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Development of an Integrated Economic and Ecological Framework for Ecosystem-Based Fisheries Management in New England

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Abstract

We present an integrated economic-ecological framework designed to help assess the implementation of ecosystem-based fisheries management (EBFM) in New England. We develop the framework by linking a computable general equilibrium (CGE) model of a coastal economy to an end-to-end (E2E) model of a marine food web for Georges Bank. We focus on the New England region using coastal county economic data for a restricted set of industry sectors and marine ecological data for three top level trophic feeding guilds: planktivores, benthivores, and piscivores. We undertake numerical simulations to model the welfare effects of changes in alternative combinations of yields from feeding guilds and alternative manifestations of biological productivity. We estimate the economic and distributional effects of these alternative simulations across a range of consumer income levels. This framework could be used to extend existing methodologies for assessing the impacts on human communities of groundfish stock rebuilding strategies, such as those expected through the implementation of the sector management program in the US northeast fishery. We discuss other possible applications of and modifications and limitations to the framework.

Keywords: Fisheries management; Ecosystem management; Food webs; Computable general equilibrium model; Economic models; Social welfare.

1. Introduction

Historically, the commercial fishing industry was a cornerstone of New England's economic development (Ackerman 1941; Hennemuth and Rockwell 1987). Until recent years, the industry was a significant source of jobs and income in the regional economy (Doeringer and Terkla 1995). Within the last three decades, however, severe recruitment over-fishing of many of the important groundfish species led to their depletion, resulting in losses of billions of dollars to the New England economy (Fogarty and Murawski 1998; Edwards and Murawski 1993). Although there have been significant successes in the rebuilding of some fish stocks, including striped bass, Atlantic sea scallops, Georges Bank haddock, and Gulf of Maine cod, numerous studies have documented the continued depletion of other fish stocks and have pointed to other significant ecological problems in this region, including habitat destruction, nutrient over-enrichment, declines in numbers of large whales, and other symptoms of resource overuse and system decline (NRC 2006, 1999; Pauly and Palomares 2005; Pauly *et al*. 2003, 1998).

1.1. Need for fisheries regulation

In order to control the problem of over-fishing, experts and fishery participants agree that effective fishery regulation is needed. To minimize costs associated with declining stocks and new regulations, the fishing industry typically adjusts activities by switching offshore operations to other target species and relocating onshore businesses. Changes in harvesting practices have implications for associated local businesses that supply the harvesting sector as well as those in the processing, distribution, and other downstream sectors. Thus, changes in the marine ecosystem and the resulting management regime can lead to changes in industrial organization and even changes in the social structure of coastal communities (Dewar 1983).

Federal laws such as the National Environmental Policy Act of 1969 and the Sustainable Fisheries Act of 1996 now require that fishery regulation take into consideration the importance of fishery resources to fishing communities. Ultimately, these broad-scale policies support the social goals of encouraging the sustained participation of coastal communities in commercial fisheries and of minimizing adverse socio-economic impacts. The federal Magnuson-Stevens Fishery Conservation and Management Act requires further that the regional fishery management councils take into account the "protection of marine ecosystems" when making determinations of the greatest overall benefit to the nation of implementing optimal yield standards. At present, precisely how marine ecosystems are to be protected has been left mainly to the discretion of the Councils.

1.2. Ecosystem-based fisheries management

Many experts have argued that traditional management of commercial fish stocks as single-species is short-sighted, wasteful, and ineffective (Halpern *et al*. 2008; Lotze *et al*. 2006; Jackson *et al*. 2001). Marine ecosystems comprise species that exhibit biological interactions, and the myopic management of one species may lead to undesirable effects on the stocks and flows of other species, the stability of the larger ecosystem, or the ecosystem's capacity to provide valuable goods and services to humans (CEEF 2006; Frid *et al*. 2006; Levin and Lubchenco 2008). Ecosystem-based fisheries management (EBFM) now is being promoted as a potential solution to the problems of traditional fisheries management.

While much attention has been directed recently at the potential benefits of implementing EBFM for commercial fisheries (Levin and Lubchenco 2008; McLeod 2005; Garcia *et al*. 2003), the realization of a more comprehensive management that takes into account broader effects on the ecosystem and associated human communities remains elusive. EBFM appears sensible at a conceptual level, but implementation may be problematic due to a lack of agreement about desirable ecological states or an inability to characterize the most appropriate fishery conservation and management measures (Pitcher *et al*. 2009; Tallis *et al*. 2009). Pikitch *et al*. (2004) argue for the need to refine and expand multi-species and eco-trophic models to assess the ecosystem-level consequences of EBFM actions.

Models of human economies that are connected to marine ecosystems, such as those linking fishing communities with marine fisheries, are needed to evaluate the effects of EBFM strategies to reverse historical patterns of marine resource overuse and decline (Murawski 2007; Crowder and Norse 2008). These models can be used to evaluate alternative fisheries regulations, highlight the effects of resource conservation, and assess economic and distributional impacts on fishing communities and associated industries. Effective models can provide decision-makers and stakeholders with critical and relevant information for making more effective and equitable decisions about restoring the productivity and value of marine ecosystems.

1.3. Need for integrated "ecosystem-based" modeling approaches

The importance of integrated economic-ecological analysis has been stressed by many experts (Arrow *et al*. 1995). To support fishery management decisions, models have been developed to investigate the relevant interactions between economic sectors and the marine ecosystem and how changes in the latter may lead to economic gains and losses within and among coastal communities. Bio-economic models link the behavior of a few species with patterns of human exploitation, but they are limited in scope because of model complexity and are not optimal for comprehensive management at ecosystem scales.

In order to analyze systems with a larger 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, such as IMPLAN (MIG 2000) and Ecopath (Christensen *et al*. 2005). Economic input-output models have been developed for the US northeast shelf coastal region (Hoagland *et al*. 2005) and marine food web models have been developed for the Georges Bank ecosystem (Sissenwine *et al*. 1984; Jones 1984; Cohen *et al*. 1979). As a theoretical example of combining these approaches, Jin *et al*. (2003) coupled a regional input-output model of the US northeast shelf coastal economy to a linear model of a marine food web for Georges Bank.

Although such linear economic-ecological models can handle a large number of variables (industry sectors and species), the approach often is limited to descriptive studies in a static framework. These models do not capture some key nonlinear interactions in economies and ecosystems. They also cannot really be used to determine which policies would provide the greatest net benefits to society. Recently-developed food web models attempt to capture the complexities of marine ecological systems (*e.g*., Steele and Gifford 2009; Link *et al.* 2008). The challenge is to develop a useful economic model that incorporates several key economic sectors related to the ecosystem, such as fish harvesting and processing, and to estimate the changes in economic gains and losses of the integrated system when policies are implemented.

A computable general equilibrium (CGE) approach yields a potentially useful economic model that can be employed for analyzing changes in social welfare. The reason for this is that a CGE model explicitly includes utility maximization by consumers, such as households, and profit maximization by producers, such as fish harvesters. In one of the first uses of a CGE in a marine ecosystem-based management context, Finnoff and Tschirhart (2008) demonstrate how such an economic model can be linked to a food web model for the Aleutian Islands and Eastern

Bering Sea to examine the welfare changes related to regulating commercial fishing and to managing ecotourism.

1.4. Integrated ecosystem-based modeling for New England fisheries

Here, we develop an integrated economic and ecological framework for evaluating the economic and distributional effects of implementing EBFM strategies in New England. In our analytical framework, the marine ecosystem is modeled as an end-to-end (E2E) food web and the socio-economic system is captured by a CGE model. The integrated framework is used to analyze marginal changes in human welfare with respect to alternative ecosystem scenarios, some of which might be the result of the implementation of fishery regulations. We apply the framework to the Georges Bank marine ecosystem, where fishery management measures, fish habitat protected areas, and other forms of intervention now are being implemented or have been proposed. As a caveat, we note that the important issues associated with the practical achievement of the ecosystem states that result from E2E simulations—through the implementation of specific conservation and management measures—are reserved for future research. We also note that the socio-economic system itself is affected by changes in technology and human preferences. The dynamics at work in effecting these changes are not addressed in the CGE model described herein.

2. Methods

2.1. The theoretical aspects of a CGE model

CGE models have been used widely for policy analysis in recent years, but their potential for use in ecosystem-based management has not yet been fully explored. A few CGE models now include environmental and resource sectors for environmental policy analysis (*viz*. Abler *et al*.

1999; Xie *et al.* 1996). Although researchers have begun to investigate the theoretical aspects of these ecosystem scale models (*e.g.*, Finnoff and Tschirhart 2008), more work needs to be done to investigate the practical application of such models to provide decision support.

Economic CGE models have several key features: (1) multiple industry sectors; (2) constraints on the availability of resources (inputs in production processes); (3) supply derived from the behavior of profit-maximizing producers; (4) demand derived from the behavior of utility-maximizing consumers; and (5) through price adjustments, supply equals demand in markets for both production factors (capital and labor inputs) and goods (industry products) (Xie and Saltzman 2000). In particular, the latter feature implies that prices are endogenous and are determined by the market.

A basic CGE model has N industry sectors (j = 1, 2,…, N) that supply goods to two demand sectors: households and government. Households provide both labor, L, and capital, K, to industry. Fig. 1 depicts an example of the supply and demand for a specific commodity j, like seafood, produced by an industry sector j, such as commercial fish harvesting.

<INSERT Fig. 1 HERE>

Economic production in a typical CGE model has a nested structure. Initially, firms, such as fish harvesters, choose levels of capital (*e.g.*, fishing vessels) and labor (*e.g.*, vessel crews) to optimize the level of a composite factor input, Y_j. More specifically, firms maximize their profits, subject to a production technology F_{Yj}:

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

where L_j and K_j are quantities of labor and capital inputs, and P_L, P_K and P_{Yj} are prices for inputs L, K, and the composite factor output, Y_j, respectively. The levels of factor inputs are calculated using the first-order conditions arising from equation (1). A firm utilizes a production input, say, L_j, until its price, P_L, equals its marginal value product, $P_{Yj} \cdot \partial Y_j / \partial L_j$.

Once production is optimized at the initial level, firms combine the composite factor input, Y_j, with intermediate inputs, X_{ij}, to produce an output, Z_j:

$$Z_j = F_{zj}(Y_j, X_{1j}, X_{2j}, ..., X_{Nj}) \tag{2}$$

where X_{ij} (i = 1,2, …, N) is commodity i used in the production of j. For example, if Z_j is the yield from a fishery, X_{ij} would comprise factors such as the bait, fuel, and ice used in the fishing activity. In a traditional model, Y_j and X_{ij} are combined in fixed ratios. For a given level of the composite factor input, Y_j, then output, Z_j, is determined.

In the center of the flow chart in Fig. 1, firms sell their products, such as seafood, in local markets and export them outside the modeled region. Export decisions are modeled by firms maximizing their total revenues subject to a function, F_{Tj}, that specifies how domestic sales are traded off with export sales:

$$\max \ P_{Zj} Z_j = P_{Dj} D_j + P_{Ej} E_j \quad s.t. \quad Z_j = F_{Tj}(D_j, E_j) \tag{3}$$

where Z_j, D_j, and E_j are quantities of total output, domestic sales, and exports, for commodity j, and P_{Zj}, P_{Dj}, and P_{Ej} are prices for Z_j, D_j, and E_j, respectively. The levels of local market sales and exports are calculated using the first-order conditions of equation (3).

In addition to local production, commodity j also is imported from outside the region. Import decisions are modeled by households, who minimize the costs of using composite goods subject to a function, F_{Aj}, that specifies, where j denotes seafood, how domestic purchases of local seafood are traded off with purchases of imported seafood:

$$min \ P_{Qj} Q_j = P_{Dj} D_j + P_{Mj} M_j \quad s.t. \quad Q_j = F_{Aj}(D_j, M_j) \tag{4}$$

where Q_j, D_j, and M_j are the quantities of seafood as a composite good, domestic products, and imports, respectively. P_{Qj}, P_{Dj}, and P_{Mj} are the prices of Q_j, D_j, and M_j, respectively. The quantities of local seafood purchases and imports are calculated using the first-order conditions of equation (4).

On the right hand side of Fig. 1, a household maximizes its utility (U) of consuming all goods X_{Cj} subject to an income constraint:

$$max\, U(X_{C1}, X_{C2}, ..., X_{CN}) \quad s.t. \quad \sum_j P_{Qj} X_{Cj} = P_L L + P_K K \tag{5}$$

The levels of consumption, X_{Cj}, are calculated using the first-order conditions of equation (5).

The model is balanced when sets of quantities and associated prices are found for which all commodity and factor markets clear (*i.e.*, supply equals demand in all markets). Although not shown in the theoretical model developed herein, the possibility to accumulate inventory is included in the applied CGE model. The commodity market clearing condition is:

$$Q_j = X_{Cj} + X_{Gj} + X_{Vj} + \sum_i X_{ij} \qquad \forall j \tag{6}$$

where X_C, X_G, and X_V are the quantities of composite goods demanded by the households, the government, and an investment sector.

The economy is endowed with fixed levels of both capital, K, and labor, L. Consequently, the factor market clearing conditions are:

$$\sum_j K_j = K \tag{7}$$

$$\sum_j L_j = L \tag{8}$$

A CGE model is calibrated initially using economic data for the study region. The resulting model calculates the status quo quantities (*e.g.*, Y, X, Z, D, E, M, and Q) for a given baseline set of prices $\mathbf{P}_0$. To simulate the effects of any policy change, such as a change in either price or quantity of a commodity, like seafood, the model is re-run after changing the levels of one or more of the variables. In practice, an optimization solver typically is used to recalculate both a new set of equilibrium prices $\mathbf{P}_1$ and corresponding changes in quantities so that all markets once again clear. A social welfare change can be evaluated as an equivalent variation (*EV*), which measures the change in household utility assuming that prices remain constant:

$$EV = F_E(U_1, \mathbf{P}_0) - F_E(U_0, \mathbf{P}_0) \tag{9}$$

where F_E is a household expenditure function. U_1 and U_0 are the household utility levels with and without the modeled policy change.

2.2. Empirical aspects of a CGE model for New England coastal communities

The specification of a CGE model begins with the compilation of a social accounting matrix (SAM) using national income data, comprising industry activities, commodity flows, household consumption (disaggregated by income categories), and government consumption (at all levels of government). While the model captures market transactions, it does not explicitly account for non-market values.

For our analysis, we begin with a regional CGE model that accepts IMPLAN data to populate the SAM (Stodick *et al*. 2004). IMPLAN is a modular input-output model that can be disaggregated to the individual county level. IMPLAN data for 2006 were selected for model development. These data contain national income and employment statistics for over 500 economic sectors, including commercial fishing and seafood processing. The IMPLAN sectors also can be grouped into several aggregated sectors (MIG 2000). Aggregation helps to simplify the model building task, but it leads to bias in the estimated impacts on specific sectors (Miller and

Blair 1985). More specifically, aggregation does not affect the total estimated economic impacts, but it may affect how these impacts are distributed among economic sectors.

According to an earlier study (Hoagland *et al*. 2005), the economic impacts of commercial fishing on the entire New England economy are mostly felt in the coastal counties, and any effects outside the coastal counties are small. We construct a CGE model of the New England coastal economy using county-level IMPLAN data for coastal counties in Maine, New Hampshire, Massachusetts, Rhode Island, and Connecticut. The model does not have spatial component and includes five sectors: commercial fishing, seafood processing, agriculture, manufacturing, and all other sectors combined. Table 1 depicts the aggregated SAM for the New England coastal economy. Because a specific sector could produce different commodities, the SAM includes both activity accounts (columns/rows 1 through 5) and commodity accounts (columns/rows 6 through 10). Production factors (labor and factor inputs) are listed in columns/rows 11 and 12. Institutions (household and government sectors) are listed in columns/rows 13 and 14. Trades are recorded in column/row 18. The column sums are total outlays, and the row sums are total incomes. Each column sum, or total outlay, equals its corresponding row sum, or total income. For example, the total outlay for the New England fishing industry in column 2 is $869.9 million, which is equivalent to the total income in row 2.

<INSERT Table 1 HERE>

As detailed in column 2, the activity in the fishing industry involves intermediate commodity inputs from fishing itself ($2.3 million), other sectors ($252.2 million), manufacturing ($120.3 million), labor ($338.8 million), capital ($26.2 million), and imports ($130.1 million). Row 2 shows that, of the $869.9 million in fishing industry income, $610.6 million are sales within the region, and \$259.3 million are exports (to both extra-regional domestic and foreign markets). Entries in the lower-right section of the SAM are transfer payments among the relevant sectors.

The baseline output, supply, and trade statistics calculated with the CGE model of the New England coastal economy are summarized in Table 2. 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. The output from fish processing is \$1.12 billion, of which \$708 million is exported to markets outside New England; the remainder, when combined with imports, is supplied to local markets (\$543 million).

<INSERT Table 2 HERE>

2.3. Marine Food Web Models

Different types of biological compartment models (food-web models with one or more species aggregated together in one compartment and linked to groups of species in other compartments) have been developed for the Georges Bank marine ecosystem (Collie *et al*. 2009; Link *et al*. 2008; Steele *et al*. 2007). Two general types of compartment models comprise recipient- and donor-controlled models, which differ in structure, aggregation of species, and stability. These models have been developed for the purpose of understanding biological stocks and flows and the resilience of the Georges Bank marine ecosystem to environmental and anthropogenic perturbations.

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 less all the losses:

$$\frac{dB_i}{dt} = e_i\left(\sum_j Q_{ij} + G_i\right) - \sum_k Q_{ki} - L_i \quad (10)$$

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 are the gains from external sources; L_i are losses from the system, and e_i is the amount of energy transferred between trophic levels (*i.e*. the transfer efficiency).

The two types of compartment models differ in the way Q_{ij} is modeled. In a donor-controlled model, Q_{ij} is a function of production in the various trophic components (P_i) and is driven by nutrient fluxes; consequently, a donor-controlled model is also known as a bottom-up model. In contrast, in a recipient-controlled (top-down) model, Q_{ij} is a function of consumption in various trophic components (C_i) and starts with fisheries yields. Note that both P_i and C_i are flows in the system, while B_i is a stock. Here, we use the steady-state scenarios that are the output of the food web model described in Collie *et al*. (2009). These authors introduce their model as an E2E-type food-web model, but they undertake simulations for alternative steady-state scenarios in a donor-controlled (bottom-up) mode.

At steady-state, the donor-controlled formulation of Equation (10) is

$$P_i = e_i\left(\sum_j a_{ij} \cdot P_j + G_i\right) - f_i \cdot P_i \quad (11)$$

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 fraction loss of P_i to the system. Fish harvesting is modeled with the final term in (11). In the above formulation, it is production at the lower trophic levels (P_j) that determines production at higher trophic levels (P_i). Equation (11) can be rewritten in matrix notation as:

$$\mathbf{P} = (\mathbf{I} - \mathbf{IeA} + \mathbf{If})^{-1}\mathbf{IeG} \quad (12)$$

If there are n trophic components in the food web, then **P**, **e**, **f** and **G** are $n \times 1$ vectors, **I** is a $n \times n$ identify matrix, and **A** is a $n \times n$ matrix. Tables 3 and 4 include data for **e**, **f**, **G**, and **A** from Collie *et al*. (2009). Terms with $e = 1$ have detritus and nutrients recycled in the food web so all ingested material is accounted for.

<INSERT Tables 3 and 4 HERE>

2.4. Scenarios

We examine the economic effects associated with different ecosystem states using four scenarios from Collie *et al*. (2009). The four scenarios (0, 1, 2, and 3) in our study correspond to scenarios 0, I, III, and V, respectively, in the Collie *et al*. study. Scenario 0, the baseline, represents the 1993-2002 food-web configuration for Georges Bank. Biological production coefficients for the three alternative scenarios are found in Table 4. The production vector **P** for the four scenarios is found in Table 5. Scenario 1 simulates the dominance of piscivores including cod, a historically important commercial fish in the region (a 200% increase in piscivore production). Scenario 2 simulates the elimination of carnivorous zooplankton believed to increase with overfishing, resulting in an increase the abundance of all fish guilds, especially the planktivorous fish, and corresponding to the 1971-1990 Georges Bank food-web. Scenario 3 simulates increased production of the suspension-feeding benthos believed to be reduced by habitat disturbance, redistributing primary production from the 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).

<INSERT Table 5 HERE>

2.5. Linkages between Economic CGE and Marine Food Web Models

Potential linkages between the ecosystem and the economy include: (1) the commercial fishing industry harvests fish from the ecosystem; (2) coastal economic activities (*e.g.*, waterfront development) and offshore economic activities (*e.g.*, bottom trawling) affect fish habitat; and (3) coastal tourism depends on marine resources (*e.g.*, recreational fishing and whale-watching).

Here, we focus only on the first linkage. We connect the marine food web model with the economic CGE model using the classical harvest function from bioeconomic analysis:

$$h = qEx \tag{13}$$

where h is the quantity of fish harvested, q is a catchability coefficient, E is fishing effort, and x is the stock size. According to Equation (13), for a fixed catchability and a given level of fishing effort, harvest is proportional to stock size.

As formulated here, the CGE model aggregates all harvested fish into a general category called "seafood." From an economic perspective, however, an increase in the stock of a low-valued species such as herring, a planktivore, is much different than an increase in the stock of a higher-valued species, such as Atlantic cod, a piscivore. To account for these differences, we weight stock changes within feeding guilds using a value-adjusted stock measure:

$$x = \sum_i s_i B_i \tag{14}$$

where s_i is the revenue share of the species in feeding guild i and B_i is the biomass of feeding guild i.

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

$$Y_j = \alpha F_{Yj}(L_j , K_j) \qquad \text{for } j = \text{fishing} \tag{15}$$

Alternative ecosystem states and associated stock levels x are incorporated into the shift parameter α (described in detail below). 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.

2.6. Estimating the shift parameter α for alternative E2E food web scenarios

We estimate the shift parameter, α, using the value-adjusted measure of effective stock size described above. Table 6 lists the quantity and revenue of commercial fishery landings by feeding guild, which is a group of organisms that uses resources in a similar way, and species in New England in 2006. The species in each of the three feeding guilds are taken from Steele *et al*. (2007). In the Collie *et al*. (2009) model, harvests from these same three feeding guilds account for 15.68% of the total value of fisheries in New England. Within this 15.68%, planktivores account for 23.27%, benthivores account for 27.85%, and piscivores account for 48.88% (see the last column in Table 7). In the New England region, landings of sea scallop and lobster accounted for about three quarters of the total value in recent years (in 2006 their shares were 31% and 44%, respectively). Because the two species are not included in the Collie *et al*. model, we hold the stock of these species constant in our study, and we simulate only the effects of changes in a subset of the fishery stock in the region.

<INSERT Tables 6 and 7 HERE>

Utilizing the data on annual food-web production (Table 5), we calculate the revenue-share weighted sum of annual production across the three guilds (row 4 in Table 7). The food-web production rate P is expressed in gCm^{-2} year^{-1}, which can be converted to biomass (B) or fish yield unit (t year^{-1}) for the entire Georges Bank (Collie *et al*. 2009). For simplicity, we work directly with P which is proportional to B.

Compared with the baseline scenario 0, total annual production (and thus biomass) for Scenarios 1, 2, and 3 is higher by 19.88%, 60.18%, and 25.98%, respectively (row 5 in Table 7). We further adjust these changes in biomass by the value share of the three feeding guilds in the total New England fish production (15.68%). The resulting adjusted changes in biomass as the ecosystem changes from baseline 0 to, 1, 2, and 3 are 3.12%, 9.44%, and 4.07%, respectively. Thus, the shift parameter, α, in the fishing industry production function is 1.0312 for Scenario 1, 1.0944 for Scenario 2, and 1.0407 for Scenario 3.

3. Results

As noted above, one of the advantages of a CGE model over an input-output model is its ability to estimate price changes and nonlinear quantity changes. For example, Table 8 illustrates changes resulting from a change in the marine food-web structure, from scenario 0 to scenario 2 (a 9.44% increase in biomass). The increase in fish biomass leads to a 10.37% increase in fishery output, a 6.39% increase in total seafood supply to the New England market, a 3.38% decrease in seafood imports, a 17.92% 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.

<INSERT Table 8 HERE>

Another advantage of a CGE model is its capability to measure welfare changes. To evaluate the welfare changes associated with switching from a baseline ecosystem state to alternative states, we run the CGE model separately with $\alpha = 1.0312$, 1.0944, and 1.0407. The results suggest that switching from baseline Scenario 0 to Scenarios 1, 2, and 3 will lead to welfare increases of $43.16 million, $134.92 million, and $56.61 million, respectively, 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 9).

<INSERT Table 9 HERE>

4. Discussion and Conclusions

Directly and indirectly, coastal ecosystems provide many valuable goods and services to society. One fundamental assumption of EBM is that information about the value of these commodities can contribute to the improved monitoring, assessment, and management of marine ecosystems. To date, however, economic values and techniques have not been utilized to their full potential in debates about the best ways to manage marine resources. We aim to elevate the level of economic analysis to increase the potential for more effective management and to clarify the distribution of economic gains and losses within and among coastal communities.

In this article, we develop an economic-ecological framework to generate information for fisheries management in New England. Specifically, we show how a CGE model that is capable of yielding estimates of social welfare changes can be connected to an E2E model of the Georges Bank ecosystem. We show how scenarios of alternative ecosystem states reflecting varying levels of biomass in three distinct feeding guilds result in different patterns of economic benefits. By capturing complex interactions among components of ecological and economic systems, this integrated framework can provide valuable information for developing ecosystem-based fisheries management strategies.

Our model results demonstrate that changes in fishing practices positively affecting the ecosystem (*e.g*., elimination of overfishing, reduced habitat disturbance), can lead to economic gains in the New England economy. When overfishing is eliminated, as in Scenario 2, outputs in the New England economy increase as fish production increases. Less seafood is imported, because more fish are available in the local region. Not surprisingly, as the supply of local fish increases, the price of seafood declines. The level of economic impact differs among the simulations, most likely due to the stock of fish that are affected in each simulation. For instance, under Scenario 2, reversing overfishing has the greatest benefits to the New England economy because overfishing directly affects several highly valued fish stocks. Interestingly, economic gains in all three simulations are not distributed evenly among household consumers, illustrating the complex linkages among components of economic and ecological systems.

Importantly, although there are clear net benefits associated with each of the alternative scenarios relative to the baseline, our results do not imply that marine fisheries would be managed optimally. The net benefits that are the consequence of alternative ecosystem states arise because there are larger biomasses of commercially important species. Producer surpluses accrue to capital and labor, and consumer surpluses accrue to consumers, but, in the absence of economically efficient conservation and management measures, it is likely that resource rents still would be dissipated. Future research might usefully involve revisions to the CGE model to permit fish stocks to be incorporated as a priced factor of production, along with capital and labor.

Another important topic for future research involves investigating the consequences of connecting the CGE model with other types of food web models, including top-down or Ecosim/Ecopath models. Such models have been under development for Georges Bank (Link *et* *al*. 2008), and they may be closer than the bottom-up models in terms of their implementation in a genuine management context.

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Table 1
Social accounting matrix (SAM) for the New England coastal economy, 2006

		Industry					Commodity					Factors		Institutions						
		AGRI	FISH	OTHER	MANU	PROC	AGRI	FISH	OTHER	MANU	PROC	LAB	CAP	HH	GOV	ENTR	CAPEXP	INVENT	EXPORT	TOTAL
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
AGRI	1						1,993.8		5.6										485.5	2,484.9
FISH	2							610.6											259.3	869.9
OTHER	3								533,926.9	818.7									205,433.1	740,178.6
MANU	4								565.2	156,055.4	2.1								37,580.5	194,203.1
PROC	5									12.5	414.1								707.6	1,134.2
AGRI	6	140.7		134.8	1,229.4	15.8								522.5	8.0			4.5		2,055.9
FISH	7		2.3	136.6	7.9	331.5								105.5	1.1			25.7		610.6
OTHER	8	292.2	252.2	168,462.7	46,477.1	324.4								239,978.2	44,306.6		41,393.2	502.2		541,988.7
MANU	9	328.9	120.3	35,044.1	45,750.4	36.1								44,656.1	11,974.8		17,829.8	1,353.7		157,094.2
PROC	10			222.7	7.8	52.8								118.1	6.1			8.7		416.2
LAB	11	442.2	338.8	277,370.8	39,144.9	184.8														317,481.4
CAP	12	629.3	26.2	197,486.7	20,682.8	6.4														218,831.3
HH	13								3,105.8			280,586.2	68,519.7	10,322.2	69,546.4	30,359.2	14,273.3		2,541.8	479,254.6
GOV	14						61.0		1,173.4	9.0		36,575.6	39,369.7	71,793.2	59,566.5	19,781.4			468.1	228,797.9
ENTR	15											319.6	55,687.3		1,885.1					57,892.0
CAPEXP	16								1,165.8				59,120.1	24,631.0	23,298.7	7,751.4		270.9	448.1	116,686.0
INVENT	17						1.1		2,046.1	198.6									834.3	3,080.1
IMPORT	18	651.7	130.1	61,320.2	40,902.8	182.5							-3,865.6	87,127.5	18,204.6		43,189.7	914.5		248,758.0
TOTAL	19	2,484.9	869.9	740,178.6	194,203.2	1,134.2	2,055.9	610.6	541,988.8	157,094.2	416.2	317,481.4	218,831.2	479,254.4	228,797.8	57,892.0	116,685.9	3,080.1	248,758.3	3,311,817.6

AGRI – agriculture, FISH – fishing, OTHER – other, MANU – manufacturing, PROCH – seafood processing, LAB – labor input, CAP – capital input, HH – households, GOV – governments, ENTR – enterprises (corporations), CAPEXP – capital expenditures, INVENT – inventory additions/deletions.

All values are in 2006 $ millions.

Table 2
New England coastal regional economy: baseline economic value (2006 $ millions)

Sector/Commodity	Output	Total Supply*	Imports**	Exports**
Agriculture	2,554	7,790	5,734	498
Fishing	870	653	42	259
Fish Processing	1,124	543	126	708
Manufacturing	194,703	247,124	90,030	37,608
Other	750,325	673,199	131,211	208,336

*Composite commodity supplied to New England market
**Including both domestic and foreign trade

Table 3
Input values of nutrient input, **G**, transfer efficiency, **e**, and fractional physical loss, **f**, from Collie *et al*. (2009)

Foodweb component		G	e	f
B1	Inorganic N (NO_3)	127.0	1.0	0
B2	Phytoplankton	0.0	1.0	0.0493
B3	Microzooplankton	0.0	1.0	0.0346
B4	Mesozooplankton	0.0	1.0	0.1849
B5	Invertebrate carnivorous plankton	0.0	0.2	0
B6	Suspension-feeding benthos	0.0	1.0	0
B7	Meiobenthos	0.0	0.2	0
B8	Deposite-feeding benthos	0.0	0.2	0
B9	Invertebrate carnivorous benthos	0.0	0.2	0
B10	Bacterial recycling	0.0	1.0	0.0426
B11	Detritus	0.0	1.0	0.1567
B12	Plankton for fish	0.0	1.0	0
B13	Benthos for fish	0.0	1.0	0
B14	Juvenile fish	0.0	0.3	0
B15	Planktivores	0.0	0.1	0
B16	Benthivores	0.0	0.1	0
B17	Piscivores	0.0	0.1	0

Table 4
The production matrix, **A**, from Collie *et al*. (2009)

	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	B11	B12	B13	B14	B15	B16	B17
B1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
B2	100	0	0	0	0	0	0	0	0	100	0	0	0	0	0	0	0
B3	0	60	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
B4	0	26	21	0	0	0	0	0	0	0	14	0	0	0	0	0	0
B5	0	0	0	14	0	0	0	0	0	0	0	0	0	0	0	0	0
B6	0	6	3	0	0	0	0	0	0	0	3	0	0	0	0	0	0
B7	0	0	0	4	0	4	0	0	0	0	0	0	0	0	0	0	0
B8	0	0	0	16	0	16	100	0	0	0	0	0	0	0	0	0	0
B9	0	0	0	0	0	10	0	54	0	0	0	0	0	0	0	0	0
B10	0	0	53	56	0	60	0	0	0	0	83	0	0	0	0	0	0
B11	0	8	23	0	0	0	0	0	0	0	0	0	0	0	0	0	0
B12	0	0	0	9	100	0	0	0	0	0	0	0	0	0	0	0	0
B13	0	0	0	0	0	10	0	46	100	0	0	0	0	0	0	0	0
B14	0	0	0	0	0	0	0	0	0	0	0	39	29	0	0	0	0
B15	0	0	0	0	0	0	0	0	0	0	0	54	26	47	0	0	0
B16	0	0	0	0	0	0	0	0	0	0	0	1	28	10	0	0	0
B17	0	0	0	0	0	0	0	0	0	0	0	6	17	43	0	0	0

The above data are for Scenario 0. For Scenarios 1, 2, and 3 changes are made as follows (see Collie *et al*. 2009: Scenarios I, III, and V):

Scenario 1: $a_{14,12} = 55$, $a_{14,13} = 42$, $a_{15,12} = 18$, $a_{15,13} = 5$, $a_{15,14} = 4$, $a_{16,12} = 1$, $a_{16,13} = 19$, $a_{16,14} = 2$, $a_{17,12} = 25$, $a_{17,13} = 33$, $a_{17,14} = 94$

Scenario 2: $a_{5,4} = 0.1$, $a_{12,4} = 22.9$

Scenario 3: $a_{4,2} = 6$, $a_{6,2} = 26$

For species in food-web components B15 (planktivores), B16 (benthivores), and B17 (piscivores), see column 1 in Table 6.

Table 5
Rate of annual production P in scenarios 0, 1, 2, and 3

	Foodweb component	P_0	P_1	P_2	P_3
B1	Inorganic N (NO3)	127.00	127.00	127.00	127.00
B2	Phytoplankton	338.54	338.54	338.54	362.13
B3	Microzooplankton	196.33	196.33	196.33	210.01
B4	Mesozooplankton	116.46	116.46	116.46	63.45
B5	Invertebrate carnivorous plankton	3.26	3.26	0.02	1.78
B6	Suspension-feeding benthos	28.08	28.08	28.08	102.46
B7	Meiobenthos	1.16	1.16	1.16	1.33
B8	Deposite-feeding benthos	4.86	4.86	4.86	5.57
B9	Invertebrate carnivorous benthos	1.09	1.09	1.09	2.65
B10	Bacterial recycling	228.23	228.23	228.23	252.99
B11	Detritus	62.45	62.45	62.45	66.81
B12	Plankton for fish	13.74	13.74	26.69	7.49
B13	Benthos for fish	6.13	6.13	6.13	15.46
B14	Juvenile fish	2.14	3.04	3.66	2.22
B15	Planktivores	1.00	0.29	1.77	0.91
B16	Benthivores	0.21	0.14	0.23	0.46
B17	Piscivores	0.28	0.83	0.42	0.40

Foodweb production rates P are expressed in $gCm^{-2}year^{-1}$

Scenarios 0, 1, 2, and 3 correspond to scenarios 0, I, III, and V, respectively, in Collie *et al*. (2009).

Table 6
Quantity and value of landings by guild and species in New England, 2006

Guild/Species	Landings (lbs)	Value	Price
Piscivores			
Spiny dogfish	4,237,824	$1,023,350	$0.24
Winter skate*			
Silver hake	9,512,456	$4,736,203	$0.50
Atlantic cod	12,612,531	$20,460,438	$1.62
Pollock	13,356,943	$7,546,435	$0.56
White hake	3,702,098	$4,238,620	$1.14
Spotted hake			
Atlantic halibut	41,299	$188,942	$4.57
Summer flounder	3,359,610	$7,813,328	$2.33
Bluefish	1,185,028	$478,128	$0.40
Sea raven	1,311	$952	$0.73
Goosefish	26,136,343	$26,570,574	$1.02
Benthivores			
Smooth dogfish	53,285	$12,418	$0.23
Barndoor skate*			
Little skate*			
Thorny skate*			
Haddock	7,197,943	$11,424,852	$1.59
Red hake	898,376	$338,550	$0.38
American plaice	2,438,887	$4,161,211	$1.71
Yellowtail flounder	4,243,411	$7,050,039	$1.66
Winter flounder	5,273,683	$10,594,263	$2.01
Witch flounder	4,084,646	$8,040,065	$1.97
Longhorn sculpin			
Cunner	911	$769	$0.00
Ocean pout			
Fourspot flounder			
Planktivores			
Atlantic herring	257,500	$28,575	$0.11
Butterfish	665,904	$376,252	$0.57
Acadian redfish	1,096,038	$790,766	$0.72
Northern sandlance			
Atlantic mackerel	99,751,029	$13,527,729	$0.14
Windowpane	137,453	$58,581	$0.43
Loligo squid	25,330,252	$20,006,231	$0.79
Illex squid			
Smooth skate*			
Other			
American lobster	90,837,286	$386,033,933	$4.25
Atlantic sea scallop	40,587,398	$263,622,840	$6.50
Quahogs	4,215,979	$26,811,019	$6.36
*All Skates	33,760,154	$6,542,726	$0.19
Not Included in Guild List	309,282,735	$120,893,828	$0.39
TOTAL	704,258,313	$953,371,617	$1.35

Species within feeding guilds are identified Table 6 in Steele *et al*. (2007)

Table 7
Fish stocks in four scenarios

Foodweb component	P_0	P_1	P_2	P_3	Revenue share
Planktivores	1.00	0.29	1.77	0.91	23.27%
Benthivores	0.21	0.14	0.23	0.46	27.85%
Piscivores	0.28	0.83	0.42	0.40	48.88%
Revenue share weighted sum	0.43	0.51	0.68	0.54	
Change in P from baseline	0.00%	19.88%	60.18%	25.98%	
Adjusted Change in P*	0.00%	3.12%	9.44%	4.07%	

*Harvests from the three guilds account for only 15.68% of the total value of fisheries in New England.

Table 8
Percent changes associated with ecosystem changes (between scenarios 0 to 2) in the New England coastal regional economy (2006 $ millions)

Sector/Commodity	Output	Supply	Imports	Exports	Price
Agriculture	0.09	0.11	0.12	0.08	0.01
Fishing	10.37	6.39	-3.38	17.92	-4.70
Fish Processing	10.05	2.29	-4.38	13.32	-3.31
Manufacturing	0.03	0.04	0.05	0.01	0.01
Other	0.04	0.04	0.05	0.03	0.01

Table 9
Welfare changes (equivalent variations) associated with changes in P from the baseline P_0 **(**2006 $ millions)

Household income categories	P_1	P_2	P_3
< 10K	0.27	0.79	0.35
10-15K	0.59	1.83	0.77
15-25K	1.70	5.31	2.23
25-35K	2.31	7.22	3.03
35-50K	5.04	15.74	6.61
50-75K	9.70	30.36	12.73
75-100K	7.68	24.02	10.08
100-150K	8.58	26.89	11.27
150K+	7.27	22.76	9.54
Total	43.16	134.92	56.61

Fig. 1. Basic components of a CGE model.