Discussion Paper

Ecosystem-based Fishery Management: A Review of Concepts and Ecological Economic Models

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Abstract

People have tried to understand ecosystems using many different models. As a result, the concept of ecosystem-based fishery management (EBFM) is evolving. The objective of this article is to review the concepts and ecological economic models related to this management systems. I start by reviewing basic concepts related to marine ecosystems and EBFM, and then outline the related economic models, address their implementation with some examples from British Columbia, and draw some conclusions. Although there is widespread agreement about the need to implement EBFM, this concept has no universal definition or consistent application. Nutrient flow also plays a crucial role in marine ecosystems and nutrients are revealed as the currency in ecological economic models for EBFM.

KEYWORDS: ecological economic models; ecosystem approach; fishery management

Introduction

Ecosystems play an important role in human societies by providing services that directly or indirectly benefit humans (Daily 1997; Fisher et al. 2008, 2009). However, there is growing evidence that ecosystems are being negatively affected by human pressures such as overfishing, eutrophication, toxic pollution, and habitat degradation (e.g., Daily 1997; Sherman & Duda 1999). In 2005, the Millennium Ecosystem Assessment revealed that about two-thirds of global ecosystem services were in a state of decline and the harmful consequences of this decline could grow significantly worse in the coming decades (Millennium Ecosystem Assessment 2005; Fisher et al. 2009). Overfishing is a typical example of humanity's impacts on marine ecosystems. Many marine fisheries are suffering from a combination of recruitment overfishing and growth overfishing of fish stocks[1] and the overcapacity of fishing fleets (Clark 2006). In 2010, the Food and Agriculture Organization estimated that 85% of the world's marine fish stocks were either fully exploited, overfished, or had collapsed (Food and Agriculture Organization 2010).[2] The global marine fishing fleet was estimated to be more than two and a half times the size that the oceans can sustainably support (Porter 1998). The rent loss due to overfishing was globally estimated to be about $50 billion annually (World Bank 2009). In addition, the ocean's productivity has also been declining because of marine environment degradation and interference with ecosystems through pollution (Crean & Symes 1996).

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The collapse of many marine fisheries is widely believed to be the result of mismanagement (Costello et al. 2008). The mismanagement of marine fisheries is not only due to poor enforcement but also because marine fishery management traditionally focusses on managing a single target species and often ignores habitat, predators, the prey of the target species, and the physical components of marine ecosystems (Pikitch et al. 2004). The conventional single-species marine fishery management approach has failed and new approaches are needed (Beverton 1995; Hilborn 2004; Beddington et al. 2007; Cardinale & Svedang 2008). A major element of the proposed new approach is a move from the conventional single-species marine fishery management to ecosystem-based marine fishery management (EBFM), which seeks to include in the management plan not only all affected species but also abiotic factors such as water pollution, the effects of weather and climate on the ecosystem, and the effects of fishing activity on the habitat itself (National Marine Fisheries Service 1998; Hilborn 2004).

An ecosystem approach has been viewed in many ways (O'neill et al. 1986; Larkin 1996). In addition, management, regardless of the context is driven by human values and what people care about. Thus, the values by which an ecosystem is managed will vary widely, depending on where a person is in the world—the environmental setting of the ecosystem, political context of the relevant agencies, and economic prosperity of the local communities. It is hard to find a standardized approach that fits all possible situations. As a result, the concept of EBFM is still evolving and has no universal definition or consistent application (Brodziak & Link 2002; Ward et al. 2002; Babcock & Pikitch 2004). Ecosystem-based marine fishery management has also been criticized as being nonspecific, immature, invalid as a basis for decision making, and not fully supported by science (Murawski 2007).

In this article, I seek to address two main questions. First, what is ecosystem-based marine fishery management and how has it been applied? Second, how have ecological economic models for EBFM evolved over time? My main focus is to summarize the current state of knowledge and succinctly review recent progress in EBFM, thus providing an understanding of EBFM for managers and helping to improve the practice of EBFM. Although this discussion is framed in a general sense, it is specifically relevant to marine fishery management in British Colombia. The next three sections address the basic concepts related to marine ecosystems, EBFM, and ecological economic models for fishery management. I then address the implementation of EBFM with some examples from British Columbia.

There is growing evidence that coastal ecosystems are being negatively affected by external factors, such as climate variations and human pressures.

Marine ecosystems

There is growing evidence that coastal ecosystems are being negatively affected by external factors (Sherman & Duda 1999; Stenseth et al. 2004), such as climate variations and human pressures. Climate variations include fluctuations of temperature, wind, and currents and their interactions (Stenseth et al. 2004). Coral reef bleaching is a typical example of the impact of climate variation (e.g., temperature change) on coral reef ecosystems. Human pressures may consist of overfishing, eutrophication, toxic pollution, and habitat degradation (Sherman & Duda 1999). To understand how the external factors affect marine ecosystems, the ecosystem approach needs to be clarified. In ecology, there are at least two ways to understand ecosystems: 1) the population-community approach and 2) the process-function approach (O'neill et al. 1986; Bocking 1994). Population-community ecologists tend to view ecosystems as networks of interacting populations. Biota ecosystems and abiotic components, such as habitats or sediments, are external influences. The biota may interact with the abiotic environment, but the environment is mainly viewed as the backdrop or frame within which biotic interactions occur. The population-community approach is partly a result of the historical development of ecology and it is an appropriate conceptualization for some observation sets, rather than the best or most fundamental way to view ecosystems (O'neill et al. 1986). Ecosystem ecologists tend to view ecosystems using the process-functional approach (O'neill et al. 1986; Bocking 1994). The ecosystem concept, in this approach, was originally defined by Tansley as "the whole system (in the sense of physics), including not only the organism-complex, but also the whole complex of physical factors forming what we call the environment of biome—the habitat factors in the widest sense" (Tansley 1935). This ecosystem concept was further developed and clarified by Lindeman (1942), Hutchinson (1948), H.T. Odum (1951), and E.P. Odum (1969). In discussing energy and material flows, E.P. Odum (1969) had this to say:

> the ecosystem, or ecological system, is considered to be a unit of biological organization made up of all of the organisms in a given area (that is, community) interacting with the physical environment so that a flow of energy leads to characteristic trophic structure and material cycle within the system.

The Millennium Ecosystem Assessment defined an ecosystem as, "a dynamic complex of plant, animal, and microorganism communities and the non-living environment interacting as a functional unit" (Millennium Ecosystem Assessment 2005).

At one extreme, a marine ecosystem may be defined as a small estuary. At the other extreme, a marine ecosystem may occupy a coastal area of around 200 000 km^2 or larger, such as "large marine ecosystems" (Sherman et al. 1993). Within the ecosystem, energy and nutrients are exchanged, consumed, and transformed, and feedback loops ensure that, within limits, the system will remain at equilibrium (Bocking 1994). Difficulties often arise in attempting to measure transfers of materials, energy, and organisms into and out of marine ecosystems (across boundaries). Therefore, scientists often choose marine ecosystems with well-defined physical boundaries, such as an estuary, a lagoon, or a mangrove forest (Franklin 1997; Jørgensen 2009). Although all ecosystems have essential similarities, some special properties will depend on location. For land-based ecosystems, these properties are defined by major vegetation characteristics but marine ecosystems tend to be described by other means (Larkin 1996). For example, large marine ecosystems are regions of ocean space surrounding coastal areas from river basins and estuaries out to the seaward boundary of continental shelves and the outer margins of coastal current systems. As such, these ecosystems are defined by the distinct characteristics of depth, oceanography, and productivity (Sherman et al. 1993; Sherman & Duda 1999).

Ecosystem-based marine fishery management

Managers are now considering ecosystem-based management approaches because of the increasing pressures that coastal and marine ecosystems face.[3] Ecosystem management is a framework that has been officially implemented in the United States since the early 1990s (Grumbine 1997). Fundamentally, ecosystem management consists of managing ecosystems to assure their sustainability (Franklin 1997). Ecosystem management is a response to deepening loss of important ecosystem qualities, such as biodiversity and fish yields, and is still a evolving concept (Grumbine 1994; Arkema et al. 2006). Grumbine (1994) summarized 10 dominant themes of ecosystem management:

1. hierarchy
2. ecological boundaries

3. ecological integrity
4. data collection
5. monitoring
6. adaptive management
7. interagency co-operation
8. organizational change
9. humans embedded in nature
10. values

These 10 themes form the basis of a working definition:

> Ecosystem management integrates scientific knowledge of ecological relationships within a complex sociopolitical and values framework toward the general goal of protecting native ecosystem integrity over the long term. (Grumbine 1994:31)

Although we know that an ecosystem perspective is desirable, it is complex and unpredictable because it is impossible to measure and control the dynamics of every species and ecosystem process (National Marine Fisheries Service 1998). Therefore, it is scientifically more accurate to speak of "ecosystem-based management" or an "ecosystem approach to management" (Christensen et al. 1996; Link 2002; McLeod et al. 2005). Ecosystem-based management does not require that we understand all things about ecosystems. Instead, it focuses on managing human activities rather than managing whole ecosystems (National Marine Fisheries Service 1998; McLeod et al. 2005). From an economic point of view, the goal of ecosystem-based management would be to optimize net benefits over a suite of ecosystem services subject to understanding detailed ecological trade-offs across species (Finnoff et al. 2012). Ecosystem services may include the following services (Millennium Ecosystem Assessment 2005):

- Provisioning services are products that people take from the ecosystems, such as fish and fuel.
- Regulating services are benefits that people gain from the regulation of ecosystem processes, such as air quality maintenance and climate regulation.
- Cultural services are nonmaterial benefits people obtain from ecosystems, such as recreational, spiritual, and religious benefits.
- Supporting services are those that are necessary for the production of all other services, such as primary production and nutrient cycling.

The ecosystem-based approach has more recently been applied in marine fisheries management, compared to other sectors such as land or forestry management (Grumbine 1994; Garcia et al. 2003; Arkema et al. 2006). Ecosystem-based fishery management has been defined as "a holistic approach to maintaining ecosystem quality and sustaining associated benefits" (National Marine Fisheries Service 1998; Brodziak & Link 2002). The term ecosystem-based management is clearly relevant to fishery systems because fish products are important provisioning ecosystem services. Therefore, the concept of EBFM is also developing and has no universal definition or consistent application (Brodziak & Link 2002). Arkema et al. (2006) reviewed the definitions of marine ecosystem-based management (including EBFM) and found that scientists used 17 criteria to describe an ecosystem-based approach. These criteria were divided into three categories: 1) ecological factors, 2) the human dimension, and 3) management. Ecological criteria focus on one or more aspects of ecosystem complexity, such as the composition, structure, and function of ecosystems. Ecological criteria also recognize that ecological processes occur on multiple temporal and spatial scales. The human dimension integrates economic factors and stakeholders into the ecosystem planning processes. Management criteria include co-management and the precautionary approach, as well as the use of science and technology (Arkema et al. 2006). Thus, ecosystem-based management and EBFM are different, but complementary. Ecosystem-based management is viewed in a broader context and applied in managing across sectors, whereas EBFM is applied in managing only the fishing sector (McLeod et al. 2005). McLeod et al. argued that:

> managing individual sectors, such as fishing, in an ecosystem context is necessary but not sufficient to ensure the continued productivity and resilience of an ecosystem. Individual human activities should be managed in a fashion that considers the impacts of the sector on the entire ecosystem as well as on other sectors. (McLeod et al:2005:6)

The single-sector approach may result in conflicts among user groups . For example, fertilizers used in the agricultural sector have caused eutrophication that has affected fisheries in the Baltic Sea (Caddy 1993; Helsinki Commission 2009). Conflicts between farmers and fishers in this situation are not adequately solved by the fishing sector itself—to solve the problem, a cross-sector approach may be needed, which is consistent with ecosystem-based management.

By introducing the concept of an "ecosystem approach to fisheries," the United Nations Food and Agriculture Organization (FAO) defined humans as members of species in an ecosystem that have interactions with each other and their environment (Garcia et al. 2003). If humans are just one of the species in an ecosystem, it is hard to find a model for EBFM because its objective is the management of human activities, which are now viewed as behaviour of the individual species in the model. In fact, the FAO ecosystem-based approach to fisheries aims to implement sustainability in fisheries (Food and Agriculture Organization 2005).

Ecological economic models for fishery management

An ecological economic model is traditionally based both on an ecological model and an economic model of the fishery. The social objective is to maximize the present value of the profit of the involved fishers over a certain time horizon subject to the ecological model. Ecological economic models have evolved largely on the ecological part. Ecological models began early in the 20th century in the form of population models and were expanded mid-century by the addition of systems analysis and ecosystem modelling (Lauenroth et al. 2003). In particular, population modelling was originally introduced by Verhulst (1838), and system analysis was introduced by Lotka (1925) and Volterra (1926) in the form of a natural predator–prey model (Billard 1977; Beryman 1992; Renshaw 1993; Eichner & Pethig 2006). The Lotka-Volterra model has been modified and applied to fisheries by numerous authors such as May et al. (1979), Flaaten (1988, 1990, 1998), and Yodris (1994). The Lotka-Volterra model was also generalized to communities or food web models (Polovina 1984; Tu & Wilman 1992; Christensen et al. 2004; Pastor 2008).

At least two approaches have been used for population modelling in fisheries: macro and micro approaches (Pethig & Tschirhart 2002; Eichner & Pethig 2006). According to Pethig and Tschirhart , the macro approach (aggregate biomass models) uses populations as basic units of analysis. Species are presented as (differential) equations containing their own populations and the populations of other species as variables such as prey and predators (May et al. 1979; Flaaten 1988, 1990). With some exceptions (e.g., Leslie matrix models), macro population models often assume that the carrying capacity of the species forms the base of the food chain or food web (e.g., Schaefer 1954; Clark 1985, 1990). The carrying capacity is believed to change with the environment and the abundance of predators, parasites, and competitors (Hart & Reynolds 2002); however, the carrying capacity parameter is just a result of a particular assumption about density dependence and has nothing explicitly to do with the environment (Pastor 2008). The complicated models of species interaction and food webs simply pushed the environment problem that is constraining species interaction down to the lowest species in the food web or community (Pastor 2008). Macro population models also ignore variability between individuals in a population. In addition, these models ignore the transactions of individual organisms and do not answer the question of how the interaction of individual organisms translates into population changes (Eichner & Pethig 2006).

According to Pethig and Tschirhart (2002), the micro approach uses individual organisms as the basic units of analysis. The representative organisms are assumed to maximize their net energy, biomass, reproduction, and avoidance of predation as price takers subject to appropriate constraints (Tschirhart 2000; Pethig & Tschirhart 2002; Eichner & Pethig 2006; Ravn-Jonsen 2009). The organisms behave as consumers who face a budget constraint requiring that their expenditure on prey biomass not exceed their revenue from supplying their own biomass (Eichner & Pethig 2006). The micro approach solves some of the limitations of the macro approach, but it still ignores the interaction between physical and biological components of the ecosystem. In other words, population models do not take into account complete ecosystem structure (e.g., the biological and physical components) and function (e.g., ecological processes) and therefore often ignore indirect use values of fish in marine ecosystems. Some population models take environmental influences on biological components of ecosystems into account. The review papers by Knowler (2002) and Armstrong (2006) are good examples of such attempts. In general, population modelling tends to view abiotic (physical) components as external factors of ecosystems, which is consistent with the population-community approach in ecology.

All nutrients flow from the non-living to the living and back to the non-living components of the ecosystem in a circular path known as a biogeochemical cycle.

Ecosystem modelling expands population modelling by integrating the biological and physical components of the environment into a single interactive system (Smith & Smith 1998; Pastor 2008). This is consistent with the process-functional approach in ecology. The interaction of living (biological component) and non-living (physical) components occurs through nutrient flows. All nutrients flow from the non-living to the living and back to the non-living components of the ecosystem in a circular path known as a biogeochemical cycle. This process is called internal cycling and represents a recycling of nutrients within the ecosystem. It is an essential feature of all ecosystems (Smith & Smith 1998). Animals and other consumers gain their nutrients by eating producer organisms or each other. When an organism dies, its remains are broken down by decomposers. The components of their cells and tissues are utilized by decomposers and later returned to the environment and recycled (Karleskint 1998). All biological entities require nutrients (matter) for their construction and energy for their activities (Begon et al. 2006). Therefore, nutrient and energy flows play a vital role in marine ecosystems. Naturally, each unit of energy can be used only once, whereas chemical nutrients can be used again and repeatedly recycled as the building blocks of biomass (Begon et al. 2006). The inflows and outflows of nutrients also tend to be easier to define and measure than their energetic counterparts (Gurney & Nisbet 1998).

According to Gurney and Nisbet (1998), ecosystem models using energy as their currency might be unsuccessful because it is difficult to precisely define the energy outflows. Therefore, modern ecosystem models often adopt one or more essential elements, usually carbon, nitrogen, or phosphorus, as their currency (Gurney & Nisbet 1998). Numerous ecosystem models have been applied to fisheries (e.g., Polovina 1984; Christensen et al. 2004; Fulton et al. 2004). Detailed descriptions and comparisons of these models can be found in Plaganyi (2007), Fulton et al. (2004), and Fulton et al. (2003). From the economic point of view, managers need to balance the economic value of fish in the present and future with their ecological values. Therefore, ecological economic models for fisheries need to integrate economic and ecological influences in order to assist managers in determining appropriate levels of stocks and catches (Knowler 2002). The economic models for EBFM may need to solve the problem of maximizing the net present value of fish while constraining the interaction of physical and biological components of the ecosystem. This is one way to take ecosystem structure and function into account and therefore to include indirect use values of fish in the marine ecosystem. In the literature, only a few ecological economic models for fishery management consider the interaction between physical and biological components of the ecosystem through nutrient flow (Knowler et al. 2001; Smith & Crowder 2005). For instance, in the paper by Smith and Crowder (2005), the nutrient dynamic is modelled by changing the carrying capacity parameter in the traditional logistic equation. Knowler et al. (2001) modelled the impact of the nutrient enrichment process on the recruitment of fish stocks. Ecopath with Ecosim, a popular ecosystem model for fishery management, includes the nutrient dynamic and economic objectives such as maximizing fishery rent or social benefits.4 Some other ecosystem models use different economic tools (e.g., input-output models) (Jin et al. 2003; Sanchirico et al. 2008); however, these models ignore the interaction of physical and biological components of the ecosystem and therefore are not consistent with the functional ecosystem concept outlined above.

Implementing ecosystem-based fishery management

There is widespread agreement about the need to implement EBFM (Brodziak & Link 2002; Pikitch et al. 2004; Pitcher et al. 2008) because the historic focus on single species management has had the unintended consequence of declining populations of many other species. Several guidelines for implementing EBFM have been published, such as in the papers by the National Marine Fisheries Service (1998), Ward et al. (2002), and the FAO (2005). These guidelines supply detailed instructions for implementing the principles, goals, and policies of fishery management in an ecosystem context. Nevertheless, the effective application of these guidelines in practice is questionable. Pitcher et al. (2008) showed that of 33 countries representing 90% of the world's fish catch, no countries achieved good performance for EBFM implementation steps, while two-thirds (21 countries) were unlikely to carry out EBFM implementation steps (fail grades). Canada and the United States are the only two countries in this study with acceptable performance of EBFM implementation steps, while Russia and Thailand have the worst performance of EBFM implementation steps. One of the reasons for ineffective implementation is that it is easier to publish good intentions for EBFM principles than to actually achieve its goals and objectives in practice (Pitcher et al. 2008). Another reason is that EBFM implementation may require a lot of resources. Pitcher et al. (2008) showed that EBFM performance ratings correlate quite well with the United Nations Human Development Index. Implementation may also require co-operation among diverse groups, including scientists, resource users, and other significant stakeholders (Finnoff et al. 2012). In addition, EBFM can be an important complement to existing fishery management approaches, but it cannot be effective if the political will to stop fishing and to protect habitat is removed (National Marine Fisheries Service 1998). All conditions for effective implementation of EBFM may not be available for many fisheries. As a result, managers are just beginning to put some EBFM principles into practice, and this implementation needs to occur on a much greater scale (Garcia & Cochrane 2005; Arkema et al. 2006).

Goodman et al. (2002) believe the move from single-species fishery management to EBFM may involve three stages.[5] The first stage focuses on managing the target species and its predators and prey. The second stage takes into account more traceable environmental effects such as the direct effects of fishing activities other than those on the target species (e.g., by-catch, incidental mortality, and effects on habitat). In the third stage, the target stock and its predators and prey as well as more traceable and less traceable environment effects, such as climate change and the indirect effects of fishing (e.g., modifying ecosystem structure), are taken into account in fishery management plans.

Some fisheries have been managed to the second stage of the EBFM process, which takes into account the direct effects of fishing (e.g., by using turtle excluder devices and by-catch reduction devices such as shrimp trawls in the United States). In British Columbia, some fisheries have also reached the second stage of EBFM because traceable environmental effects are included in their management plans. For instance, commercial groundfish bottom trawling has high impacts on benthic habitats of Canada's Pacific marine waters (Ban et al. 2010). These impacts have been taken into account in the integrated fisheries management plan of in Pacific Region (Fisheries and Oceans Canada 2011a). Numerous studies have looked at the less traceable environment effects on fisheries, such as those by Pauly et al. (1998), Knowler et al. (2001), and Smith (2007). It is hard to find these effects taken into account in fishery management plans and British Columbia is no exception. Climate change is one of the key factors affecting fisheries in the province. The Strait of Georgia has warned almost 1°C over the past 40 years, which may result in declining production of Pacific salmon (Beamish & Riddell 2009); however, this impact has not been included in the integrated fisheries management plans of salmon fisheries in Pacific Region (Fisheries and Oceans Canada 2011b, 2011c).

Summary

From the previous discussion, we draw the following important conclusions about EBFM and its application.

- Ecosystem-based marine fishery management is a new direction for fishery management that prioritizes the management of the entire ecosystem rather than the target species individually.
- Most ecological economic models for EBFM follow the population approach, which ignores the interaction between the biological and physical components of marine ecosystems. It may be necessary to apply the process-functional approach for ecological economic models. Nutrients may be chosen as the currency for ecological economic models because nutrient flow connects biological and physical components of marine ecosystems.
- The move from single-species marine fishery management to EBFM may require several stages, and it is important to include the physical component of the ecosystem in fishery management plans in addition to the target stock and its predators

and prey. The less traceable environment effects on fisheries such as climate change should be also investigated and included in the management plans.

- Managers are just beginning to put some EBFM principles into practice because implementation may require a lot of resources, co-operation among diverse groups, and political will. Implementation of EBFM needs to occur on a much greater scale.

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Notes

1. Recruitment overfishing means that the adult population was fished so heavily that the number and size of the adult population (spawning biomass) was reduced to the point that it did not have the reproductive capacity to replenish itself. Growth overfishing occurs when animals are harvested at an average size that is smaller than the size that would produce the maximum yield per recruit.
2. If the biomass of a fish stock falls below the minimum stock size threshold, a threshold used by fishery managers to indicate 30–40% of spawning biomass, a stock is determined to be overfished or collapsed. A fish stock is considered fully exploited when the catch has reached the maximum sustainable yield.
3. I am very grateful for these comments from a reviewer.
4. See: http://www.ecopath.org/about
5. This is the general way to implement EBFM, although it is not necessarily applied for all cases.

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Test your Knowledge

How well can you recall the main messages in the preceding article? Test your knowledge by answering the following questions.

Ecosystem-based Fishery Management: A Review of Concepts and Ecological Economic Models

1. Which countries have the best performance in implementing EBFM?
   a) Canada and the United States
   b) Australia and New Zealand
   c) United States and Australia
   d) Canada and New Zealand

2. Why are managers just beginning to put some EBFM principles into practice?
   a) It is difficult to achieve EBFM's goals and objectives in practice
   b) Lack of resources and political will
   c) Lack of co-operation among significant stakeholders
   d) All of the above

3. How far has EBFM been implemented in British Colombia?
   a) Has not yet been implemented
   b) Has reached the first stage of implementation
   c) Has reached the second stage of implementation
   d) Has reached the third stage of implementation

ANSWERS: 1=a; 2=d; 3=c