Ecosystem-based fisheries management: some practical suggestions

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Abstract: Globally, there is increased scientific and public interest in the concept of ecosystem-based fisheries management (EBFM). This trend is fueled by a widespread perception that large-scale fishing operations are powerful forces altering the structure and function of marine ecosystems. It is acknowledged that management needs to better account for variations in ocean productivity, stock structure, and changing social values. Many countries are contemplating how to improve ocean fishery management. In the United States, fishery management bodies are experiencing pressure to undertake the daunting task of moving from their current single-species management plans to EBFM. Impediments include lack of a clear definition of EBFM, what it entails, or how to proceed. In this paper, characteristics of fishery management that are unique to EBFM are identified. The transition to EBFM needs to be evolutionary rather than revolutionary. A course of action is outlined that can be used to guide this transition. Modeling approaches and metrics useful for planning, implementing, and evaluating EBFM are discussed, with particular emphasis on management strategy evaluation.

Résumé : Il y a, à l’échelle globale, un intérêt croissant chez les scientifiques et le public en général pour le concept de gestion des pêches axée sur les écosystèmes (EBFM, ecosystem-based fisheries management). Cette tendance est alimentée par la perception que les opérations de pêche de grande envergure constituent des forces puissantes qui altèrent la structure et le fonctionnement des écosystèmes marins. On reconnaît que l’aménagement doit mieux tenir compte des variations de la productivité océanique, de la structure des stocks et des valeurs sociales changeantes. Plusieurs pays cherchent comment améliorer la gestion des pêches dans l’océan. Aux États-Unis, les organismes responsables de la gestion des pêches subissent de fortes pressions pour remplacer leurs plans actuels axés sur les espèces individuelles par l’EBFM. Une des difficultés est l’absence de définition claire de l’EBFM ; il est aussi nécessaire d’en connaître les implications et de savoir comment procéder. Nous identifions ici les caractéristiques de la gestion des pêches qui se retrouvent exclusivement dans l’EBFM. La transition vers l’EBFM doit se faire par évolution plutôt que par révolution. Nous proposons un plan d’action pour guider cette transition. Nous discutons aussi des méthodologies de modélisation et des métriques utiles pour la planification, la mise en œuvre et l’évaluation de l’EBFM avec une attention particulière portée à l’évaluation des stratégies de gestion.

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Introduction

The desire to move towards ecosystem-based fisheries management (EBFM) is a common theme in fisheries policy and management discussions worldwide. While EBFM means different things to different people, the underlying aim is ecologically sound resource conservation that responds to the reality of ecosystem processes. There is concern about the overexploitation of fishery resources that has occurred despite the declaration of 200 mile (1 mile = 1,609 km) Exclusive Economic Zones and the establishment of governmental institutions with fisheries management authority. Fisheries extraction is the anthropogenic effect most commonly invoked as an example of the forces altering the structure and function of marine ecosystems (Pauly et al. 2002; Essington et al. 2006). Consequently, increasing attention is being focused on changing fisheries management practices and principles to protect living marine resources on an ecosystem scale.

Historically, ecology, fisheries biology, oceanography, and fisheries economics have not been well integrated in fisheries management. It is generally acknowledged that far more attention needs to be focused on a coupled understanding of many factors for more successful fisheries management. Information on physical, chemical, and biological oceanography; population biology; ecological interactions of the various species of the fish community; and the likely social and economic ramifications of management changes must be considered explicitly. This integration should be carried out with a view to better management of resources on a sustainable basis (Charles 2001).

Many countries are contemplating how to implement modern ocean fisheries management concepts. The 13th International Council for the Exploration of the Sea (ICES) Dialogue Meeting (26–27 April 2004) discussed how ICES plans to introduce an ecosystem approach (Anonymous 2004b). As an outgrowth of this meeting, fisheries advice from ICES in 2004 was supplemented with ecosystem considerations dealing with both the impact of fisheries on the ecosystem and the impact of ecosystems on fisheries (Anonymous 2006b). In 2005, ICES began discussions on reforming the structure of its expert groups that deliver science and advice, and a special meeting took place in March 2006 to develop a blueprint for the new science and advisory structures that will be required within ICES to service the demands of the ecosystem approach (Anonymous 2006b). The Australian Fisheries Management Authority has set out to assess the risks that fishing poses to the ecological sustainability of the marine environment for major Commonwealth fisheries (Anonymous 2006a). Ecological risk assessments are considered to be a key component of EBFM by the Australian Fisheries Management Authority. In 2002, Canada issued the "... Policy and Operational Framework for Integrated Management of Estuarine, Coastal and Marine Environments", which provided conceptual guidance on integrated management and planning (Anonymous 2005). This policy, which includes the concept of an ecosystem-based approach, is being tested for the Eastern Scotian Shelf (Anonymous 2004c). Echoing concerns contained in reports and studies regarding the sustainability of marine ecosystems and the depletion of many fish species, the US Commission on Ocean Policy (Anonymous 2004c) recently recommended that the United States move towards EBFM. Despite all the interest, substantial operational and definitional issues remain with EBFM and how it might be implemented.

Within the United States, Fishery Management Councils (FMCs), established in the mid-1970s under the authority of the Magnuson–Stevens Fishery Conservation and Management Act (Magnuson–Stevens Act), are the rule-making bodies charged with developing federal fishery management (consistent with other applicable policy). FMCs are faced with growing national momentum to adopt EBFM. Congressional reauthorization of the Magnuson–Stevens Act includes provisions to help redirect fishery management policies and procedures away from the traditional emphasis on single-target species and towards EBFM. Many of the FMCs' management actions can arguably be considered to reflect an overall ecosystem philosophy (Witherell 2004), and some Magnuson–Stevens Act provisions have already led to protection of essential fish habitat (EFH), reduction of bycatch, and rebuilding of overfished stocks. However, attempts at making these concepts operational based on clearly specified ecosystem guidelines and standards are still in an early stage.

There have been numerous reviews, workshops, and conferences that have addressed what EBFM is and how it should be implemented (NMFS 1999; NRC 1999; Witherell 2004). This review (initiated at the request of the Pacific States Marine Fish Commission) addresses three practical issues related to EBFM: (i) How should EBFM be defined for use by FMCs and other regulatory bodies? (ii) What characteristics are specific to an EBFM approach? (iii) What are the next steps that FMCs and other regulatory bodies should take to move forward from the existing management approaches to a management system that would, over time, explicitly incorporate EBFM considerations into fishery assessment and management?

While the discussion that follows draws extensively from experience in the United States, it is believed that the guidance provided will be relevant worldwide to most parties and agencies responsible for the management of fisheries.

Defining EBFM

At present, the dominant fishery management paradigm focuses on individual species and does not incorporate ecosystem considerations in a comprehensive and transparent way. The shortcomings of this paradigm have been recognized, but not yet fully corrected (Mangel et al. 2002). Many definitions of an ecosystem-based approach to natural resource and fisheries management have recurring themes (Table 1). There is recognition of a broader constituency of uses and users of the marine environment (including fishing) and the need to accommodate and reconcile the many goals of these users so that future generations can also benefit from the full range of ecosystem goods and services. There is recognition that humans are an essential component of the ecosystem in which fishing takes place. Most importantly, these definitions recognize the interactions among physical, biological, and human components within the system. Therefore, it can be concluded that the purpose of an EBFM approach is to plan, develop, and manage fisheries in a
Table 1. Some existing definitions of an ecosystem-based approach to management (or fisheries management).

The North Pacific Fishery Management Council (Witherell et al. 2000)
An ecosystem-based approach to fisheries management is defined as the regulation of human activity towards maintaining long-term system sustainability (within the range of natural variability as we understand it) of the North Pacific covering the Gulf of Alaska, the Eastern and Western Bering Sea, and the Aleutian Islands region.

The Food and Agricultural Organization of the United Nations (FAO Fisheries Department 2003)
An ecosystem approach to fisheries strives to balance diverse societal objectives by taking into account the knowledge and uncertainties about biotic, abiotic, and human components of ecosystems and their interactions and applying an integrated approach to fisheries within ecologically meaningful boundaries.

The Scientific Consensus Statement on Marine Ecosystem-Based Management (McLeod et al. 2005)
Ecosystem-based management is an integrated approach to management that considers the entire ecosystem, including humans. The goal of ecosystem-based management is to maintain an ecosystem in a healthy, productive, and resilient condition so that it can provide the services humans want and need. Ecosystem-based management differs from current approaches that usually focus on a single species, sector, activity or concern; it considers cumulative impacts of different sectors.

The National Research Council (NRC 1999)
Ecosystem-based management is an approach that takes major ecosystem components and services — both structural and functional — into account in managing fisheries. It values habitat, embraces a multispecies perspective, and is committed to understanding ecosystem processes. Its goal is to achieve sustainability by appropriate fishery management.

National Oceanic and Atmospheric Administration (Murawski and Matlock 2006)
An ecosystem approach to management (EAM) is one that provides a comprehensive framework for living resource decision-making. In contrast to individual species or single-issue management, EAM considers a wider range of relevant ecological, environmental, and human factors bearing on societal choices regarding resource use.

manner that addresses the multiple needs and desires of society without jeopardizing the options for future generations to benefit from the full range of ecosystem goods and services.

The authors propose the following as a definition of EBFM: "Ecosystem-based fishery management recognizes the physical, biological, economic, and social interactions among the affected components of the ecosystem and attempts to manage fisheries to achieve a stipulated spectrum of societal goals, some of which may be in competition."

Characteristics of EBFM
The identification of characteristics of EBFM is facilitated by recognizing its aim as defined above. Numerous lists of characteristics or elements have been proposed by, for example, the Ecosystem Principles Advisory Panel (NMFS 1999), the Scientific Consensus Statement on Marine Ecosystem-Based Management (McLeod et al. 2005), and the Marine Fisheries Advisory Committee’s Ecosystem Approach Task Force (Busch et al. 2003). Table 2 (taken from McLeod et al. 2005) represents a good starting point for characterizing EBFM as proposed heretofore, but the authors believe that additional factors are also important. The following seven elements are specific to EBFM and are distinct from those considered routinely in single-species approaches to fisheries management. (1) Ensure that broader societal goals are taken into account. (2) Employ spatial representation. (3) Recognize the importance of climatic-ecologic conditions. (4) Emphasize food web interactions and pursue ecosystem modeling and research. (5) Incorporate improved habitat information (target and nontarget species). (6) Expand monitoring. (7) Acknowledge and respond to higher levels of uncertainty. These should, therefore, be the focus for changes to current approaches. The following sections outline each of these elements further.

Broader goal specification and recognition
EBFM acknowledges differing uses of an ecosystem and its resources. Since fisheries goals are only a subset of societal goals, EBFM needs to embrace a broader set of impacts and goals. In the United States, this may require expanded participation and representation in the FMC process. Pertinent societal goals should include national, regional, and fishery-specific goals, but also would extend beyond conventional fisheries goals. In the United States, goals are based to a greater or lesser degree upon the Magnuson-Stevens Act, the Endangered Species Act, and the Marine Mammal Protection Act. Within an EBFM approach, broader goals reflecting society’s changing values for ecosystem products and services will need to be accommodated more explicitly in management models and actions, for example as embodied in the Marine Sanctuaries Act. However, moving from high-level policy goals to operational goals remains a major challenge in situations where the goals are broad concepts such as "ecosystem integrity", "ecosystem health", and "biodiversity" (Sainsbury et al. 2000). Given a broader stakeholder base under EBFM, there also will be a need for institutions to coordinate consultations. Joint decision-making will be needed between fisheries and other non-fishery-related user groups that operate and interact in the same geographic area. Initial steps in this direction have been taken by some FMCs, as they broaden representation of civic and environmental groups on advisory committees.

Spatial representation
Accounting more explicitly for space (spatial thinking) is a practical way of moving forward with EBFM. Although accounting for space is fundamental to an understanding of
Table 2. Characteristics of an ecosystem-based approach to fisheries management identified. (From McLeod et al. 2005, reproduced with permission of Communication Partnership for Science and the Sea (COMPASS).)

1. Make protecting and restoring marine ecosystems and all their services the primary focus, even above short-term economic or social goals for single services.
2. Consider cumulative effects of different activities on the diversity and interactions of species.
3. Facilitate connectivity among and within marine ecosystems by accounting for the import and export of larvae, nutrients, and food.
4. Incorporate measures that acknowledge the inherent uncertainties in ecosystem-based management and account for dynamic changes in ecosystems. In general, levels of precaution should be proportional to the amount of information available; the less that is known about a system, the more precautionary management decisions should be.
5. Create complementary and coordinated policies at global, international, national, regional, and local scales, including between coasts and watersheds (appropriate scales for management will be goal-specific).
6. Maintain historical levels of native biodiversity in ecosystems to provide resilience to both natural and human-induced changes.
7. Require evidence that an action will not cause undue harm to ecosystem functioning before allowing that action to proceed.
8. Develop multiple indicators to measure the status of ecosystem functioning, service provision, and effectiveness of management efforts.
9. Involve all stakeholders through participatory governance that accounts for both local interests and those of the wider public.

population dynamics processes (e.g., fish movements over time and space) and stock structure, single-species management has tended to focus more on temporal and age-structured considerations. Spatial thinking can help define how and where human activity (both fishing and nonfishing) affects the ecosystem, and spatial management can help to resolve conflicts among user groups through zoning for different uses, including nonextractive uses (the latter, for example, through the implementation of a system of no-take Marine Protected Areas). Without an explicit consideration of space when making management decisions, species are managed as homogeneous populations, which may impede the ability to develop prudent management measures, such as spreading catch out spatially and temporally to protect life-history characteristics and biodiversity. Spatial considerations are already being accounted for to some extent when fishery management decisions are made in the United States. For example, (i) restrictions were placed on the eastern Bering Sea and Gulf of Alaska walleye pollock (Theragra chalcogramma) fisheries to protect local availability of prey for Steller sea lions (Eumetopias jubatus) around haul-out and breeding locations; (ii) salmon fisheries on the west coast of the United States are managed both spatially and temporally to maintain a complex stock structure and to allocate benefits among coastal communities and user groups (PFMC 2006a); and (iii) west coast groundfish management has included extensive closures to reduce bycatch of overfished stocks and to protect EFH (PFMC 2006b).

Although a wide variety of spatial models have been developed (Quinn and Deriso 1999), there has been limited application of these models in fisheries because of the lack of necessary data on fish movement and spatial variation in biological parameters. Even when movement data are available, (e.g., Pacific halibut (Hippoglossus stenolepis), Quinn et al. 1990; and Gulf of Alaska sablefish (Anoplopoma fimbria), Heifetz and Quinn 1998), spatial models are rarely used as the basis of stock assessments, because of their greater complexity. Exceptions to this are the assessment of hoki (Macrourus novazelandiae) off New Zealand (Francis 2004) and sharks off southern Australia (Punt et al. 2005). Integral to the move to EBFM is the routine examination in stock assessments of the evidence for stock and spatial structure. The lack of evidence for spatial structuring owing simply to lack of data should not be a reason to ignore the possibility of such structure. Moreover, in many cases, reasonable recommendations regarding how harvests should be distributed spatially can be made using data from surveys and catch information if there is evidence for spatial structuring, but there are insufficient data to conduct stock assessments that are spatially structured. For example, survey and catch information is already used to distribute catches spatially for many of the stocks managed by the North Pacific Fishery Management Council (NPFMC) (e.g., Gulf of Alaska walleye pollock, Pacific cod (Gadus marcocephalus), and sablefish; Heifetz et al. 1997).

The increasing application of geographic information systems (GIS) can be combined with traditional tagging techniques, more recent methodologies such as highly variable genetic markers (Hankin et al. 2005), and otolith microchemistry (Campana and Thorrold 2001; Miller et al. 2005; Barnett-Johnson et al. 2006) to identify population structure and estimate the extent of mixing and migration for a species. Such combined approaches will also facilitate taking better account of the spatial considerations in management.

Climatic–oceanic conditions

There is ample evidence of the importance of regime shifts in climate and interannual variation in oceanographic conditions on the growth, reproduction, and survival of fish and other marine species (Logerwell et al. 2003; King et al. 2005; Wells et al. 2006). Some regimes favor some species over others, and this depends on life-history characteristics (e.g., longevity and maturity schedules), their position in the food chain, and other factors. For example, it is known that salmon, sardines, marine mammals, Alaska crab, walleye pollock, and other groundfish species on the west coast of the United States are sensitive to regime changes (Beamish 1995; McGinn 2002). In this respect, the difference between the North Pacific and US west coast in the last 30 years is instructive. The North Pacific (the Gulf of Alaska and the Bering Sea) experienced good environmental conditions for fish productivity beginning in about 1976. In contrast, Washington, Oregon, and California experienced poor environmental conditions over the same period (Hare et al. 1999; Peterson and Schwing 2003; King et al. 2005). As a result,
fisheries in the North Pacific have been extremely productive, while those on the west coast have suffered. The poor environmental conditions off the west coast contributed to some extent to the decline of many of the groundfish species off the west coast (although fishing was almost certainly the main cause) and therefore have contributed to the need for the stringent management measures that have been implemented in this area (PFMC 2004).

Calculations of maximum sustainable yield and the rate at which overfished species are likely to rebuild are generally based on data for a period of years where it assumed that productivity was constant and will continue to be so for the projected future (Punt and Methot 2005). It therefore would be prudent for management strategies to respond to the possibility of climate changes that alter population or ecosystem productivity to detect climate-regime-related changes as soon as possible and to develop indicators to anticipate them. Necessarily, the information on how climatic–oceanic patterns might impact fish species has been obtained from retroactive analyses of oceanographic conditions and is seldom used for projection. Nevertheless, while predictive capability is still low, an important part of EBFM is to identify management strategies that are robust to ocean climate factors and their effects on species’ life histories. However, it may someday be possible to develop fisheries management processes that can respond rapidly, when changes are initially detected, if ongoing efforts to expand ocean observation systems are successful. Further research to understand how ocean climate affects ecosystem processes will help in this process (Field et al. 2006) as will research into which factors provide the earliest indication of a change in the productivity regime.

Food web interactions

Food web considerations are important in EBFM. For example, there have been indications that harvesting species low on the food chain has disproportionately larger impacts on species at the top of the food chain. Similarly, there are indications that selective harvest of desirable top predator species can lead to simplified community structure and redirection of fisheries toward lower and lower trophic levels (Pauly et al. 2002; Essington et al. 2006).

Collection and analysis of fish stomachs to determine prey consumption by predators is crucial for the development of the information base to model and understand food web interactions. As foraging theory predicts, many species are opportunistic in their feeding habits within trophic categories (e.g., piscivores, benthic carnivores, etc.) and will switch prey if presented with appropriate-sized prey and encounter opportunity. Information on diets and how diets change over time within trophic categories is necessary to develop adequate trophic ecosystem models. Unfortunately, with the exception of databases maintained by the NMFS Northeast Fishery Science Center for the northwest Atlantic and by the Alaska Fisheries Science Center for the Gulf of Alaska and eastern Bering Sea, there are no comprehensive, long-term databases in the United States upon which reliable ecosystem models could be based.

Information on diet composition is, however, not sufficient to quantify the functional relationships between predators and prey. Changes in ocean climate can cause temporal changes in predator and prey distributions that in turn lead to changes in trophodynamics. For example, Humboldt squid (Dosidicus gigas) have recently extended their northern range along the west coast of the United States. Top predators such as seabirds may not be able to switch prey quickly when their preferred prey species is depleted. The impact of the loss of forage species is then evidenced by increased seabird mortality (Ainley et al. 1995; Sydeman et al. 2001).

The predictions from ecosystem models can be sensitive to assumptions regarding the functional relationships determining predation. As a result, the ability to quantify and predict how natural mortality of fish and other organisms changes over time and space is currently limited. This leads to increased uncertainty and the need for precautionary management. Some management jurisdictions (e.g., the NPFMC; Anonymous 1998a) have responded to this uncertainty by banning or severely restricting harvests of forage fish (Constand and de la Mare 1994; Butterworth and Punt 2003). Unlike the current generation of single-species models, most ecosystem models as presently implemented do not adequately treat uncertainty (International Whaling Commission 2004). However, even if interactions are poorly quantified, ecosystem models can be used to help shift focus to ecosystem thinking.

The implications of trophodynamic changes for fisheries management will become clearer as models are refined and species interactions are better understood. The current generation of ecosystem models should therefore be modified to more explicitly treat uncertainty. Once modified, they should be used to evaluate the benefits of additional field research and to identify the most critical data gaps. Ecosystem modeling for management support should be more focused on quantifying trade-offs among diverse goals.

It is necessary to identify the data that are cheap or easy to collect (e.g., remote sensing data collected by others), as well as to set priorities for the most important information that may be expensive to collect, but that would provide insight into important ecosystem processes. For example, there is a need to collect ecosystem data that are not associated with data already collected during fishing activities, since fishery operations are frequently limited in space and time. Further, it is important to continue research on how climatic–oceanic patterns impact target and nontarget species.

Habitat

An increased and expanded focus on habitat considerations is needed for EBFM. The Magnuson–Stevens Act calls for the protection of EFH from fishing impacts to the extent that practical, current understanding of physical habitat for spawning, rearing, feeding, etc. of fishery species is limited. However, existing knowledge of ephemeral pelagic habitat (e.g., oceanographic features like fronts, eddies, and current patterns) is even more rudimentary (Grimes and Kingsford 1996; Grimes 2001; De Robertis et al. 2005). Similarly, habitat is an important consideration for protected species and for nonmanaged species, but habitat needs are understood for only a small fraction of these species. There
also is a need to focus more attention on understanding cumulative effects from both fishing and nonfishing (e.g., point and nonpoint pollution, industrial development, and habitat alteration) activities on habitat and how productivity of both the target and nontarget species is affected.

Expanded scope of monitoring and research

Monitoring and research for EBFM will be qualitatively new, in that it will involve new and different subject matter, but it will not replace the need for continuing current monitoring activities such as fishery-independent surveys to monitor target species. EBFM monitoring and research will be more focused on achieving a quantitative understanding of biological interactions. At an immediate and practical level, EBFM will require monitoring of total fishery removals for both target and nontarget species. There will also be a need to understand the cumulative effects of anthropogenic impacts on productivity, including those from nonfishing activities. In addition, monitoring is essential to determine the magnitude and timing of ocean climate changes and to understand how changes affect various target and nontarget species. The evaluation and improvement of marine ecosystem models should receive high priority, although the initial focus of this work should be on quantifying uncertainty and identifying critical data needs. Ecosystem modeling also needs to be more focused on quantifying trade-offs among diverse goals.

Acknowledgment and respond to high levels of uncertainty

High levels of uncertainty are a prominent feature of the present scientific understanding of ecosystem functioning, interactions among ecosystem components, and feedback loops within the ecosystem. Furthermore, the present generation of marine ecosystem models is rudimentary. Therefore, the harvest decision rules used by the FMCs to determine catch limits need to evolve in the direction of incorporating explicit probabilities (e.g., as is already the case for the decision rule used by the International Whaling Commission (1999) for the management of commercial whaling) to cope systematically with the high level of uncertainty. This will also require an evolution of policy guidelines to include a quantitative standard for what is adequately precautionary.

Implementation of EBFM

EBFM is neither inconsistent with nor a replacement for current fisheries management. This means that EBFM should be adopted as an incremental extension of current fisheries management approaches. The challenge is to find ways to move forward given the potential costs imposed by the probable decreased harvests and the high degree of uncertainty likely to be associated with EBFM and not allowing the costs and uncertainty to be a license to maintain the status quo. Rather, the uncertainty should be taken as a mandate to improve current understanding.

The single-species assessment and management approach has a long empirical record, with well-defined models (Quinn and Deriso 1999), and research is being conducted to fill data gaps to further improve these models (Quinn 2003; Quinn and Collie 2005). Properly used, the single-species approach has been effective. Overt failures have not, for the most part, been due to the science and management approach, but rather have been due to data limitations and the lack of political will (Fogarty and Murawski 1998; Sissenwine and Mace 2001).

The single-species approach does incorporate some ecosystem considerations at least implicitly or indirectly. For example, some of the emergent properties of ecosystems can be captured, at least retrospectively, in assessment models by allowing weight-at-age to change over time and by estimating annual recruitments. However, the ecosystem is generally treated as a single, collapsed background factor in these models. Other examples where ecosystem features have been included in single-species stock assessments and management decisions are (i) a stock recruitment curve with density dependence for the target species that arises from predation by another species (Quinn and Deriso 1999); (ii) modeled, time-varying, natural mortality that may be due to predation or disease effects (Fu and Quinn 2000; Marty et al. 2003); (iii) a set of years used to define biological reference points that takes into account perceived regime shifts (Quinn and Collie 2005); and (iv) management that accounts for stocks with low productivity by restricting harvest on all species to avoid bycatch of overfished or protected species (PFMC 2004; Brenn et al. 2003). Such "weak stock" management recently restricted commercial Chinook salmon (Oncorhynchus tsawytscha) fishing along most of the US west coast to protect the endangered Klamath River fall Chinook salmon (PFMC 2006c).

Perhaps the most important change required for EBFM is the change to a set of goals beyond those associated with harvest of targeted fish species. Additional scientific inputs will be needed to construct models that accommodate broader goals and alternative management strategies. As noted by Goodman et al. (2002), "... Moving from the conventional assessment view towards an ecosystem view involves a shift in the components of fundamental underlying ecological science that is relied upon. In essence, for current fishery management, population ecology is the fundamental ecological science, but for an approach that takes ecological and ecosystem considerations into account, community ecology is the fundamental ecological science. For example, when one thinks about single species, there can be "excess production" from a stock, but when one thinks about the "needs" of all the other species in an ecosystem, the notion of excess production from a single member of the community becomes far more complicated."

To be practical, the move to EBFM must be evolutionary rather than revolutionary. According to Goodman et al. (2002), the evolution involves three stages. In the first stage, assessments focus on the status of the target species and its predators and prey. Assessments are broadened in the second stage to (i) take into account environmental effects in a more direct fashion when determining the status of the target species and (ii) incorporate measures for the direct effects of fishing activities other than those on the target species (e.g., bycatch, incidental mortality, and effects on habitat). In stage three, the environment, target stock, and its predators and prey are integrated explicitly into an assessment before catch limits and other management measures are selected.
Table 3. Actions to promote ecosystem-based fisheries management (NMFS 1999).

1. Delineate the geographic extent of the ecosystem(s) that occur(s) within FMC (Fishery Management Council) authority, including characterization of the biological, chemical, and physical dynamics of those ecosystems, and "zone" the area for alternative uses.
2. Develop a conceptual model of the food web.
3. Describe the habitat needs of different life-history stages for all plants and animals that represent the significant food web and how they are considered in conservation and management measures.
4. Calculate total removals — including incidental mortality — and show how they relate to standing biomass, production, optimum yields, natural mortality, and trophic structure.
5. Assess how uncertainty is characterized and what kinds of buffers against uncertainty are included in conservation and management actions.
6. Develop indices of ecosystem health as targets for management.
7. Describe available long-term monitoring data and how they will be used.
8. Assess the ecological, human, and institutional elements of the ecosystem that most substantially affect fisheries and are outside FMC – Department of Commerce authority. Included should be a strategy to address those influences to achieve both Fishery Management Plan and Fishery Ecosystem Plan objectives.

The second and third stages both recognize the existence of ecosystem interactions. The second stage differs from the third in that it does not attempt to quantify the surplus production that must be reserved to satisfy ecosystem needs, nor does it attempt to modify fishing behavior to specifically mitigate adverse impacts other than those on the target species. The focus of the second stage is on the determination of the status of target and nontarget species and the evaluation of measures for the more tractable problems, such as EFH and bycatch.

In moving to EBFM, the challenge will be to diagnose the respective influences of individual environmental and ecological factors (e.g., climate and oceanographic conditions) and to develop an understanding of important processes and interactions. High levels of uncertainty will be associated with the representation of these relationships. The uncertainty results from the limitations of currently available data for estimating parameters for ecosystem models, for validating these models, and for understanding critical processes and the inherent limits of predictability of some of the underlying biological and oceanographic processes.

A critical danger is that without any track record for such models, the assumptions could be completely wrong. For this reason, changes to management strategies should also be evolutionary. During the transition to EBFM, management strategies should be similar to those used at present, (e.g., based primarily on conservative single-species management). However, selection of new management strategies that are more robust to uncertainty is possible when the results of several different ecosystem models are consistent and a management strategy evaluation shows good performance across the spectrum of possibilities. In other words, there are technical means for filtering out the most risky aspects of new, unproven models, while still being innovative.

The management system may look similar to that used at present during the transition to EBFM. However, the increased importance and use of ecosystem models will assist in the identification of approaches to consider when selecting the technical basis for providing assessments, selecting the decision rules that use the results from the assessments to define management measures, and planning investments in research and monitoring. The design and use of new models also should assure that there is at least qualitative consideration of interactions before management decisions are made.

NMFS (1999) provided a list of actions that could be taken to promote EBFM (Table 3). While the information associated with the eight items in Table 3 is relevant, it is not clear how practical they are. The concepts contained in Table 3 can be modified and extended to provide more implementation-related detail. The authors’ proposed modifications are organized around application of the management strategy evaluation (MSE) approach (Goodman et al. 2002). MSE assesses the performance of a range of management strategies against a set of management goals and allows comparisons of performance among the different strategies. MSE evaluates how sensitive management strategies are to uncertainty (e.g., climate, spatial distribution, and sampling effectiveness) and may be used to evaluate a decision process that has already been adopted. Management strategies, as evaluated using the MSE approach, need to be fully specified, including, for example, specification of the data that are to be collected to support decision-making, how those data are to be analyzed to provide the input to any decision rules, and the decision rules themselves. The outcomes of an MSE are predictions of the expected performance, the trade-offs among the various (usually conflicting) management goals, and the sensitivity of the outcomes of the management strategies to various sources of uncertainty. The process of conducting an MSE to achieve EBFM involves several steps. Though the level of information and data available will change over time, the considerations identified will apply in both the short and long term.

The authors’ modified list of actions is as follows: (1) Delineate and characterize the ecosystem including the ecological, human, and institutional elements of the ecosystem that most substantially affect fisheries. (2) Determine and quantify management objectives that reflect societal goals (e.g., in a single-species context, one of goals of the PFMC for groundfish is to minimize the probability that any stock is depleted to below the overfished level of 25% of the unfished biomass; however, ecosystem goals related, for example, to quantitative representations of the metrics identified by Murawski (2000) also need to be defined). (3) Develop conceptual models of (a) the food web and (b) the influence

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of oceanographic and climatic factors. (4) Describe the habitat needs of different life-history stages of plants and animals that represent the “significant food web” and how they are considered in conservation and management measures. (5) Expand and modify the conceptual model of the ecosystem to include life-history characteristics and spatial variation. (6) Calculate total removals, including incidental mortality, and show how they relate to standing biomass, production, optimum yields, natural mortality, and trophic structure. (7) Construct a range of alternative system models (often referred to as operating models) based on the conceptual models. Ideally, the range of system models (and the values for their parameters) should be sufficiently broad so that all plausible hypotheses regarding ecosystem processes are represented. Existing data will be used to estimate some of the parameters of these models, while for parameters that are poorly determined by existing data sensitivity will need to be explored until additional data are collected. (8) Identify a set of candidate management strategies. This will involve (a) assessing how uncertainty is characterized by the management agency and what kinds of buffers against uncertainty are included in conservation and management actions; (b) developing indices or indicators of ecosystem health as targets for management, including those based on models and how these indices can be used as the basis for decision-making. “Traffic light” approaches may be useful (Caddy 2002). Traffic light approaches assemble suites of environmental, biological, and socio-economic data into matrices of colored indicators across time. Examples for the Bering Sea and Gulf of Alaska ecosystems are given in Boldt (2006). Some have proposed using these indicators as “stop” or “go” recommendations for management. For example, if forage fish density falls below a set level, then fishing mortality would be reduced. (c) Describing long-term monitoring that is expected to continue and define how these data will be used for updating the parameter estimates used in the decision rules. (9) Use the management strategies to manage the simulated ecosystems represented by the system models and keep score of the achieved performance as defined by the management objectives. (10) Use the results of the simulations to (a) identify robust management strategies, critical data gaps, and ecological processes and (b) drop plans in place to address the critical data gaps. (11) Select from among management strategies in light of their calculated performance and implement the selected management strategy. (12) Monitor to verify success of the management strategy and the validity of the system model on which its selection was based. (13) Revise the set of system models (hopefully the monitoring will have shown that some of the original system models were more plausible than others) and the management strategy (based on discrepancies between actual and target harvest outcomes based on the monitoring data).

Clearly the current portfolio of implemented ecosystem models does not yet span the full range of plausible system models. However, substantial progress towards implementing EBFM can take place if attempts are made to follow each of the above steps. Specifically, several ecosystem models have been developed for the US west coast, the Gulf of Alaska, and the Bering Sea – Aleutian Islands regions (Livingston and Methot 1998; Jurando-Molina et al. 2005; Guénette et al. 2006). These ecosystem models could form the basis for initial work to determine how robust current single-species management strategies are to trophic interactions and whether management strategies that include some ecosystem features are likely to outperform current approaches. Moreover, this exercise will provide an initial way to identify key sources of uncertainty and hence focus data collection strategies. In particular, if the performance of the management strategies differs markedly depending on which of several processes are actually present, experiments could be designed to attempt to distinguish among the alternative hypotheses. This approach has been used to identify causes for the marked (and undesirable) changes in the composition of the fish community on Australia’s Northwest shelf and which strategy is best suited to reverse this (Sainsbury 1991; Sainsbury et al. 1997). Similarly, simulations were used to develop the current decision rule for Pacific sardine (Sardinops sagax caerulea) (Anonymous 1998b). This decision rule sets the target fishing mortality as a function of temperature because productivity of sardine has been shown to depend on temperature.

Evaluating current management strategies using existing ecosystem models as operating models may provide results of immediate use for EBFM. For example, Schweder et al. (1998) used a simple ecosystem model to assess the implications of achieving the management goals for baleen whales on likely sustainable yields for commercially important fish species. Also, Punt and Butterworth (1995) evaluated the impact of seal culls off South Africa on fish yields when the total allowable catches (TACs) for the fish species were based on the actual management strategies for these species. Similar analyses have yet to be conducted for the areas managed by the PFMC and NPFMC even though ecosystem models are available for these regions. Although the implications of simple management strategies (e.g., constant effort) have been examined using existing ecosystem models (Kitchell et al. 2002), such strategies do not adequately mimic how (single-species) management operates in reality. Only by evaluating the strategies as they are actually implemented by the FMCs will the necessary insights be achieved.

A necessary research activity to evaluate management strategies based on current ecosystem models is to expand these models so that they represent species at the same resolution as stock-assessment models (i.e., usually by age and sex). Age structure has already been added to some ecosystem models (Aydin 2004), but this is not the norm. Expanding beyond examining the implications of trophodynamics requires the construction of system models that are spatially explicit. Spatial models already exist that include trophodynamics and that could form the basis for MSE evaluations (Fulton et al. 2005). While these models are unlikely to be sufficient to evaluate all likely management strategies, the insights gained using such models at this early stage will provide decision makers with ideas regarding the way in which management strategies will have to be modified to better achieve management goals that include ecosystem considerations.

Goodman et al. (2002) suggested the need for metrics of ecosystem status in evaluating the success of EBFM. These metrics could be used as the basis for status thresholds to assess whether ecosystems are becoming unhealthy. An example of a set of ecosystem-based metrics from Murawski
(2000) is as follows: (1) The biomass of one or more important species assemblages or components falls below minimum biologically acceptable limits, such that (a) recruitment prospects are substantially impaired, (b) rebuilding times to levels allowing catches near maximum sustainable yield are extended, (c) prospects for recovery are jeopardized because of species interactions, and (or) (d) any species is threatened with local or biological extinction. (2) Diversity of communities or populations declines substantially as a result of sequential “fishing-down” of stocks, selective harvesting of ecosystem components, or other factors associated with harvest rates or species selection. (3) The pattern of species selection and harvest rates leads to greater year-to-year variation in populations or catches than would result from lower cumulative harvest rates. (4) Changes in species composition or population demographics as a result of fishing greatly decrease the resilience or resistance of the ecosystem to perturbations arising from nonbiological factors. (5) The pattern of harvest rates among interacting species results in lower cumulative net economic or social benefits than would result from a less intense overall fishing pattern. (6) Harvests of prey species or direct mortalities resulting from fishing operations impair the long-term viability of ecologically important, nonresource species (e.g., marine mammals, turtles, and seabirds).

Adopting such metrics for ecosystem status would help management bodies manage fisheries sustainably and provide thresholds for measuring their success.

Discussion — the next steps

Many years will be required for implementation, testing, and adaptation of EBFM. However, there are ways of moving forward with most of the elements above. As a start, management bodies need to create and implement processes and institutional structures that will facilitate the identification of the full range of goals, especially those related to concerns beyond targeted species, and to make these operational.

There are also activities, such as using models to identify critical data gaps, and ecological processes that could be implemented immediately. Furthermore, ecosystem models should be developed to identify areas of high uncertainty and hence guide research and data collection. It is also important to encourage a modeling culture that rigorously quantifies the predictive power of all the models that are utilized, so that managers can make informed decisions when they consider using these models to guide actual management. It should be expected that the models on which scientific management advice is based would evolve over time from population models (single-species) to community models (taking into account food web considerations) and then to ecosystem models (taking into account environmental considerations such as habitat and climate).

Additionally, as research progresses, the fishery management approach will evolve from implicit and nonquantitative consideration of the ecosystem to a more specific and explicit quantification. It will also progress from treating ecosystem considerations outside fishery assessment and management to where these considerations are fully integrated into the process (Goodman et al. 2002).

Until the necessary research is done, it is not possible to know what the optimal management tools and their data requirements will be for EBFM. It could be that a set of single-species models combined with a collection of ecosystem indicators and prudent management strategies could suffice for many systems. For other systems, it may be necessary to develop complex ecosystem models with links among fish species, oceanography, climate, habitat, and human elements. It is also possible that the lofty goals of understanding the ecosystem and managing human uses sustainably are not fully achievable with finite resources and modeling capabilities. In that case, the goal may have to be limited to an achievable one, in which the risks of ecosystem harm are minimized through robust management strategies that set margins of safety for errors due to incomplete understanding.

Clearly the task of progressing towards EBFM will be difficult and will require substantial new investments. Management that takes ecological and ecosystem effects into account will require greatly expanded monitoring; improvement in the understanding of behavioral relationships among fishermen, the fish they catch, and the predators and prey of the harvested species; and social and economic relationships among various resource users. Additional funding and resources will be needed to get this work done. The benefits will be the explicit incorporation of societal goals in fishery management, more stable and predictable long-term yields, and the maintenance of ecosystem goods and services into the future.

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