

TOWARD AN INTEGRATED ECONOMIC-ECOLOGICAL ANALYSIS

Aquaculture and Capture Fisheries: A Conceptual Approach toward
an Integrated Economic-Ecological Analysis

Di Jin

Marine Policy Center

Woods Hole Oceanographic Institution

Woods Hole, MA 02543 USA

Phone: 508-289-2874

Fax: 508-457-2184

Email: djin@whoi.edu

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Abstract

This study presents a framework for analyzing the interactions between aquaculture and capture fisheries in the context of ecosystem-based management. We extend a model of the economic and ecological systems in coastal New England by incorporating an aquaculture sector in a computable general equilibrium (CGE) model and by examining the forage fish and aquaculture link in a marine food web. We show that aquaculture and commercial fisheries interact in a complex way throughout the economic and ecological systems.

Key words: Aquaculture, fisheries, ecosystem-based management, CGE model, food web model, forage fish

1. Introduction

The aquaculture industry has been growing rapidly to meet a rising demand for seafood in many parts of the world. The potential for the future expansion of aquaculture in a region is typically affected by several types of external factors, including nutrient pollution and interactions with capture fisheries. A wide range of potential interactions may arise between aquaculture and commercial fisheries. The type of interaction may depend upon the classes of species grown or caught and the technologies utilized for each activity. Interactions may involve a decrease in the physical space available for operating a fishery; possible increases in the costs of either wild harvest or aquaculture as more space is devoted to an alternative use; the culling of juvenile fish from a wild stock for growout in a culturing facility; and the risks of genetic mixing or displacement and the spread of disease (Hoagland et al., 2003). In addition, the farming of carnivorous species requires large inputs of forage fish for feed, potentially stressing ecosystems with which the forage fish are associated (Naylor et al., 2000). Finally, the products from aquaculture and capture fisheries compete in downstream markets, which may lead to other indirect effects throughout the economic system.

To develop effective management policies for sustainable aquaculture, these complex interactions are best examined in the framework of ecosystem-based management (EBM).

Ecosystem-based management is an integrated approach to management that considers the entire

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ecosystem, including humans. According to Pikitch et al. (2004), the objectives of ecosystem-based fishery management are: (1) to avoid degradation of ecosystems as measured by indicators of environmental quality and system status; and (2) to account for the requirements of other ecosystem components (e.g., nontarget species, protected species, habitat considerations, and various trophic interactions). The implementation of EBM requires the development of new analytical tools to integrate different environmental, ecological, and socio-economic data from various sources, to capture explicitly interactions among different components in the entire ecosystem, and to simulate and assess the effects of different management options.

The objective of this study is to present a framework for analyzing the interactions between aquaculture and capture fisheries in the context of ecosystem-based management. We will show that: (1) recent developments in model building and user friendly software have made linked economic-ecological analysis possible at multi-sector level; (2) the most efficient approach to develop multi-sector economic and ecological analyses is to utilize existing state-of-the-art food web models and economic models (e.g., computable general equilibrium (CGE) models); and (3) the economic and ecological interactions between aquaculture and fisheries can be effectively evaluated through comparative statics analyses.

To help assess the implementation of ecosystem-based fisheries management (EBFM) in New England, we have developed an integrated economic-ecological framework by linking a

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CGE model of a coastal economy to an end-to-end (E2E) model of a marine food web for Georges Bank (Collie et al., 2009). In the present study, we extend our basic model of the economic and ecological systems in coastal New England by incorporating an aquaculture sector in the CGE model and by examining the forage fish and aquaculture link in a marine food web. It should be emphasized that the conceptual framework described in this paper has not been fully implemented. Building multiple links between the economic and ecological models will be the focus of our future studies.

2. The Economic-Ecological Framework

The importance of integrated economic-ecological analysis has been stressed by many experts (Arrow et al., 1995). Most classical bioeconomic models involve the dynamic control of nonlinear biosystems (Clark, 1976). Because of complexity, these models include a small number of variables (e.g., biomass, and either fishery yield or fishing effort). The advantage of this approach is that it can be used to conduct both positive and normative analyses. In order to analyze systems with a large number of interacting elements, such as industries and consumers in an economy, or species in an ecosystem, economists and ecologists have explored the use of linear models (e.g., IMPLAN and ECOPATH). Economic input-output models have been developed for the Northeast coastal region (Hoagland et al., 2005 and 2010) and marine food

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web models have been developed for the Georges Bank ecosystem (Sissenwine et al., 1984; Link et al., 2008; Collie et al., 2009).¹ Following Isard et al. (1968), we have developed a procedure for merging a regional input-output model of a coastal economy with a linear model of a marine food web (Jin et al., 2003).

Although linear economic models (e.g., input-output models) can handle a large number of variables (industry sectors), they are limited to positive (descriptive) studies and unable to develop welfare estimates that are relevant for policy analysis. For normative analysis, we need to construct CGE models. A fundamental tradeoff exists between the number of variables and the nonlinear dynamics. As a consequence, we must carefully examine linkages between ecological and economic systems in order to identify the key economic sectors to be modeled explicitly for specific purposes.²

The economic-ecological framework that we developed is an extension of the traditional bioeconomic approach. Our approach is designed to be used to characterize the existing economic and ecological conditions and to demonstrate the potential wealth to society that may be derived from the consumption of marine resources, goods, and services associated with a well-managed marine ecosystem (cf. Edwards & Murawski, 1993). The framework can be used to assess the change in wealth associated with changes in the quality and quantity of natural and

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environmental resources in the ecosystem and the distribution of these changes across industries and consumers.

CGE models have been widely used for policy analysis in recent years (Shoven & Whalley, 1992). Traditional economic CGE models have been expanded to include environmental and resource sectors for environmental policy analysis (viz. Abler et al., 1999; Xie et al., 1996). A number of CGE models have been developed specifically for fishery studies (Chiang et al., 2004; Pan et al., 2007; Waters & Seung, 2010). Recent developments in linking dynamic economic and ecological general equilibrium models can be found in Finnoff and Tschirhart (2008).

2.1. Economic CGE model

The major features of an economic CGE model include the following: (1) prices are endogenous and are determined by the market; (2) supply and demand for goods and production factors are equated by adjusting prices based on Walrasian general-equilibrium theory; (3) supply and demand functions are derived from the behavior of profit-maximizing producers and utility-maximizing consumers; and (4) the model is multi-sectoral and nonlinear with resource constraints (Xie & Saltzman, 2000).

A basic CGE model for a study region has N industry sectors ($j = 1, 2, \dots, N$) that supply goods to two demand sectors: household and government. The household sector provides capital

(K) and labor (L) to the industry sectors. Suppose each industry sector j produces a specific commodity j , the supply and demand of commodity j is depicted in Figure 1.

Production is typically modeled through a nested structure. In the first nest, the producer chooses the levels of capital and labor inputs so that the level of composite factor input (i.e., value added) is optimized. Specifically, the producer maximizes the profit subject to production technology F_{Y_j} :

$$\max P_{Y_j} Y_j - P_L L_j - P_K K_j \quad \text{s.t.} \quad Y_j = F_{Y_j}(L_j, K_j) \quad (1)$$

where L_j , K_j and Y_j are the quantities of labor, capital, and composite factor respectively, used in producing commodity j . P_L , P_K and P_{Y_j} are the prices of L , K and Y_j respectively. The functional form of F_{Y_j} is typically either CES (constant elasticity of substitution) or Cobb-Douglas. The levels of factor inputs (L_j and K_j) are calculated using the first order conditions of problem (1).

In the second nest, the composite factor (Y_j) is combined with intermediate inputs (X_{ij}) to produce output (Z_j).

$$Z_j = F_{Z_j}(Y_j, X_{1j}, X_{2j}, \dots, X_{Nj}) \quad (2)$$

where X_{ij} ($i = 1, 2, \dots, N$) is commodity i used in the production of j . For example, if Z_j is the output from commercial fishing, X_{ij} represents food, fuel, or ice used in fishing. In the basic model, the functional form for F_{Z_j} is Leontief in which Y_j and X_{ij} are in fixed ratios. For a given level of composite factor input (Y_j), local output (Z_j) is determined.

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In the middle section of Figure 1, trade is added to the commodity's supply and demand.

The producer in the study region sells its output to both the local market and markets outside of the region. In addition to local production, commodity j is also imported from outside the region.

On the right side of Figure 1, the household sector maximizes its utility (U) of consumption (X_C) subject to income constraint:

$$\max U(X_{C1}, X_{C2}, \dots, X_{CN}) \quad s.t. \quad \sum_j P_{Qj} X_{Cj} = P_L L + P_K K \quad (3)$$

The functional form for U is typically Stone-Geary or Cobb-Douglas. The levels of consumption (X_{Cj}) are calculated using the first order conditions of problem (3).

2.2. Marine Food Web Model

There are two basic approaches to formulate a food web model for a specific ecosystem. Steele (2009) provides a review of these alternative approaches. Both formulations start from the following equation stating that the change in biomass at time t equals the sum of gains from all sources minus all losses:

$$\frac{dB_i}{dt} = e_i \left(\sum_j Q_{ij} + G_i \right) - \sum_k Q_{ki} - L_i \quad (4)$$

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where B_i is the biomass of trophic component i , Q_{ij} is the rate at which B_j is consumed by B_i , G_i is the gains from external sources; L_i is the losses from the system (e.g., fishing), and e_i is the transfer efficiency.

The two types of models differ in the way in which Q_{ij} is modeled. In a donor-controlled model, Q_{ij} is a function of production, P_i , in each of the i trophic components. In contrast, in a recipient-controlled model, Q_{ij} is a function of consumption, C_i , in each of the i trophic components. Note that P_i and C_i are both flows, while B_i is a stock.

At steady-state, the donor-controlled formulation of Equation (4) is

$$P_i = e_i \left(\sum_j a_{ij} \cdot P_j + G_i \right) - f_i \cdot P_i \quad (5)$$

where P_i is the production in trophic component i , a_{ij} is the fraction of P_j flows to P_i , and f_i is the fractional loss of P_i to the system. Fish harvesting is modeled in the last term in (5). In the above formulation, production at the lower trophic levels (P_j) determines the production at the upper trophic levels (P_i). Thus, a donor-controlled model is also called a “bottom-up” model. Bottom-up models typically have been designed to capture the effects of changes in primary production associated with environmental perturbations, such as those associated with climate change.

In a recipient-controlled (“top-down”) formulation, at steady state, Equation (4) becomes³

$$e_i \cdot C_i = \sum_k b_{ik} \cdot C_k - e_i G_i + L_i \quad (6)$$

where C_i is consumption by trophic component i , b_{ik} is the fraction of C_i that is consumed by species k . Note that consumption by k , C_k , is at the upper trophic level, and it is consumption at the upper trophic levels that influences consumption at lower trophic levels. In a top-down formulation, fish harvesting is modeled in the last term (L_i). Top-down models typically have been designed to assess the impacts of fish harvesting on other ecosystem components and processes.

2.3. *Links between Economic and Ecosystem Models*

As the commercial fishing industry harvests fish from the ecosystem, we can link a marine food web model with the economic CGE model using the classical harvest function often used in bioeconomic analysis:

$$Y = qEB \quad (7)$$

where Y is the quantity of fish harvested, q is a catchability coefficient, E is fishing effort [= $F(L, K)$], and B is the stock biomass modeled in the food web [see Equation (4)]. According to Equation (7), for a fixed catchability and a given level of fishing effort, harvest is proportional to stock biomass.

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We model the effect of changing stock size (B) by modifying the production function for the fishing sector in the CGE model:

$$Y_j = \alpha F_{y_j}(L_j, K_j) \quad \text{for } j = \text{fishing} \quad (8)$$

Alternative ecosystem states and associated stock levels B are incorporated into the shift parameter α . For example, under the baseline conditions 0, $\alpha = 1$. When x increases, $\alpha > 1$. This, in turn, leads to an adjustment in fishing effort, which is a function of capital and labor inputs in the CGE model. The economy-wide effects of stock variation are then estimated by the CGE model (Figure 2).

The feedback from the economic model to the food web model can be modeled using Equation (5). For a change in fish catch f_i , we can re-estimate the corresponding changes in the productions and consumptions in different trophic components throughout the food web.

Equation (5) can be rewritten in matrix notation as:

$$\mathbf{P} = (\mathbf{I} - \mathbf{IeA} + \mathbf{If})^{-1} \mathbf{IeG} \quad (9)$$

If there are n trophic components in the food web, then \mathbf{P} , \mathbf{e} , \mathbf{f} and \mathbf{G} are $n \times 1$ vectors, \mathbf{I} is a $n \times n$ identity matrix, and \mathbf{A} is a $n \times n$ matrix. Thus, the change in fish catch can be modeled as a change in the vector \mathbf{f} , and the production vector \mathbf{P} can be easily calculated.⁴

3. Economic Interactions between Commercial Fishing and Aquaculture

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To examine the economic interactions between commercial fishing and aquaculture, we adapt the regional CGE model by Stodick et al. (2004), which can take IMPLAN data as input data. IMPLAN is a modular input-output model that works down to the individual county level for any county in the United States. IMPLAN data are updated annually and contain national income and employment statistics for over 500 economic sectors, including commercial fishing and seafood processing. The IMPLAN sectors can be grouped into several aggregated sectors (Minnesota IMPLAN Group, 2000). We have built a CGE model of the New England coastal economy using county-level data from IMPLAN. The model includes six sectors: aquaculture, commercial fishing, seafood proceeding, agriculture, manufacturing, and all other sectors combined.

The baseline output, supply, and trade statistics calculated with the CGE model of the New England coastal economy are summarized in Table 1. The output from the fishing sector is \$870 million. The total fish commodity supplied to the New England regional market (Q) is \$653 million, which is equal to the local output (Z) of \$870 million plus imports (M) of \$42 million minus exports (E) of \$259 million to foreign countries (Table 1; see also Figure 1). The output from aquaculture is \$127 million, and the total supply is \$684 million. Most of the aquaculture supply to the New England market is imports from other regions of the United States (Table 2). The output from fish processing is \$1.12 billion, of which \$708 million is exported to

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markets outside New England; the remainder, when combined with imports, is supplied to local market (\$543 million).

We link the CGE model with the end-to-end (E2E) model of a marine food web for Georges Bank by Collie et al. (2009) to examine the economic effects of different ecosystem states.⁵ Specifically, Scenarios 0 and III described in Collie et al. (2009) are simulated to estimate changes in the economic system. Scenario 0 is the baseline and Scenario III represents an increase in the total biomass of commercial fish stocks.⁶ The shift parameter, α , in the fishing industry production function is 1.0944. See Jin et al. (2012) for details.

The simulation results are summarized in Tables 3 and 4. Looking at the commercial fishing sector in Table 3, we see that the increase in fish biomass leads to a 10.33% increase in commercial fishery output, a 6.35% increase in total seafood supply to the New England market, a 3.43% decrease in seafood imports, a 17.87% increase in seafood exports, and a 4.70% decline in the seafood price in local markets. Similar effects occur also in the fish processing sector, leading to increasing regional output, supply, and exports, and declines in imports and prices. In contrast, the effects of increasing fish biomass on aquaculture is somewhat different: a 1.25% decline in output, a 3.34% decline in exports, and a slight (0.21%) increase in the price of aquaculture products, which may be a result of market competition between aquaculture products and landings from capture fisheries.

The results suggest that an increase in fish biomass will lead to a welfare increase of \$131.02 million for the entire New England coastal economy. Due to differences in seafood consumption patterns, households in the middle and higher income categories tend to enjoy greater welfare increases than those in lower income categories (Table 4).

4. Ecological Interactions between Commercial Fishing and Aquaculture

An example of ecological interactions between commercial fishing and aquaculture involves the management of forage fish. Forage fish can be either harvested to produce feed for aquaculture or conserved as prey for upper trophic-level species with commercial values (Figure 3). Hannesson et al. (2009) have presented a framework to analyze the ecological and economic tradeoffs associated with alternative management options using the management of the Pacific sardine as a case study.

We apply Hannesson et al.'s method to marine ecosystems in New England using parameters from the EMAX model⁷ of Georges Bank developed by Link et al. (2008) to examine management options for small pelagic species (e.g., herrings). Let species j be the commercially harvested small pelagic species, and species i be a predator of species j . The relationship between the change in biomass of prey species j and that of a predator species i is:

$$\Delta B_i = \frac{a_i}{C_i/P_i} \Delta B_j \quad (10)$$

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where ΔB is the change in biomass, a_i is the share of ΔB_j eaten by species i , C is consumption, and P is production. The share a can be calculated as:

$$a_i = \frac{B_i (P_i / B_i) D_{ij} (C_i / P_i)}{m_j B_j} \quad (11)$$

where D_{ij} is the share of species j in predator i 's diet, and m_j is the predation mortality of species j .

Ecological parameters from Link et al. (2008) are shown in Table 5. The predators of small pelagic species include groundfish species, large pelagic species, marine mammals, and sea birds. The coefficient that converts prey biomass change to each predator biomass change s_i ($= a_i / (C_i / P_i)$) is listed in the last column. The predation mortality (m) and biomass (B) for small commercial pelagic species are 0.44 and 9.947 (g m^{-2}), respectively. Figure 4 depicts the percent changes in predator biomass associated with one unit (g m^{-2}), about 10% change in the prey biomass. The results suggest that a reduction in the stock of small commercial pelagic species will have the most significant impacts on groundfish species, highly migratory species, and sea birds.

As discussed above, the economic consequences of reductions in these predator species may be simulated using the CGE model. Similarly, the economic benefits associated with the increase in landings of small pelagic species for aquaculture feed can also be simulated.⁸ The

results of these policy simulations can be used to identify the optimal solution for managing forage fish species.

5. Summary

This study presents a framework for analyzing the interactions between aquaculture and capture fisheries in the context of ecosystem-based management. We extend our basic model of the economic and ecological systems in coastal New England (Jin et al., 2010) by incorporating an aquaculture sector in the CGE model and by examining the forage fish and aquaculture link in a marine food web. Specifically, the extended CGE model of the New England coastal economy includes six sectors: aquaculture, commercial fishing, seafood processing, agriculture, manufacturing, and all other sectors combined. The economic consequences of an increase in the commercial fish biomass are simulated. The results indicate that aquaculture and commercial fisheries may interact in complex ways throughout the economic system. For example, the two operations may compete in downstream markets.

We use ecological data from the EMAX model of Georges Bank (Link et al., 2008) and a method developed by Hannesson et al. (2009) to examine the effects on various food web components of different management options for forage fish (e.g., as prey for commercially harvested species or feed for aquaculture). We show that the culturing of one species could affect the status of a range of species or the characteristics of an entire ecosystem. The economic

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tradeoffs associated with alternative management policies could be simulated using a linked economic CGE and marine food web model framework, and the optimal social policy could be identified.

Typically, model development in marine ecology and economics are on separate tracks, and bioeconomic studies are usually based on simplified biological models or stock conditions. The main advantage of linking state-of-the-art models from both fields is to bridge the gap between the two fields so that the latest results from marine ecosystem research can be effectively incorporated into socioeconomic analyses. The integrated approach will be a useful tool for the implementation of ecosystem-based fishery management that focuses on the interactions among multiple ecosystem components and multiple economic sectors. Models in both fields are becoming increasingly complex, and these models are costly and time consuming to build. Thus, the most efficient approach is to utilize existing state-of-the-art models from both fields. Because of the tradeoff between the number of variables and nonlinear dynamics, the most practical approach is to run the two models separately and then exchange information between them in a comparative static analysis.

To develop an integrated model that is useful for analyzing policies related to aquaculture development and fisheries management, it is necessary to extend the CGE model by improving the resolution of fishing and aquaculture related sectors and to develop model specifications for

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the links between the ecosystem (e.g., forage fish biomass) and relevant aquaculture production.

These will be the focus of future studies.

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Table 1. New England coastal regional economy: baseline economic value (2006 \$ millions)

Sector/Commodity	Output	Total Supply*	Imports**	Exports**
Agriculture	2,428	7,107	5,305	626
Aquaculture	127	684	565	7
Fishing	870	653	42	259
Fish Processing	1,124	543	126	708
Manufacturing	194,703	247,123	90,029	37,608
Other	750,325	673,199	131,211	208,336

*Composite commodity supplied to New England market

**Including both domestic and foreign trade

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Table 2. Foreign and domestic imports and exports (2006 \$ millions)

Sector/Commodity	Foreign Imports	Domestic Imports	Foreign Exports	Domestic Exports
Agriculture	1,118	4,187	161	465
Aquaculture	99	466	7	0
Fishing	42	0	259	0
Fish Processing	28	98	66	643
Manufacturing	30,537	59,491	37,608	0
Other	341	130,870	15,532	192,804

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Table 3. Percent changes associated with ecosystem changes in the New England coastal regional economy (2006 \$ millions)

Sector/Commodity	Output	Supply	Imports	Exports	Price
Agriculture	0.00	0.02	0.03	-0.01	0.01
Aquaculture	-1.25	0.86	1.28	-3.34	0.21
Fishing	10.33	6.35	-3.43	17.87	-4.70
Fish Processing	9.96	2.27	-4.35	13.21	-3.28
Manufacturing	0.03	0.04	0.04	0.01	0.01
Other	0.04	0.04	0.05	0.03	0.01

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Table 4. Welfare changes (equivalent variations) associated with changes in fishery stock (2006 \$ millions)

Household income categories	Equivalent variations
< 10K	0.77
10-15K	1.78
15-25K	5.16
25-35K	7.02
35-50K	15.29
50-75K	29.48
75-100K	23.31
100-150K	26.10
150K+	22.10
Total	131.02

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Table 5. Ecosystem effects of a change in small commercial pelagic stock*

Compartment	<i>B</i>	<i>P/B</i>	<i>D</i>	<i>C/P</i>	<i>a</i>	<i>s</i>
Small pelagic-squid	0.962	0.95	1.4	2.89	0.0084	0.0029
Medium pelagic	0.1928	0.45	53.5	5.4	0.0568	0.0105
Demersals-benthivores	5.02	0.45	10.1	2.04	0.1054	0.0517
Demersals-omnivores	3.779	0.45	12	1.84	0.0850	0.0462
Demersals-piscivores	4.254	0.45	24.3	5.42	0.5710	0.1054
Sharks-pelagics	0.0244	0.1	21	5.55	0.0006	0.0001
Highly migratory species	0.0352	0.68	14.4	3.01	0.0023	0.0008
Baleen whales	0.4167	0.04	5.8	118.36	0.0259	0.0002
Odontocetes	0.122	0.04	35.2	360	0.1401	0.0004
Sea birds	0.0144	0.28	27.3	15.92	0.0040	0.0002

* Ecological parameters are from Link et al. (2008). Units for biomass (*B*) are in g m^{-2} ; and units for production (*P*) and consumption (*C*) are in $\text{g m}^{-2} \text{yr}^{-1}$.

Figure 1. Basic components of a CGE model

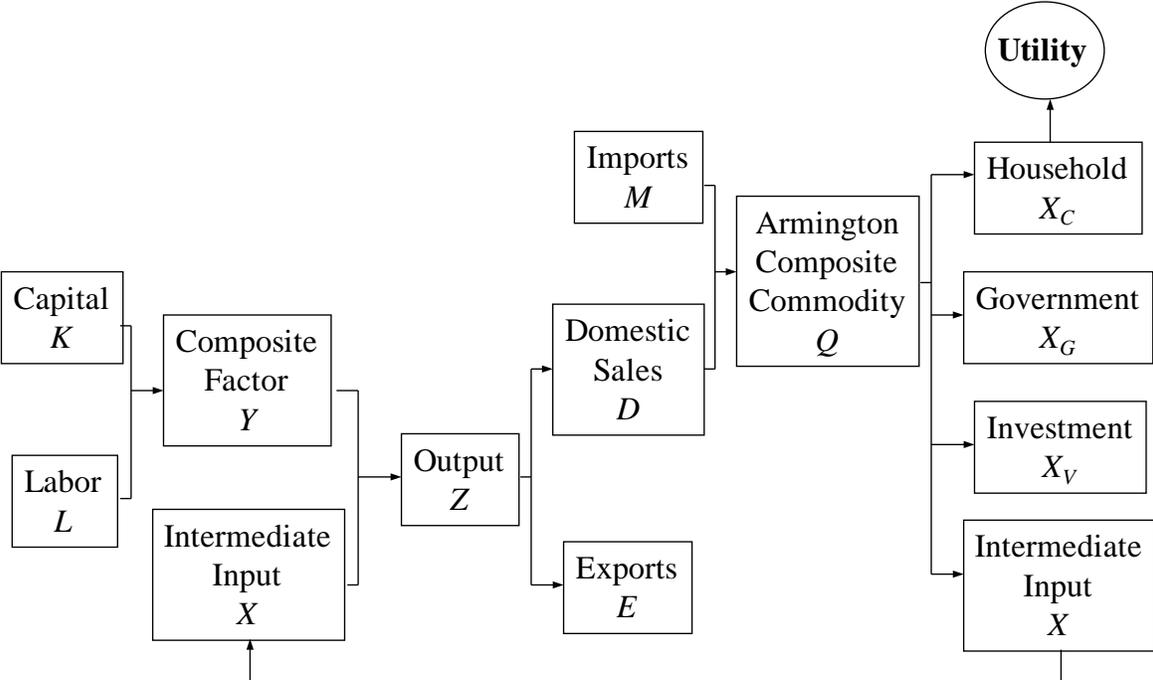


Figure 2. Linking of a CGE model with a marine ecosystem model for fisheries policy analysis

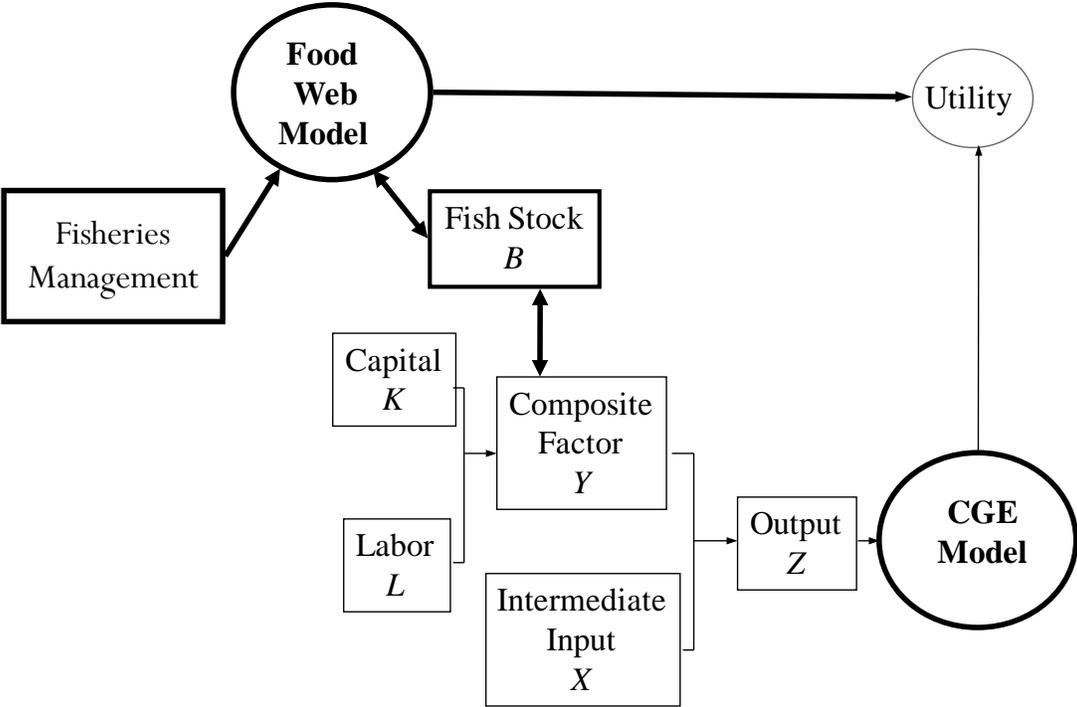
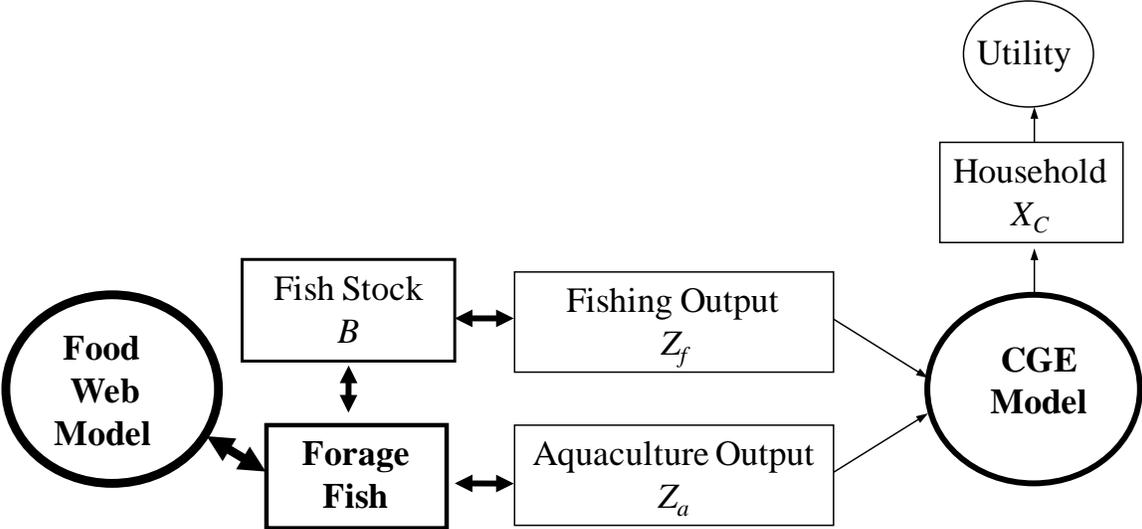
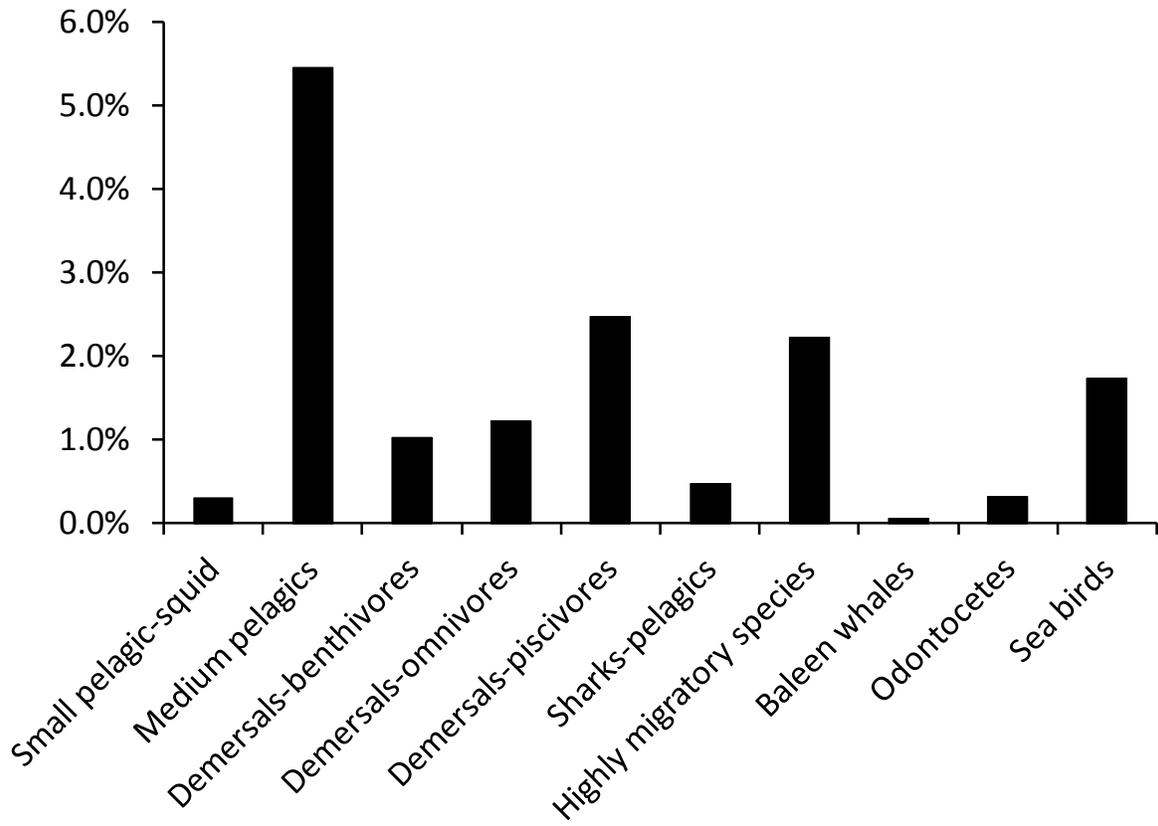


Figure 3. An integrated economic-ecological analysis of forage fish management



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Figure 4. Percent changes in predator biomass resulting from one unit (g m^{-2}) change in prey biomass (small commercial pelagic species)



¹ For an excellent review of different food web models, see Plagányi (2007).

² For example, the CGE model by Waters and Seung (2010) includes 2 fish harvesting sectors, two fish processing sectors, and other aggregate sectors in the economy. In contrast, the partial equilibrium model by Chiang (2005) is focused on the fishery sector, which consists of 40 products and 68 fishing activities.

³ Derivation of the equation can be found on page 187 of Steele (2009).

⁴ Note that the standing stock biomass (B) can be calculated from production rate (P) using the P/B ratio. A specific example on how to estimate changes in fish harvesting resulting from changes in production (P) can be found on page 2228 of Collie et al. (2009).

⁵ E2E is a donor-controlled model, see Equation (5).

⁶ Collie et al. (2009) examined four scenarios representing different ecosystem states in different historical periods (Scenarios 0, I, III, and V). Scenario 0, the baseline, represents the 1993-2002

food web configuration for Georges Bank. Scenario I simulates the dominance of piscivores including cod, a historically important commercial fish in the region (a 200% increase in piscivore production). Scenario III simulates the elimination of carnivorous zooplankton believed to increase with overfishing, resulting in an increase in the abundance of all fish guilds, especially the planktivorous fish, and corresponding to the 1971-1990 Georges Bank food web. Scenario V simulates increased production of the suspension-feeding benthos believed to be reduced by habitat disturbance, redistributing primary production from mesozooplankton to the benthos. This change leads to a large increase in benthivore production and a smaller increase in piscivores (similar to the 1921-1950 Georges Bank food web). Understanding ecosystem states in different periods is important for the development of stock rebuilding strategies.

⁷ The EMAX is a recipient-controlled model, see Equation (6).

⁸ This involves the modifications of production functions for both the commercial fishing and aquaculture sectors in the CGE model, and corresponding adjustments in the fish harvesting vector in the food web model.