The role of marine habitat mapping in ecosystem-based management

Christopher B. Cogan, Brian J. Todd, Peter Lawton, and Thomas T. Noji

Ecosystem-based management (EBM) and the related concept of large marine ecosystems (LMEs) are sometimes criticized as being too broad for many management and research applications. At the same time, there is a great need to develop more effectively some substantive scientific methods to empower EBM. Marine habitat mapping (MHM) is an example of an applied set of field methods that support EBM directly and contribute essential elements for conducting integrated ecosystem assessments. This manuscript places MHM practices in context with biodiversity models and EBM. We build the case for MHM being incorporated as an explicit and early process following initial goal-setting within larger EBM programmes. Advances in MHM and EBM are dependent on evolving technological and modelling capabilities, conservation targets, and policy priorities within a spatial planning framework. In both cases, the evolving and adaptive nature of these sciences requires explicit spatial parameters, clear objectives, combinations of social and scientific considerations, and multiple parameters to assess overlapping viewpoints and ecosystem functions. To examine the commonalities between MHM and EBM, we also address issues of implicit and explicit linkages between classification, mapping, and elements of biodiversity with management goals. Policy objectives such as sustainability, ecosystem health, or the design of marine protected areas are also placed in the combined MHM–EBM context.

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Introduction

Ecosystem-based management (EBM) and the often similar ecosystem approach to management represent effective and much-needed approaches to conservation and management of marine systems (De Young et al., 2008). With increasing pressures from a burgeoning human population, we are depleting the natural capital from the world's marine ecosystems and altering habitats in ways we have only recently been able to measure and monitor. Parallel with the developments in terrestrial ecology, the concepts of marine EBM can be tied to the writings of Aldo Leopold in the 1940s (Leopold, 1941, 1949), the development of modern biodiversity initiatives such as the Convention on Biodiversity (United Nations Environment Programme, 1992), and actions such as the U.S. Sustainable Fisheries Act of 1996 and the recent reauthorization (2006) of the Magnuson–Stevens Fishery Conservation and Management Act. Recent publications calling for an increased pace of marine EBM include the Pew Oceans Commission (2003) report, the US Commission on Ocean Policy report (2004), the Millennium Ecosystem Assessment (2005), a Scientific Consensus Statement on Marine Ecosystem-based Management (McLeod et al., 2005), and a Food and Agriculture Organization of the United Nations (FAO) Fisheries Technical Paper on the ecosystem approach to fisheries (Garcia et al., 2003).

Unfortunately, although the need for EBM is widely acknowledged as urgent, and efforts such as the EU Marine Strategy Framework Directive (European Parliament, 2008) and the Australian sustainable fisheries guidelines (Anon., 2001) offer encouraging progress, EBM is seldom fully implemented. This may be due to political and administrative bottlenecks (Young et al., 2007) which restrict implementation beyond the conceptual level (Ehler and Douvere, 2007), or we may simply be in the early stages of EBM adoption and only require better coordination among sectors (Murawski, 2007). EBM, as with the ecosystems it addresses, is a complex entity, involving a set of interconnected concepts, disciplinary approaches, and technical issues that must be interpreted, synthesized, and communicated across an extended community of scientists, policy-makers, and stakeholders. Clarifying the context, opportunities, constraints, and contributions of specific components of EBM will foster communication and help to avoid the mistaken appearance of insurmountable complexity.

Here, we deconstruct the key components of EBM, building on previous theory from the ecological and marine science literature.

Our focus is on EBM of marine systems, but our examples and conclusions do have terrestrial analogues. By working with separate EBM components, we present a new perspective on the position and role of marine habitat mapping (MHM) within EBM frameworks. We also establish key guidelines for using MHM effectively in managing human interactions within the natural complexity of marine ecosystems.

To promote EBM, and to clarify how its concepts are communicated, Grumbine (1994) conducted one of the first surveys to identify the dominant themes and major goals of EBM. The goals of EBM are broad-reaching, encompassing viable populations, representation, ecological process, management, and the role of humans in ecosystems (Table 1). Although there is not universal agreement that these goals are achievable (Larkin, 1996), Grumbine's landmark paper nonetheless set the stage for modern approaches to marine EBM, including the FAO Code of Conduct (FAO, 1995, 2008) and guidelines for marine management in accordance with the Convention on Biological Diversity (AIDEnvironment et al., 2004). Building on the major themes outlined by Grumbine (1994) and many other subsequent authors including Christensen et al. (1996), there is now general agreement on a working definition of EBM covering both marine and terrestrial applications (Table 2).

Despite the overwhelming evidence that marine EBM is needed and that we are now poised to combine science and policy to undertake greatly improved marine management practices, EBM applications are not trouble-free. As one example, EBM and the related concept of large marine ecosystems (LMEs) used to categorize ecological management units are sometimes criticized as being too broad to allow any "real progress" in management (Longhurst, 2003). Additionally, technological challenges remain, so emphasizing the need to develop more effective "toolkits" to empower EBM (Tudela and Short, 2005), and governance issues exist when working with wide-ranging ecosystem scales (Young et al., 2007). To help alleviate some of these criticisms and concerns over methodological approaches, it is helpful to place EBM in context with examples of ongoing research and management and to show how existing methods and organizational guidelines are, when carefully planned, solid examples of marine EBM. In a general form, this comparison has been introduced by Murawski (2007), but here we focus on the specific science and management elements. Early on, Grumbine (1994) described EBM as a "reframing", forecasting our current evolution rather than revolution in marine management practices. Indeed, even the methods employed by the pioneering scientists of the *Challenger Expedition* (1872–1876) directly supported marine EBM by providing nearly 30 000 pages of descriptive text on the worlds oceans. What is now beneficial is a rethinking as to how our existing data and methods can be applied to best support a management strategy that is ecosystem-based.

Rethinking MHM as a launch point for marine EBM

One of the first steps following the establishment of EBM goals (Table 1) should be to characterize the habitat features of the ecosystem. As with habitat mapping in terrestrial ecology, MHM is a powerful approach to support modelling and management of marine ecosystems. MHM is becoming a standard activity in surveys of both national waters and international areas of interest. However, it has not been commonplace to associate individual MHM efforts with EBM. The process of MHM includes interpretation and classification of ship-based acoustic mapping of depth,

Table 1. Five goals of EBM. Within the overall goal of sustaining ecological integrity over the long term, Grumbine (1994) identified five specific goals.

1	Maintain viable populations of all native species *in situ*
2	Represent, within protected areas, all native ecosystem types across their natural range of variation
3	Maintain evolutionary and ecological processes (i.e. disturbance regimes, hydrological processes, nutrient cycles, etc.)
4	Manage over periods long enough to maintain the evolutionary potential of species and ecosystems
5	Accommodate human use and occupancy within these constraints

Table 2. Five elements of marine EBM, modified from a scientific consensus statement presented by McLeod *et al.* (2005).

What is EBM for the oceans? EBM is an integrated approach to management that considers the entire ecosystem, including humans. The goal of EBM is to maintain an ecosystem in a healthy, productive, and resilient condition so that it can provide for the maintenance of biodiversity. EBM differs from current approaches that usually focus on a single species, sector, activity, or concern; it considers the cumulative impacts of different sectors. Specifically, EBM includes five main elements:

1	EBM includes an emphasis on the protection of ecosystem structure, functioning, and key processes
2	EBM is place-based in focusing on a specific ecosystem and the range of activities affecting it
3	EBM explicitly accounts for the interconnectedness within systems, recognizing the importance of interactions between many target species or key services and other non-target species
4	EBM acknowledges interconnectedness among systems, such as between air, land, and sea
5	EBM integrates ecological, social, economic, and institutional perspectives, recognizing their strong interdependences

substratum, and geomorphology, in addition to satellite-based surface measures of roughness, currents, temperature, and productivity. Each of these measures is further associated with local sampling surveys. With a close look at the relationships between the activities of MHM and the goals of EBM, we cannot only, as Grumbine (1994) suggests, "reframe" and refine our mapping activities, but we can document the initial condition for EBM and therefore more efficiently prepare for its implementation. In this sense, MHM is part of a logical sequence within EBM. Although differences in specific objectives will exist from one research project to another, a general approach to marine EBM places MHM early in the process followed by evaluations of biodiversity, functional processes, and the development of management procedures (Figure 1).

Notably, the implementation of a new multi-agency US initiative, the National Fish Habitat Action Plan (Association of Fish and Wildlife Agencies, 2006), reflects the essential role of MHM for EBM. In response to a need to conserve fish habitat to promote sustainable fisheries and conserve biodiversity, several US Departments and Agencies formed an alliance to tackle this problem. After two years of consultations with experts and stakeholders, the first phase of research activities involves two main components: (i) aquatic habitat mapping and classification, and (ii) habitat condition modelling, whereby key components in the modelling include an index of biological integrity (closely related to biodiversity) and anthropogenic stressors. The findings from
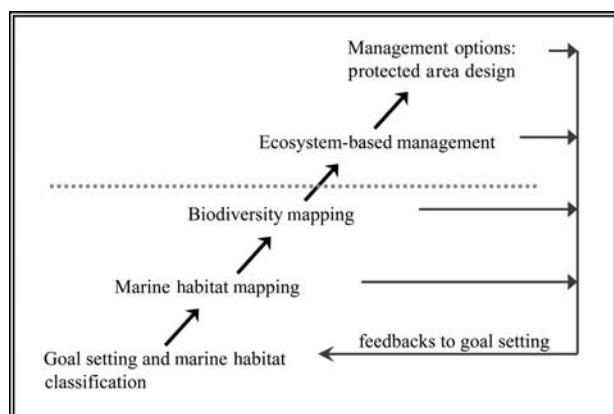
Figure 1. MHM as an early phase of EBM. The dashed line in the centre represents a typical (and potentially problematic) division between project activity and institutional or governmental responsibility. Modified from Cogan and Noji (2007).

this research phase will be used within the context of EBM to establish conservation and restoration measures. This pattern of habitat classification, mapping, and modelling is increasingly used for marine management. The European Nature Information System (EUNIS) is another example where hierarchical habitat types are mapped and integrated with species and site data to support management decisions such as protected area design under the Natura 2000 programme of the European Commission.

In support of the premise that MHM is a logical starting point for marine EBM, we outline here the correspondence between the dominant themes of EBM and the practice of MHM. In addition to articulating the general goals of EBM, the review paper by Grumbine (1994) outlines a series of ten dominant themes for EBM. These and similar characterizations of EBM have since been reinforced in the terrestrial and marine literature by many authors, including a historic overview and call for increased application of EBM by Christensen *et al.* (1996), a Scientific Consensus Statement on Marine Ecosystem-Based Management (McLeod *et al.*, 2005), a survey paper by Arkema *et al.* (2006), and a paper on the challenges of marine EBM by Ruckelshaus *et al.* (2008). Although mapping management connections are of general interest and show that MHM is an important element of EBM, perhaps more important are the insights that can be gained by deconstructing this combination of MHM and EBM to show the potential improvements from this synergistic combination. Conversely, MHM that is conducted without explicit consideration for the elements of EBM is likely to fall short of its potential. Below is a point-by-point comparison between all ten of the specific elements originally proposed by Grumbine (1994) for EBM and the corresponding characteristics of a well-planned MHM programme.

1. Hierarchical context

It is important to conduct EBM such that connections between thematic, temporal, and spatial scales are addressed. For example, studies at the species, community, or ecoregion extent can be integrated as a hierarchy to strengthen individual results. One of the most straightforward methods for documenting spatial grain and extent as well as corresponding habitat homogeneity is through the use of habitat maps. In MHM, this is achieved

through a combination of mapping techniques including broad-scale satellite quantification of the ocean surface (Hardman-Mountford *et al.*, 2008), medium-grain acoustic surveys of the benthos, and high-resolution photograph transects. In some cases, when working with large, previously unmapped areas, combinations of MHM and environmental modelling are also employed (Pickrill and Kostylev, 2007).

2. Ecological boundaries

A key element of EBM is the recognition that species distributions and derived ecological boundaries, and not administrative or political boundaries, should guide marine management. As ecological boundaries are largely documented through the marine mapping process, it is critical that the mapping areas, techniques used, and classification concepts are consistent within the framework of LMEs. Global examples of marine ecoregion mapping include the "GOOD's" open oceans classification (Vierros *et al.*, 2008) and the coastal shelf "marine ecoregions of the world" (MEOW; Spalding *et al.*, 2007). With such frameworks in place, consistently mapped ecological boundaries and zones can be used to support specific applications such as sea use management and marine spatial planning (Ehler and Douvere, 2007), as well as EBM. This approach to MHM has already been implemented successfully in several ecoregions, including the development of consistent acoustic mapping methods across national boundaries in the United States and Canada in the Gulf of Maine (Valentine *et al.*, 2005). Recent European examples include mapping activities by a consortium of northwest European nations [MESH (Mapping European Seabed Habitats), 2008].

3. Ecological integrity

Ecological integrity was clearly an important consideration for Leopold (1949), who wrote of the "integrity, stability, and beauty of the biotic community". More specifically, integrity is now considered to be the "capability of supporting and maintaining a balanced, integrated, adaptive community of organisms having a species composition, diversity, and functional organization comparable with that of natural habitat in the region" (Karr and Dudley, 1981). Andreasen *et al.* (2001) further characterize integrity as an index of "wholeness, completeness, and intactness" which can be compared with the measures of "natural reference conditions" (Mattson and Angermeier, 2007). In quantifying ecological integrity, it is useful to consider this ecosystem attribute as a series of measures of total native diversity, including species composition, population dynamics, and ecosystem diversity, each of which have appropriate spatial scales for sustainable management over time (Norton and Ulanowicz, 1992). Although ecological integrity measures will require a wide range of habitat parameters, MHM specifically supports these measures by targeting the relationship between physiographic (e.g. seafloor bathymetry and substratum) and biological habitat requirements. By designing MHM to incorporate integrity parameters, MHM provides the foundation for species–habitat models and provides the basis for the quantitative analysis of structural, functional, and compositional biodiversity. One such MHM study was conducted off southwest Nova Scotia, where a sea scallop fishery is being managed effectively based in part on seafloor mapping surveys (Smith, 2006). Repeat mapping in such temporally dynamic areas facilitates monitoring and management of the fisheries, benefiting integrity by reducing bycatch and damage to epibenthic communities.

4. Data collection

Habitat inventory and classification, measures of disturbance regime dynamics, baseline species, and population assessments all require basic data collection. MHM integrates physical sampling, satellite, aircraft, and shipboard remote sensing data, surface water analysis, and pelagic and benthic observations into a common framework, often using geographic information systems (GIS) for data organization as well as spatial analysis. With appropriate planning, MHM acts to integrate a variety of data types, often making possible the otherwise challenging consolidation of information from differing spatial, temporal, and thematic scales. Moreover, the wide range of data types integrated into GIS and consolidated across spatial scales is ideal to address multiple scientific objectives, extending our ability to extract information from basic data, and facilitating data synthesis for a broad range of research and EBM needs.

5. Monitoring

Monitoring allows us to identify and track "normal" temporal dynamics, and hence the consequences and efficacy of management operations. As with other change detection approaches common to remote sensing, benthic habitat maps and maps of sea surface condition portray many kinds of structural and compositional change. Although there are many spatial and non-spatial metrics to evaluate integrity or quantify biodiversity, by highlighting areas of change, more detailed investigations can be prioritized to determine management priorities and recommended actions. Change detection based on MHM baselines is a logical and efficient part of EBM. The International Council for the Exploration of the Sea (ICES) North Sea Benthos Survey (Rees et al., 2007) is an example of repeated benthic monitoring which has led to management advice for the development of a research plan on the effects of broad-scale hydrographic (i.e. temperature and salinity) changes on biota in the North Sea.

6. Adaptive management

Recognizing that our knowledge of marine ecosystems is provisional, it is widely recognized that EBM should incorporate feedbacks from ecosystem monitoring and be able to adapt management policies to work from new understandings or changing conditions (Christensen et al., 1996). Using existing MHM techniques, the process of mapping and monitoring provides a consistent ecosystem-wide approach to determine when management changes are needed. Examples of adaptive management in marine ecosystems could include, for example, changes in practices resulting from monitoring seafloor recovery following trawl operations.

7. Interagency cooperation

For the same reasons that ecological boundaries are advantageous over political boundaries when working with ecosystems, it is also logical that the various governing bodies within the framework of LMEs will need to cooperate to be effective. Common MHM data, based on ecological boundaries, facilitates cooperation across agencies, departments, and intergovernmental organizations (IGOs) by providing common scientific data and advice for a range of sectoral efforts. Examples of MHM at the multinational level demonstrate the feasibility of intergovernmental cooperation, including a five-country MHM programme being conducted in Northwest Europe (Coggan et al., 2005), and Canada–US

partnerships to map the Gulf of Maine (Noji et al., 2004). There are also many examples of interagency cooperation within national governments such as those in Australia (Harris et al., 2002; Porter-Smith et al., 2004), the National Fish Habitat Action Plan in the United States (Association of Fish and Wildlife Agencies, 2006), and a memorandum of understanding between the US Geological Survey (USGS) and the National Oceanic and Atmospheric Administration (NOAA) to coordinate and cooperate in activities involving physical sciences, biological sciences, and environmental studies (US Department of the Interior and US Department of Commerce, 2005).

8. Organizational change

In addition to interagency cooperation, the recognized need for MHM and EBM has also acted to promote organizational change within agencies responsible for managing marine ecosystems. This change has cut across many levels of government, with entirely new divisions created to fulfil the EBM mandate. NOAA, for example, established an Ecosystems Goal Team consisting of nine programmes with broad national participation from offices throughout the agency. The programmes include Coastal and Marine Resources, Habitat, Ecosystems Observations, and Ecosystems Research, all with MHM an important part of their mission. MHM is well-positioned to help make these organizational changes successful by providing a consistent data source that directly supports interdisciplinary research and biodiversity assessment. For each management group, standardized structural information derived from multibeam hydroacoustic maps of the benthos and other physical science measures such as temperature, salinity, and currents provide a foundation from which to build biodiversity knowledge by integration with biological composition and ecosystem function.

9. Humans embedded in nature

It has long been recognized that human factors are of basic importance to ecosystems and that humans are in turn affected by them (Leopold, 1941; Rapport, 1998; Callicott, 2000). In this sense, humans are integral components of marine ecosystems. Habitat mapping with biodiversity assessment in marine systems is a primary approach to measuring and monitoring habitat alteration by fisheries, coastal and offshore development, aquaculture, aggregate mining, oil and gas extraction, military acoustics, and other direct anthropogenic effects. MHM is also a critical tool for detecting less obvious changes to marine ecosystems by providing the observational basis to characterize the effects of climate change, and providing policy-makers with critical time-series information to support regulatory modifications. In addition to mapping and modelling various ecosystem parameters, it is also possible to measure how humans interact with their environment as the ecosystem changes. As just one example of this expanding area of research, the Science Plan for Arctic Coastal Processes recently established a combined programme of habitat mapping integrated with social science expertise as a funding priority for the international Arctic coastal zone (Cogan and Rachold, 2007). By quantifying anthropogenic (e.g. fisheries) effects, natural (e.g. ice flow) processes, and social interactions with ecosystems, MHM is well positioned to move beyond bathymetry, supporting the inclusion of human elements in EBM.
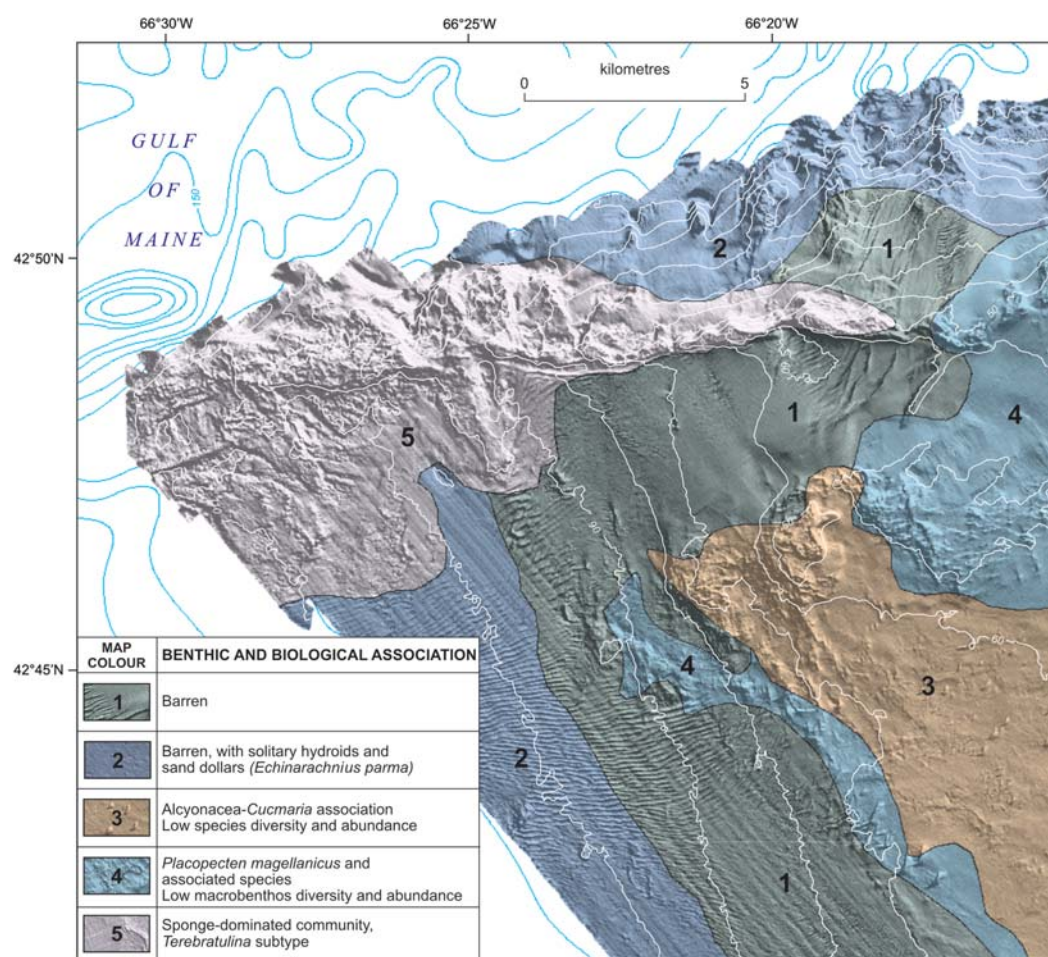
Figure 2. Enlarged segment from a marine habitat map designed for compliance with national map standards. The map depicts benthic habitat and sun-illuminated seafloor topography, in the region of Browns Bank, Scotian Shelf, offshore Nova Scotia. Modified from Todd *et al.* (2006).

10. Values

Perhaps the most important overarching theme of EBM is our changing attitude for valuing ecosystems. Sociocultural and economic factors are basic marine policy drivers. In essence, how people value marine ecosystems ultimately guides policy and can result in organizational changes for the empowerment of EBM. Public perceptions and values depend, however, on a series of feedbacks. These include spiritual and aesthetic values, scientific information, measures of productivity such as goods and services (e.g. fisheries), policy, and regulation. As societies shift from a perspective of marine ecosystems as exploitable resources to one of sustainable management of ecosystem capital, stakeholders and policy-makers alike require more extensive standardized and accessible information on different ecosystem components, as well as techniques to visualize the implications of alternative management strategies. Understanding and accessing the multiple mapped layers of information that can be provided by MHM for the valuation of marine ecosystems is facilitated by GIS.

One of the strongest tools for communicating the status of marine ecosystems is the map. MHM provides the means to visualize marine habitats. For policy-makers and society in general, marine habitats are often out of sight—and out of mind. Producing pictures in the form of habitat maps builds public awareness, enhances general knowledge of the marine spatial landscape, and provides a starting place, or entry point, for values that can then be developed more fully. Maps, like pictures, are often worth a thousand words and offer a medium for quickly communicating environmental status with a minimum of technical jargon. As demonstrated by the now famous "earthrise over the lunar horizon" photo from Apollo 8 (NASA, 1968), images facilitate public engagement with ecosystems. In addition to the basic power of marine habitat images, a series of marine habitat maps that follow in the footsteps of nationally standardized terrestrial topographic maps provide a combination of photo-realistic imagery and cartographically accurate base maps for spatial analysis with GIS (Figure 2; see also Pickrill and Kostylev, 2007). In this sense, the basic product of MHM serves two needs: images to promote public engagement with marine ecosystems and, concomitantly, a critical dataset for EBM.

General overview of the elements of EBM

Directly supporting each of the ten principal elements of EBM, MHM brings new focus to the power of marine habitat maps and provides a pathway for the biological and ecological sciences to support urgently needed advances in management. Discrete spatial data themes that build into habitat maps represent

ecological processes at multiple spatial and temporal scales. Maintaining individual map layers as model parameters provides the transparency, flexibility, and analytical power needed to proceed with ecosystem-based approaches. As specific types of data are collected and synthesized into map layers, the ten MHM/EBM elements can help guide data collection methods. Rather than a unidirectional methodology to gather, aggregate, and generalize complexes of ecosystem data, we will be increasingly challenged to interpret individual components. This deconstruction of our maps and data models can better support transparency and flexibility, at the same time supporting new combinations of our data to represent the big picture. Keeping the parts while building the whole is challenging, but our deconstruction and linkages between MHM and EBM offer a way forward to achieve this. At the same time, investigations of discrete marine habitat elements and their interconnections to EBM shed new light on the interconnections between habitat classification, mapping, biodiversity, and management.

Design considerations and needs for MHM in context with biodiversity and EBM

When developing marine habitat maps, cartographic design and appropriate map scale (i.e. the combination of spatial grain and spatial extent) must be identified. In addition, thematic scales also determine the utility of a map. A bathymetric map depicts only water depth (often based on acoustic data) and has limited utility; map suites are more powerful and consist of bathymetric information displayed in conjunction with sonar backscatter strength and maps of seafloor surficial geology (Todd and Kostylev, 2000). Temporal scales also apply to marine habitat maps, given the value of time-series maps to support the EBM elements of monitoring and adaptive management. A central question, therefore, is how to determine appropriate spatial, thematic, and temporal scales when designing marine habitat maps for EBM?

Technological mapping capabilities are continually improving, and it is sometimes all too easy to let technology drive the methods of mapping habitats. This is also a potential problem with classification systems (Parsons and Wand, 2008). In terrestrial habitat mapping, satellite and aircraft sensors are used in conjunction with field data to determine land cover, often discriminating vegetation types that in turn can be used to model the potential presence of vertebrate species. A common source of error is an inadequate model of the relationship between remotely sensed spectral reflectance and actual land-cover types that have ecological relevance. In marine systems, a similar problem exists with associating particular marine habitats with classifications based on remote sensing technologies, such as multibeam sonar acoustic mapping of the seafloor. Marine habitat classification systems should be robust enough to work independently of minor changes in evolving remote sensing technologies, and they should function at multiple spatial grains, along with a hierarchical range of thematic resolutions (Valentine *et al.*, 2005; Greene *et al.*, 2007). It is natural to strive to use the best available technology, but intelligent choices (guided by EBM criteria) regarding, for example, habitat classification design or trade-offs between spatial resolution and mapping area can help us remain science-based rather than technology-driven.

In addition to ever-changing technologies and modelling capabilities, MHM must also respond to changes in conservation

targets and policy priorities. ICES recently adopted a new 5-year Science Plan (ICES, 2008) to anticipate and support new needs for scientific advice. Such proactive realignment is needed to support requests for advice on ecosystems issues, as presented by the European Commission, the Oslo–Paris (OSPAR) Commission for the Northeast Atlantic, and other international regulatory authorities. Notably among the high-priority topics identified by ICES, most require an ecosystem approach and will be facilitated by MHM. These priorities include:

 (i) marine spatial planning, including the effectiveness of management practices, and its role in the conservation of biodiversity;

 (ii) biodiversity and the health of marine ecosystems;

 (iii) sensitive ecosystems (deep-sea coral, seamounts, Arctic), as well as rare and data-poor species;

 (iv) contributions to socio-economic understanding of ecosystem goods and services, and forecasting of the impact of human activities;

 (v) the role of coastal zone habitat in population dynamics of commercially exploited species;

 (vi) influence of the development of renewable energy resources (e.g. wind, hydropower, tidal, and wave) on marine habitat and biota;

 (vii) population and community level impacts of contaminants, eutrophication, and habitat changes in the coastal zone;

 (viii) impacts of fishing on marine ecosystems;

 (ix) climate change processes and predictions of impacts;

 (x) introduced and invasive species, their impacts on ecosystems, and interactions with climate change processes.
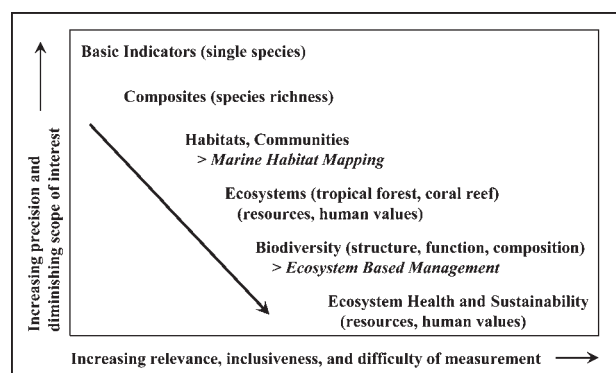
Each of these priorities includes a strong spatial component. Each can benefit from GIS-based spatial modelling which in turn is well assisted by habitat mapping. For example, mapping deep-sea corals is a logical early step in their management. Modelling the spatial distribution and health of multiple habitat types helps us to quantify incremental habitat degradation resulting from combinations of harvest pressures. Also, spatial patterns of point and non-point source contaminant release can be mapped and analysed in conjunction with marine habitat maps. We do not suggest that MHM is an end-all solution to each of these priorities; they will require many interdisciplinary collaborations and analysis types. We do, however, propose that MHM will be increasingly important to address these pressing management issues.

Adaptive management, as a basic EBM element (see EBM specific element 6), specifically calls for a flexibility that must be supported by MHM. Another EBM element, organizational change (EBM specific element 8), also allows for transitions in policy. One way to ensure that marine habitat maps have maximum value is to design the maps specifically to support broad-based biodiversity assessment and analysis, which along with social and economic considerations can guide EBM towards specific management strategies (Figure 1). Producing habitat maps with singular, more restrictive goals in mind, Marine Protected Areas, for example, is less adaptable, less suitable for data synthesis, and likely to result in habitat map data of reduced value.

Changes in management goals and policy objectives are influenced by shifts and advances in the methodologies of MHM and EBM, and vice versa. In the past, marine management and science have been predominantly focused on single-species indicators (McLeod *et al.*, 2005). Although such research is important, providing a detailed understanding of how a certain species interacts with its environment, knowledge of a single species does not in itself answer the broad questions of ecosystem sustainability that marine managers are faced with now. Resource managers of today are not only interested in the management and conservation of single species, but are also required to work with a hierarchy of multiple targets to achieve precision (a focused scope of interest) and broader, more inclusive relevance (Figure 3). This does not mean that "less relevant" research such as single-species investigations are not important; indeed such projects are prerequisites for the development of general studies.

From the biological perspective dealing with species habitats and communities, MHM is more inclusive than single-species research and similar indicators, but less inclusive generally than

biodiversity studies and EBM. One way to visualize this is to place MHM and EBM as transition phases within the continuum of applied research elements that covers species, communities, ecosystems, and human values (Figure 3, italicized text). From this perspective, MHM is well positioned to integrate a series of basic indicators and present a spatially explicit data synthesis of habitat conditions that can be used for modelling and analysis of biodiversity and ecosystem level management.

Some pioneering examples of MHM which have been strategically positioned to transition to "high-relevance" biodiversity assessment already exist. Recent investigations (Noji *et al.*, 2008) in the US Gulf of Maine exemplify how discrete data can be aggregated across thematic scales through modelling to help identify conservation targets. Data on sediment grain size, wave height, suspended chlorophyll, mixed layer depth, bottom currents, bottom temperature, and bottom salinity were used in a model modified from Kostylev *et al.* (2005) to describe the benthic habitats in terms of scope for growth and mechanical disturbance. For example, a portion of Georges Bank (indicated by an arrow in Figure 4a) is characterized by large scope for growth and moderate disturbance (Figure 4b). Scope for growth and disturbance can also be presented together using a habitat template matrix to map habitat types according to these two properties. A map of these habitat properties can be used to predict usage by biota including managed fish species such as Atlantic cod (*Gadus morhua*; Figure 4c). The importance of habitat types for recruitment of fish is an important consideration for managers establishing marine managed areas.

In the context of EBM, biodiversity is a multidimensional complex of structural, functional, and compositional elements over a range of spatial and temporal scales (Figure 5). Following such a biodiversity template, marine habitat maps can logically inform users on a range of key biodiversity elements such as functional disturbances, habitat structure, and physiognomy, and habitat components associated with species and community composition. The biodiversity template therefore serves as a checklist for data elements (or data surrogates) included or omitted from the habitat maps and management goals.

Figure 3. Thematic scales and conservation targets: biodiversity in context with trade-offs. Precision or diminishing scope of interest orders the vertical axis, and relevance and inclusiveness are measures along the horizontal. Narrow-scope research, though important in its own right, synergistically supports increasing inclusiveness, a research trend indicated by the diagonal arrow to the lower right. MHM is approximately associated with the habitat community level, whereas EBM is more closely associated with biodiversity analysis. Adapted from Costanza (1992) and Redford *et al.* (2003).

Conclusions

Marine management based on ecosystem level processes is a daunting task, but an important responsibility for us and future
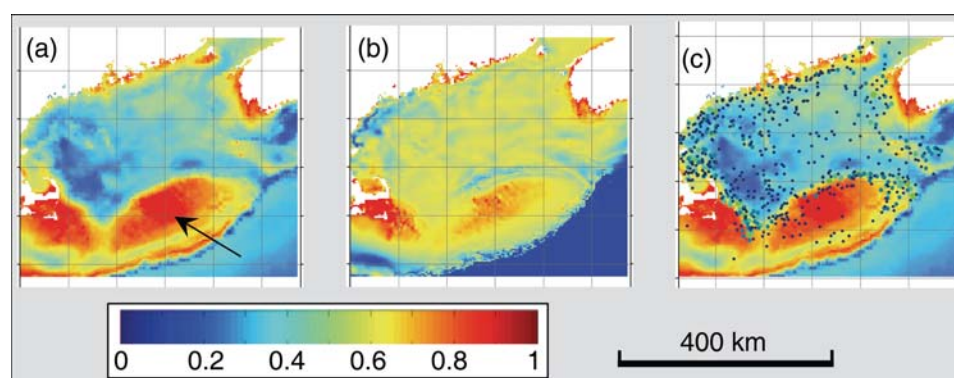
Figure 4. Scope for (a) growth and (b) disturbance of bottom habitats of the Gulf of Maine and Georges Bank (arrow), modelled after Kostylev *et al.* (2005). Model results are colour-coded from low (in blue) to high (in red). (c) Atlantic cod distribution is also shown in relation to scope for growth (unpublished data, courtesy of S. Fromm).
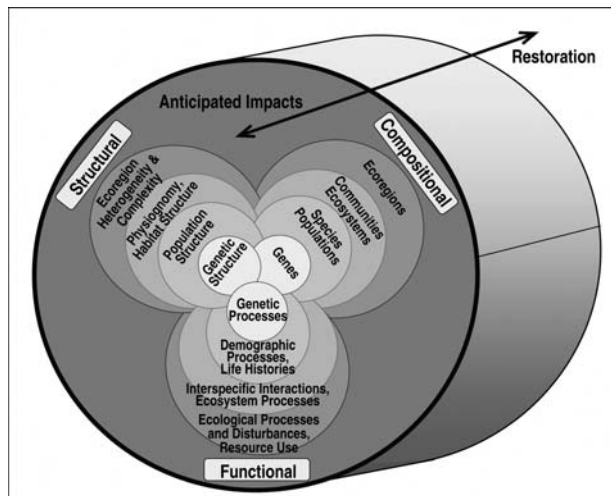
Figure 5. Biodiversity elements. Structural, compositional, and functional elements of biodiversity, operating on different spatial and temporal scales. Restoration and anticipated impacts refer to past biodiversity states that may be changed by future restoration and future impacts in a temporally dynamic biodiversity system. MHM relates directly to several of these elements (see text). Figure adapted from Barkman (1978), Franklin *et al.* (1981), Noss (1990), and Cogan and Noji (2007).

generations. Such management programmes must consider multiple scientific, social, and cultural priorities and data, and it is sometimes difficult to make the jump from focused research projects to ecosystem-level management actions. Here, we have drawn from both the terrestrial and marine ecological sciences to revisit the ten essential components of EBM and show how each of these is directly supported by MHM. By directly positioning the science of MHM to support biodiversity assessment and EBM, a focusing of research priorities is suggested, and we gain a useful perspective on marine EBM progress.

Designing a survey programme to conduct MHM in support of EBM calls for careful consideration of a series of critical design parameters. Aside from spatial, thematic, and temporal scale considerations (represented in Figure 5), pitfalls in classification design can lead to technology-driven approaches that may be ill-suited to work with the range of elements desirable in marine habitat maps. MHM, biodiversity analysis, and EBM are best designed as flexible tools, resulting in datasets suitable for synthesis and adaptive management appropriate for use by multiple agencies and IGOs. A powerful mechanism to preserve flexibility in habitat map products is to tailor the map applications for compatibility with biodiversity theory, allowing biodiversity to act as a bridge to allow habitat data to be used in support of EBM. In this sense, MHM, biodiversity analysis, and EBM are sequential. In practice, many management decisions are not made this way because (for example) of the need to act on a decision quickly. The steps from basic indicators (species) to EBM are, nevertheless, a useful target, helpful in prioritizing research funding to understand better the range of conservation targets for management.

By outlining the linkages between classification systems, MHM, biodiversity, and EBM, we have identified a series of compelling reasons to build on existing MHM programmes worldwide. We have also offered guidelines for improving the science of MHM, to build a stronger theoretical base to support and guide future MHM and EBM developments.

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