to classify the type of impact affecting ecosystem services and can be used to inform specific strategies within an EBM plan.

Our findings suggest which components should be the focus of an EBM plan for this ecosystem; a more comprehensive assessment is needed, however, before specific recommendations can be made. Obtaining evaluations from additional experts would ensure the most robust evaluation of effect scores possible. It may also be important to consider the level of certainty associated with scores (or their variability if individual scoring is used), before using results in a management context. Despite these limitations, the GOM case study illustrates how our methods may be applied to a diverse ecosystem characterized by numerous

Table 1. Costs and benefits of various user-group decisions

Decision	*Alternatives*	*Benefits*	*Costs*	*Additional considerations*
Users	Diverse group of experts	Individual users have detailed knowledge within their area of expertise	Individual users may have limited knowledge outside their area of expertise	What are the practical considerations associated with gathering a group of users?
	Diverse group of non-experts	Pooled knowledge of the group is broad ranging	Group knowledge may be less specific	
Ecosystem components	Broad categories	Fewer effects to score, decreased time and effort required to complete exercise	Lack of detailed information to inform next steps of developing an EBM plan	What is the stage of EBM planning? How will the results of the exercise be used?
	Detailed categories	Provides a more detailed picture of the ecosystem and more specific information to guide next steps	More effects to score increases the time and effort to complete the exercise; information for some effects may be limited	
Scoring approach	Group scoring (ie consensus scoring resulting in a single set of results)	Pooled knowledge of the group may provide less biased information regarding scores	Social dynamics among the group may influence scoring decisions	What is the knowledge base of the group?
	Independent scoring (ie individuals score matrices independently resulting in multiple sets of results)	Variability among scores can be determined and analyzed	Variability among scores has to be dealt with as a separate step; averaging of scores can mute strong differences in independent scores	
Scoring system	Explicit consideration of additional factors in scoring (eg temporal scale, spatial scale, level of certainty)	Results reflect a high level of detail regarding the interactions among ecosystem components	Increased time and effort required to complete the exercise	What is the stage of EBM planning? How will the results of the exercise be used?
	No consideration of additional factors in scoring (eg temporal scale, spatial scale, level of certainty)	Fewer considerations limit the time and effort required to complete the exercise	Results may be too general to be useful in later steps of EBM planning	
Matrix analyses (ecosystem drivers, cumulative impacts, indirect effects)	Additive methods	Provides a general picture of ecosystem change and the human-derived causes of change	Assumption that effects are linear may be false	Are there non-linearities in the system that are documented and understood?
	Non-additive methods	May provide a more detailed and accurate picture of ecosystem change and human-derived causes of change	Consideration of non-linearities increases time and effort to complete the exercise; knowledge of non-linearities may be highly uncertain	

human uses, and our results serve as a foundation upon which future EBM efforts in this region can be built.

Our methods provide a framework to focus critical thinking on the magnitude and importance of multiple factors in ecosystems. In theory, the results could inform hypotheses that could be tested with quantitative data. Our general framework can easily be applied to any target ecosystem, but differences in ecosystem dynamics, composition of user groups, and stages of EBM planning may necessitate adaptations. The identification of human impacts and ecosystem services will obviously be dependent on the system in question. Classifications of services and impacts outlined here (WebPanel 1), in the Millennium Ecosystem Assessment (MA 2003), and in de Groot *et al.* (2002) can serve as a starting point for developing ecosystem-specific matrices. Many aspects of our methods are highly flexible and can be tailored to the specific needs of user groups. These include decisions about whom to include in user groups, the degree of specificity with which to define ecosystem components, whether scoring should be based on individual assessment or group consensus, and whether scores should be analyzed based on additive or non-additive methods. We provide some guidance about the costs and benefits of these decisions (Table 1); however, individual user groups must carefully consider how specific adaptations will affect results.

Ecosystems are not static, and their dynamic nature requires that EBM be an iterative process. We suggest that these methods be applied on an ongoing basis, and that plans be adapted to address the most current understanding of the ecosystem. Although we have provided a tool for practitioners to take steps toward implementation of EBM, our methods do not address the numerous political, institutional, and research obstacles that must be met for successful implementation of EBM in marine systems. Such challenges include mismatches of scale over which regulatory bodies and ecosystems operate (Crowder *et al.* 2006) and information uncertainty that hinders determination of the outcome of particular plans (Balmford and Bond 2005). Responding to these challenges will require concerted and sustained effort to change the current regulatory structure and to fill information gaps. Finally, policy makers must move toward supporting ecosystem approaches to management. This requires recognition that an EBM approach is essential, as are institutional changes that better enable integrated decision making.

In spite of these obstacles, it is critical that EBM practitioners continue to move forward (Rosenberg and McLeod 2005), before impacted ecosystems are pushed beyond an ecological threshold into alternative states (Scheffer *et al.* 2001; Folke *et al.* 2004). In this context, our approach can serve as a model for practitioners working to develop EBM plans for ecosystems worldwide. Our methods help users approach environmental problem-solving through an ecosystem-wide lens and facilitate tangible progress toward ecosystem-based approaches to management.

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