ICES Journal of Marine Science Advance Access published March 9, 2011

ICES Journal of Marine Science; doi:10.1093/icesjms/fsr023

A general equilibrium model for Atlantic herring (*Clupea harengus*) with ecosystem considerations

James E. Kirkley[1], John Walden[2]*, and Rolf Färe[3]

[1]*College of William and Mary, School of Marine Science, Gloucester Point, VA 23062, USA*
[2]*Northeast Fisheries Science Center, National Marine Fisheries Service, 166 Water Street, Woods Hole, MA 02543, USA*
[3]*Departments of Economics and Agricultural and Resource Economics, Oregon State University, Corvallis, OR 97331-3612, USA*

**Corresponding Author: tel: +1 508 495 2355; fax: +1 508 495 2054; e-mail: john.walden@noaa.gov.*

Kirkley, J. E., Walden, J., and Färe, R. A general equilibrium model for Atlantic herring (*Clupea harengus*) with ecosystem considerations. – ICES Journal of Marine Science, doi:10.1093/icesjms/fsr023.

Received 18 August 2010; accepted 2 February 2011.

A framework is presented for assessing the economic ramifications of ecosystem-based management decisions, with attention focused on Atlantic herring (*Clupea harengus*) in New England. The Atlantic herring has often been referred to as the most important fish in the northeastern United States because it is a filter-feeder, is believed to improve water quality, and is very important to the health, growth, and abundance of major gamefish, marine mammals, seabirds, and several species of fish. Although many approaches for examining the potential economic ramifications of ecosystem-based management are possible, attention is focused on one method that can be used given existing data. A static, deterministic input/output (I/O) optimization (IOLP, input/output linear programming) model is developed that breaks out the impact of different decisions on herring allocation on the 2006 New England regional economy of Maine, New Hampshire, Massachusetts, and Rhode Island. The IOLP model is a promising approach for informing policy-makers of the economic implications of various allocation choices. The framework is also flexible enough to allow further disaggregation of the small model presented to include additional fishing and non-fishing sectors.

Keywords: allocation, Atlantic herring, input/output models, linear programming.

Introduction

Interest in ecosystem-based management or the ecosystem-based approach to fisheries management has increased rapidly on a global basis, with various nations initiating their own research programme and agenda relative to some semblance of ecosystem management (FAO, 2003). For the most part, the emphasis has been on biological research and better understanding of the physical, natural, and biological linkages. Options for ecosystem-based management have generally emphasized some type of biological and natural conservation or non-use. For example, the Pew Oceans Commission (2002) apparently favours the use of marine reserves as a major management regime. Minimal attention has been given to assessing the social and economic ramifications of ecosystem-based management or even to approaches for managing marine ecosystems.

US management of ecosystems explicitly requires consideration of the social and economic ramifications of management and regulation. Edwards *et al*. (2004) and Finnoff and Tshchirhart (2003) provide perhaps the most comprehensive introduction and discussion on marine ecosystem management and link economics to the underlying ecosystem. On the social side, this means a comprehensive description of various communities, their demographics, and a full description of social and cultural aspects, as well as a comprehensive assessment of the social ramifications of management and regulatory options. On the economic side, US ecosystem management of marine ecosystems requires an assessment of economic impacts and the economic value or net benefits of management and regulatory decisions. In other words, the economic assessment needs to include estimates or an assessment of economic impacts such as changes in sales or output, employment, and income, along with estimates of the economic value or net benefit of each management/regulatory option, i.e. the value to stakeholders of various states of the ecosystem.

There are few studies that integrate economics and an ecosystem-based management system. A notable exception is that of Edwards *et al*. (2004), which provides one of the most comprehensive state-of-the-art frameworks to date of a management scheme for ecosystem-based management. The study by Finnoff and Tshchirhart (2003) generated the most complete framework at the time for examining the economic impacts and the value of ecosystem management designed to protect Steller sea lions (*Eumetopias jubatus*) in the Pacific Northwest. Both these works were cutting edge, but provided little more than either a theoretical introduction to management options or a very limited empirical analysis of the general equilibrium of an economy under extremely restrictive conditions. Neither reported potential economic ramifications for other sectors of the economy, but they do offer starting points or frameworks for developing management and regulatory options while simultaneously considering the social and economic ramifications.

An approach put forward by Jin *et al*. (2003) combined an input/output (I/O) model of a coastal community with a marine foodweb model. That model incorporated an ecosystem matrix into resource multipliers and showed how the multipliers could be calculated. They also linked the New England coastal economy with a marine ecosystem on Georges Bank and showed changes in both coastal communities and ecosystem components that were not being consumed directly by the economy. This was accomplished by constructing resource multipliers to capture the full effects of ecological–economic interactions, and the work also highlighted the importance of developing accurate measures for the key ecological and economic parameters and of conducting further research to develop these key variables.

Here we use a somewhat different approach from that of Jin *et al.* (2003) by developing a static, deterministic I/O optimization (IOLP, input/output linear programming) model for the 2006 New England regional economy of Maine, New Hampshire, Massachusetts, and Rhode Island. Other studies, such as those by Andrews and Rossi (1986), Steinback (1999), Jin *et al.* (2003), and Steinback and Thunberg (2006), used I/O models to examine the economic impacts of marine-related activities in New England, but none linked the models with an LP model. With existing data, an IOLP model can be used to examine alternative allocation schemes for Atlantic herring (*Clupea harengus*) in New England. The model, as noted by Bhattarai (2007), is a general equilibrium type model. Atlantic herring is a species believed to be highly important to the health, growth, and abundance of major gamefish, marine mammals, seabirds, and many other species of fish, e.g. large pelagic fish (Overholtz and Link, 2007). It is also at the centre of a three-way (recreational anglers, environmentalists, industry) debate concerning its importance to the ecosystem—all three groups are taking part in a debate to determine how much herring can be taken by other groups, as well as by themselves. The IOLP allows managers to examine the economic trade-offs that result from various allocation schemes.

After briefly describing the herring stock and its fishery, we describe the IOLP model and provide a description of the data. This is followed with a comparison of outcomes using different scenarios regarding the quantity of herring consumed by each predator group. The scenarios presented are hypothetical, but they do show the power of the IOLP model for examining changes in allocations. Finally, key findings from the models are presented and conclusions drawn.

Atlantic herring

Atlantic herring are distributed widely, from Labrador to Cape Hatteras (Overholtz, 2006). Their potential importance to predators and water quality has been a major issue for environmental and conservation groups. It has been well documented that whales, seabirds, demersal fish, and large pelagic fish all feed on herring, but the exact importance of herring to the diets of these predators is not well known. In addition, there is no evidence linking the abundance or biomass of herring to water quality. Herring larvae feed on zooplankton (Sherman and Perkins, 1971), the primary prey being copepods. Juveniles feed on up to 15 different groups of zooplankton, and adults feed mainly on euphausids, chaetognaths, and copepods. Herring are harvested and processed for sardine, steaks and tidbits, and bait, which is widely used in the commercial fishery for American lobster (*Homarus americanus*). The most recent stock assessment indicates that the stock is at a healthy level and overfishing is not occurring (Transboundary Resources Assessment Committee, 2009). The species is harvested commercially in all states between Maine and North Carolina. Maine has traditionally yielded the most, 2.18 million tonnes between 1950 and 2007, with Massachusetts ranked second with 771 000 t over the same period. Delaware had the lowest level of reported landings between 1950 and 2007; 20 t for the entire period.

Herring are harvested primarily by trawls, purse-seines, weirs, and stop-seines. Historically, weirs and stop-seines were the main gear, but purse-seines and midwater trawls now yield most of the herring. Total landings of Atlantic herring have varied widely over time (Figure 1). They were very high during the 1950s, then declined dramatically during the late 1960s and early 1970s. After a sharp upward spike in landings during the early 1980s, the landings declined dramatically again, but then increased gradually to levels not seen since the 1950s in the years 2000–2008. Unfortunately, though, the inflation-adjusted value generally declined since the 1950s (Figure 1). Although it has increased since the low values of the mid-1980s, the total inflation-adjusted value has not regained the high level seen in the late 1950s.

The domestic fishery for Atlantic herring is managed by individual states under the purview of the Atlantic States Marine Fisheries Commission in state waters and by the New England Fishery Management Council in the Exclusive Economic Zone. State regulations vary by state, but typically involve gear restrictions, seasons, and limits or quotas. At the extreme, Connecticut prohibits all commercial fishing and landings of herring, and New York has no regulations. In 2009, US management had an allocatable biological catch of 194 000 t, and an optimum yield (OY) of 145 000 t.

The IOLP model

An I/O model represents a national or regional economy in matrix form and allows one to predict how changes in one industry, or sector, influence other sectors of the economy. The IOLP model utilizes coefficients from an I/O model in an LP model and calculates changes in economic activity such as employment and income. Although this type of model may appear to be recent, it actually has a long history, dating back to the early 1970s (Penn *et al.*, 1976), who demonstrated that the multipliers derived from the standard I/O analyses generally overstated the impacts of economic losses. A multiplier determines how much $1 of additional spending in a sector generates in economic activity through the whole economy. For example, a multiplier of 1.07 means that $1 in additional expenditure generates $1.07 in total economic activity. A standard I/O multiplier of 2.0 for a reduction of $1.0 million in output in sales would overstate the losses; the actual losses would be <$2.0 million. Penn *et al.* (1976) provide a comprehensive overview of assessing impacts incorporating an I/O model into an LP model with primary input constraints.

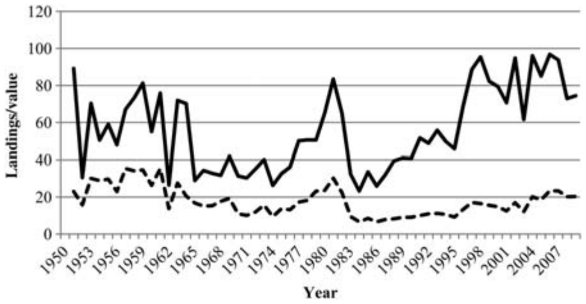

Figure 1. Landings (line) and value (at $ value for 2008; dashed line) of Atlantic herring, 1950–2008.

More recent work by Zhu *et al.* (2009) provides an illustration of the methodology using data for the US economy.

The objective of an IOLP model is to maximize the total output of a stated economy subject to constraints on total possible demand for each sector's production in the economy. In mathematical terms, the model is as follows (Penn *et al.*, 1976):

$$\max_{X} \quad i'X$$
$$\text{subject to} \quad \begin{array}{c} (I - A)X \leq Y \\ X \geq 0, \end{array}$$

where i is a vector of ones, I an identity matrix,$'$ is the transpose operator, X the output vector, Y the final demand vector, and A the direct requirement matrix. The A matrix consists of a_{ij} elements and is calculated as $a_{ij} = x_{ij}/x_j$, where x_{ij} the transaction between sectors i and j, and x_j is the jth sectoral output.

Here, that IOLP framework is adopted and modified to reflect the economy of four New England states (Maine, New Hampshire, Massachusetts, and Rhode Island). We use aggregated sectors, which consist of 20 two-digit North American Industry Classification System (NAICS) sectors, and a separate sector for herring and non-herring fisheries, for a total of 22 sectors, and 2006 as our baseline year. The total output of the four-state New England regional economy is represented by gross revenue generated by aggregate production in the region and equalled \$877.77 billion (US billion = 1 × 10^9). Total employment was 6.3 million, and total income was \$492.6 billion. These impacts were estimated with IMPLAN, an available off-the-shelf I/O software package (IMPLAN, 2006).

The base model was then modified by including constraints on the availability of herring for harvest by the fishing sector, and additional constraints were added to account for the dietary needs of predators. The modified New England model is

$$\max_{Q} \; TV = \sum_{i=1}^{22} Q_i \tag{1}$$

subject to:

$$Q_i = P_i X_i, \tag{2}$$

$$\sum_{i=1}^{22} A_{ij} Q_i \leq \mathrm{FD}_j, \tag{3}$$

$$C_s \geq \sum_{s=1}^{4} D_s B_s, \tag{4}$$

$$X_\mathrm{h} + C_s \leq 0.5\ \mathrm{HB}, \tag{5}$$

where Q_i is the 2006 dollar value of output of each sector, P_i the price of goods produced by each sector i, X_i the total output from sector i, h denotes herring, A_{ij} the input coefficients for sectors i and j, FD_j the final demand for output from sector j, C_s the quantity of herring consumed by predator species s, D_s the dietary requirements in terms of pounds of herring per unit biomass for predator species s, HB the herring biomass, and B_s the biomass of predator species s.

The model maximizes the value of total output from 22 (20 non-fishing and 2 fishing) sectors. It assumes a linear relationship between input use and outputs. Equation (2) is an identity that says that the value from each sector is equal to the price of goods produced by the sector times the output from each sector. Equation (3) states that the value of output from each sector (industry) does not exceed the use of that output in final demand (Zhu *et al.*, 2009). Equation (4) returns the dietary requirements of predator species, and Equation (5) states that the quantity of herring harvested by the herring sector plus the herring consumed by predators cannot exceed one-half the herring biomass. An increase (decrease) in X_h increases (decreases) Q for the herring sector in Equation (2) and the objective function [Equation (1)]. Note that the one-half of biomass limit [Equation (5)] is imposed arbitrarily; the limit could be set at any amount up to 100% of biomass.

Predator information was obtained from Jason Link and Bill Overholtz (Northeast Fisheries Science Center, Woods Hole, MA, USA). They provided biomass data for five broad groups, herring, marine mammals, large pelagic fish, seabirds, and demersal species (Figure 2). Consumption data were provided on the four predator groups marine mammals, large pelagic fish, seabirds, and demersal species (Figure 3). Data covered the period 1977 through 2001 and were the most recent available when the study was carried out. We used an average predation rate for the whole period, which could be changed to be more representative of the current period. This was a first-order pass at the problem, and changing predation rates could certainly be included in sensitivity analyses.

An initial baseline run was accomplished to replicate the *status quo* output levels using output and final demand levels for 2006, the most recent year for which data were available when the research began. Landings and average prices for all other species and herring for calendar year 2006 were used, and a price of one for the output from non-fishing sectors [the total output X for the non-fishing sectors in Equation (2) is measured in value terms]. This baseline scenario replicates the *status quo* in that estimated output, employment, and income levels equal the reported values obtained from IMPLAN (Table 1). Biomass and consumption constraints [Equations (4) and (5)] for predators and herring were not included in this baseline run; we merely tried to replicate the 2006 output, employment, and income levels that were returned from IMPLAN. Subsequent model runs then incorporated 1977–2001 average predator biomass and consumption

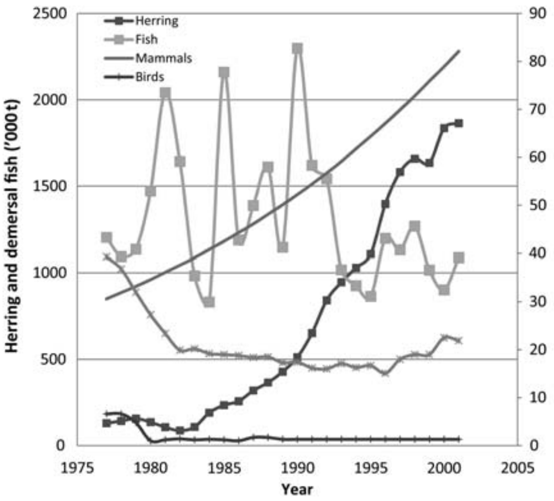

Figure 2. Estimated biomass of herring and herring predators in the Northwest Atlantic, 1977–2001.

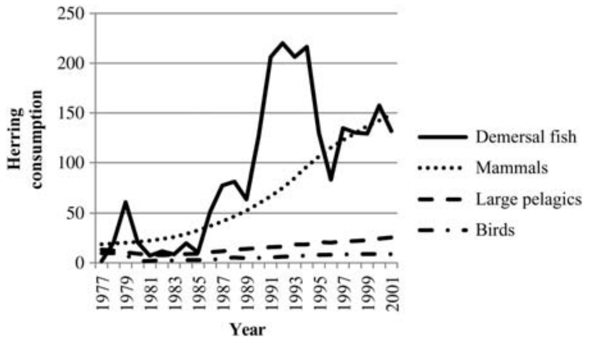

Figure 3. Estimated consumption ('000 t) of Atlantic herring by four predator groups, 1977–2001.

Table 1. Output, employment, and income for two-digit sectors and the fishing sector of Maine, New Hampshire, Massachusetts, and Rhode Island in 2006 (US billion $= 1 \times 10^9$).

Sector	Output ($, billions)	Employment ('000)	Income ($, billions)
Agriculture, forestry, and hunting	4.20	41.20	1.59
Fishing: non-herring	0.83	20.65	0.35
Fishing: herring	0.02	0.49	0.01
Mining	0.77	3.69	0.40
Utilities	10.92	16.65	7.58
Construction	45.94	367.23	22.04
Manufacturing	186.37	500.55	55.12
Wholesale trade	46.71	221.25	31.50
Transportation and warehousing	19.78	187.60	10.79
Retail trade	51.14	688.78	34.01
Information	42.78	139.24	21.58
Finance and insurance	80.20	331.81	49.06
Real estate and rental	47.70	226.91	31.80
Professional, scientific, and technical services	72.87	527.70	44.11
Management of companies	18.59	85.03	11.51
Administrative and waste services	22.65	330.07	13.94
Educational services	17.21	278.67	10.58
Health and social services	72.83	805.25	44.77
Arts, entertainment, and recreation	7.05	146.11	4.18
Accommodation and food services	25.02	418.43	13.26
Other services	19.12	315.76	10.20
Government and non-NAICs	85.05	657.37	74.26
Total	877.8	6 310.5	492.6

data. The quantity of herring that had to be left in the ocean (end herring biomass) could be changed by altering the right side of Equation (5).

The IOLP model facilitates a wide range of analyses. For example, output prices for herring can be changed and the impacts on the regional economy assessed. Similarly, predator consumption on a per biomass (pounds) basis can be changed and the corresponding economic impacts assessed. Changes in final demand and production costs can also be examined. Finally, the herring biomass can be reduced to examine the impacts on the regional economy.

As might be expected, the framework has some limitations. One major one is that there is no way to determine real herring production by the fishery simultaneously as predator populations change; only the regulatory body can ensure that the predators are initially allocated sufficient resources for their predation. In simple terms, there is no way to determine who first consumes the resource, predators or the commercial fishery. All that can be shown are the economic ramifications of alternative consumption and commercial production levels. The model is deterministic and static; no rigorous dynamics or random noise is included, though that could be done in future work.

Three management scenarios were considered to demonstrate the application of the IOLP framework. These were not meant to reflect current management strategies, but rather to examine potential trade-offs from different allocations of herring between predator groups and commercial herring fisheries. To explore the implications of allocating the herring resource to the commercial harvesting sector or as prey for other species in an ecosystem setting, possible regulatory requirements were considered in which the predators were initially allocated herring. Under the first scenario, the population of marine mammals triples, and more herring is consumed by marine mammals. In the second scenario, the population of demersal and pelagic species is doubled, leading to a doubling of their landings, and greater consumption of herring by those two predator groups. The third scenario allocates herring for predator consumption and reserves a certain stock size for the following year until the commercial fishery is forced to a zero harvest. In other words, we accounted for predator consumption first, then incrementally increased the herring left for succeeding years until commercial herring landings were reduced to zero. Note that under all these scenarios, sufficient herring was always reserved for predator demand. An alternative outcome would have the commercial fishery harvesting the herring first, and predator populations declining.

Results

Before examining the three scenarios, the *status quo* was replicated first using the IOLP framework to determine whether the model was correctly calibrated. This resulted in a total output for the four-state (Maine, Massachusetts, Rhode Island, and New Hampshire) New England economy of $877.8 billion in 2006, which was the correct output level (Table 1). It also correctly generated employment of 6.3 million persons (full- and part-time jobs). Examination of the individual sectors showed that the manufacturing sector dominated all others in terms of output generated. The health and social services sector, with a much smaller level of output, generated the most jobs.

Scenario 1: tripling the biomass of marine mammals

Under this scenario, the biomass of marine mammals triples from 52 400 to 157 200 t. Marine mammals are assumed to remove their required level of herring from the resource, and no other changes are made. Initial conditions for the other species assumed a herring resource of 709 000 t; demersal fish biomass was ~1 310 400 t; marine mammal biomass was ~52 400 t; large pelagic fish biomass was 21 000 t; and biomass of seabirds was 1900 t.

The solution returned, given the initial conditions, was equal to the *status quo* solution. This means that tripling the marine mammal population, without a resource balance constraint, does not limit the commercial herring fishery. The predicted end biomass for herring was 433 500 t, which is below the 2009 US/Canadian stock biomass corresponding to maximum sustainable yield. It is not until the initial population of marine mammals is increased by a factor of 8 or more, with no end resource requirement, that landings by the commercial fishery decline. Increasing the population of marine mammals by a factor of 9, holding individual predator consumption constant, resulted in a decline in the total output to $878 billion and a decrease in output for the economy of $18 million. When we add the constraint that the end population of herring must be $\geq$50% of the initial biomass of herring, and triple the population of marine mammals, total economic output declines by $16.47 million, employment declines by 281.2 persons, and income drops by $7.31 million (Table 2).

Scenario 2: doubling the population of demersal and pelagic fish predators

The demersal and large pelagic fish populations were next allowed to double in biomass—from 1 331 400 to 2 662 800 t. The *status quo* or baseline landings of the demersal and large pelagic species equalled 33.4 t. If landings also doubled, they would equal 66.8 t. Retaining our end constraint of 50% of the initial level of the herring resource with the subsequent increase in landings yields an economic gain of $148.9 million to the economy and 2557 jobs, and an income gain of $66.34 million (Table 3). The non-herring portion of the fishery increased by $93.98 million, with an increase of 2335 jobs, and the commercial herring fishery experienced a decline in total output of $6.94 million, employment of 172 persons, and income of $2.92 million. Without the end balance constraint, doubling the population of demersal and large pelagic fish species, along with a subsequent doubling of their landings, increased output by $160.61 million, employment by 2760 jobs, and income by $71.56 million. The end herring resource declines by 54.3%. Therefore, for an additional 4.3% of herring biomass, output increased by $11.71 million, employment by 203, and income by $5.22 million.

Table 2. Changes in economic activity given a tripling in the marine mammal population and an end resource constraint equal to 50.0 % of the initial resource.

Sector	Output ($, millions)	Employment (individuals)	Income ($, millions)
Agriculture, forestry, and hunting	− 0.71	− 6.96	− 0.27
Fishing: non-herring	0.00	0.00	0.00
Fishing: herring	− 9.38	− 232.96	− 3.94
Mining	− 0.01	− 0.04	0.00
Utilities	− 0.03	− 0.05	− 0.02
Construction	− 1.10	− 8.79	− 0.53
Manufacturing	− 2.10	− 5.64	− 0.62
Wholesale trade	− 0.75	− 3.55	− 0.51
Transportation and warehousing	− 0.85	− 8.06	− 0.46
Retail trade	− 0.10	− 1.35	− 0.07
Information	− 0.05	− 0.16	− 0.03
Finance and insurance	− 0.29	− 1.20	− 0.18
Real estate and rental	− 0.17	− 0.81	− 0.11
Professional, scientific, and technical services	− 0.32	− 2.32	− 0.19
Management of companies	− 0.08	− 0.37	− 0.05
Administrative and waste services	− 0.13	− 1.89	− 0.08
Educational services	0.00	0.00	0.00
Health and social services	0.00	0.00	0.00
Arts, entertainment, and recreation	− 0.26	− 5.35	− 0.15
Accommodation and food services	− 0.03	− 0.50	− 0.02
Other services	− 0.04	− 0.66	− 0.02
Government and non-NAICS	− 0.07	− 0.54	− 0.06
Total	− 16.47	− 281.2	− 7.31

Scenario 3: satisfying predator demand and end resource constraint

In this scenario, we consider satisfying predator demand and determining the end resource constraints for which the commercial fishery would have zero catch. In other words, the percentage of the initial resource level at which minimal predator consumption would be satisfied but the fishery would be closed was determined. This was done by iteratively increasing the percentage of the initial herring biomass that would be saved for the next period to the point where herring landings would be zero.

The outcome of this process showed that with an end resource level equal to 73.3% of the initial resource level, the herring fishery would close. At that level, the change in output for the herring

Table 3. Changes in economic activity with a doubling of demersal and pelagic fish population and landings, and end herring resource constraint equal to 50.0% of initial resource.

Sector	Output ($, millions)	Employment (individuals)	Income ($, millions)
Agriculture, forestry, and hunting	1.18	11.57	0.45
Fishing: non-herring	93.98	2 335.09	39.51
Fishing: herring	− 6.94	− 172.44	− 2.92
Mining	0.07	0.33	0.04
Utilities	0.32	0.49	0.22
Construction	10.19	81.45	4.89
Manufacturing	20.56	55.22	6.08
Wholesale trade	7.05	33.39	4.75
Transportation and warehousing	7.86	74.53	4.29
Retail trade	0.32	4.31	0.21
Information	1.06	3.45	0.53
Finance and insurance	2.73	11.29	1.67
Real estate and rental	1.72	8.18	1.15
Professional, scientific, and technical services	3.03	21.94	1.83
Management of companies	0.74	3.38	0.46
Administrative and waste services	1.19	17.34	0.73
Educational services	0.04	0.65	0.02
Health and social services	0.00	0.00	0.00
Arts, entertainment, and recreation	2.40	49.74	1.42
Accommodation and food services	0.34	5.69	0.18
Other services	0.32	5.28	0.17
Government and non-NAICS	0.74	5.72	0.65
Total	148.90	2 556.62	66.34

fishery declined by $19.78 million, the total output of the industry, employment in the fishery would drop by 491.4 persons, and income would fall by $8.43 million (Table 4). The overall reduction in total output of the entire economy would equal $34.04 million, employment would decline by 586, and income by $15.2 million.

Conclusions

Herring has been referred to as the most important fish in New England. Historically, its fishery was extremely important commercially in the state of Maine, and once supported many canneries along the Maine coast. The importance of the resource, however, extends well beyond its direct contribution to the economy. Herring are forage for a large group of predators, which include marine mammals, demersal fish, large pelagic fish, and seabirds. As the US moves towards ecosystem management, the role of forage fish has become of increasing importance.

A critical issue facing resource managers is finding the right balance between necessary levels of the resource to support predator demand, the commercial fishery, and other user groups, such as aquaculture firms that require herring as food, or lobster fleets that use herring as bait. Additionally, there may be an existence value for herring where the public values herring as part of the overall ecosystem. Determining the optimum balance would be accomplished preferably via a benefit–cost analysis (BCA) and a very complex ecosystem model. For the herring resource, however, the data to support a rigorous BCA are not available, and information to construct a rigorous ecosystem model, with all its linkages, is unavailable.

Table 4. Changes in economic activity with an end herring resource constraint that yields no herring fishery.

Sector	Output ($, millions)	Employment (individuals)	Income ($, millions)
Agriculture, forestry, and hunting	−0.73	−7.17	−0.28
Fishing: non-herring	0.00	0.00	0.00
Fishing: herring	−19.78	−491.41	−8.32
Mining	−0.02	−0.07	−0.01
Utilities	−0.07	−0.11	−0.05
Construction	−2.32	−18.54	−1.11
Manufacturing	−4.50	−12.09	−1.33
Wholesale trade	−1.59	−7.53	−1.07
Transportation and warehousing	−1.78	−16.88	−0.97
Retail trade	−0.21	−2.83	−0.14
Information	−0.10	−0.33	−0.05
Finance and insurance	−0.61	−2.52	−0.37
Real estate and rental	−0.37	−1.76	−0.25
Professional, scientific, and technical services	−0.67	−4.85	−0.41
Management of companies	−0.17	−0.78	−0.11
Administrative and waste services	−0.27	−3.93	−0.17
Educational services	−0.01	−0.16	−0.01
Health and social services	0.00	0.00	0.00
Arts, entertainment, and recreation	−0.54	−11.27	−0.32
Accommodation and food services	−0.07	−1.17	−0.04
Other services	−0.07	−1.16	−0.04
Government and non-NAICS	−0.16	−1.24	−0.14
Total	−34.04	−585.80	−15.16

Given the need to understand better the economic ramifications of choices between satisfying predator demands and the needs of the commercial fishery, an IOLP model was developed to ascertain the economic impacts of alternative predator demands and commercial needs. The IOLP framework allowed the impacts on all sectors (two-digit NAICS) of a four-state New England economy to be identified and assessed using 2006 economic data. Four scenarios of alternative allocations of herring were examined. For all four, the economic impacts, in terms of sales, output, and income, did not appear to be overly large when compared with the regional economy. The greatest decline in output was under scenario 3, where herring landings were forced to zero, resulting in a loss of $34 million, 586 jobs, and $15.2 million in income. This loss in output is <1% of the economic output of the four-state region. Economic output increased by $148.9 million, employment by 2557 jobs, and income by $66.3 million when demersal and pelagic catches doubled following a doubling of demersal and pelagic fish biomass levels. Again, this is a <1% gain in total economic output from the four-state region.

The framework presented here offers a useful analytical tool for assessing the economic ramifications of ecosystem-based management strategies, particularly relative to predator–prey issues. It is generally recognized by economists that decisions regarding allocation of public trust resources such as fisheries need to address economic values, i.e. individuals' willingness to pay for the benefits from the resource. However, managers are also concerned about economic impacts that provide information about income and employment generated by the industries that utilize the resource, particularly at a community level. The current framework permits a wide range of assessments to be conducted, e.g.the economic impacts of (i) changes in herring resource level, (ii) changes in the populations of predators, (iii) changes in the consumption of prey by individual predators, (iv) potential changes in specified total allowable catch or OY, (v) changes in allowable landings of herring, (vi) changes in final demand, (vii) changes in production costs, and (viii) changes in output prices.

Unfortunately, there are also serious limitations of the analytical framework. First, and perhaps most important, is that the frame work is static and deterministic, which implies an absence of dynamic concerns as well as realizing that the system may have a lot of noise or random variation. Another major concern is the absence of linkages between the predators and the herring resource, i.e. we do not address how the population of predators might change if the biomass of herring changes or how the biomass of herring might change over time as the populations of predators vary. And, of course, the emphasis was on economic impact and not economic value, which should be assessed for informed management and regulation. A third concern is the need to update the analytical framework when new versions of IMPLAN are available.

Despite its limitations, the framework can provide a useful tool for management by accommodating a wide range of "what if" scenarios. More important, however, is that several model improvements are possible. Consumer and producer surplus can be added to the model for the commercial sector. Benefit transfer or meta-analysis might be used to assess economic values for the predator groups. The model can be decomposed to reflect more detailed sectors of the economy (e.g. three-digit NAICS sectors). Utilizing EMAX (Energy Modelling and Analysis eXercise), it might be possible too to provide a more-detailed ecosystem framework and useful information about the underlying population dynamics and resource linkages. Finally, development at a state level can be done to provide more information about the economic impacts relative to each state.

Acknowledgements

We thank Rita Curtis, Jonathan Deroba, Chang Seung, Scott Steinback, Jason Link, Bill Overholtz, two anonymous reviewers, and the editor for helpful comments and suggestions. The research was funded by the National Marine Fisheries Service, Office of Science and Technology. Any errors or omissions are solely the responsibility of the authors; the views expressed are the authors' and do not represent those of the College of William and Mary, the National Marine Fisheries Service, or Oregon State University.

References

Andrews, M., and Rossi, D. 1986. The economic impact of commercial fisheries and marine-related activities: a critical review of northeastern input–output studies. Coastal Zone Management Journal, 13: 335–367.

Bhattarai, K. 2007. Input–output analysis using linear programming. Advanced Economic Theory 2007, Lecture 6, 5 March 2007. Business School, University of Hull, UK. http://www.hull.ac.uk/php/ecskrb/AET/Linear_programming%20and%20Input_output.pdf (last accessed 10 June 2010).

Edwards, S. F., Link, J. S., and Rountree, B. P. 2004. Portfolio management of wild fish stocks. Ecological Economics, 49: 317–329.

FAO. 2003. Fisheries Management. 2. The Ecosystem Approach to Fisheries. FAO Technical Guidelines for Responsible Fisheries, 4(Suppl. 2). 112 pp.

Finnoff, D., and Tshchirhart, J. 2003. Harvesting in an eight-species ecosystem. Journal of Environmental Economics and Management, 45: 589–611.

IMPLAN. 2006. Minnesota IMPLAN Group Incorporated. Stillwater, Minnesota.

Jin, D., Hoagland, P., and Dalton, T. M. 2003. Linking economic and ecological models for a marine ecosystem. Ecological Economics, 46: 367–385.

Overholtz, W. 2006. Atlantic herring. Status of the fishery resources off the Northeastern US. http://www.nefsc.noaa.gov/sos/spsyn/pp/herring/ (last accessed 10 June 2010).

Overholtz, W. J., and Link, J. S. 2007. Consumption impacts by marine mammals, fish, and seabirds on the Gulf of Maine–Georges Bank Atlantic herring (*Clupea harengus*) complex during the years 1977–2002. ICES Journal of Marine Science, 64: 83–96.

Penn, J. B., McCarl, B. A., Brink, L., and Irwin, G. D. 1976. Modeling and simulation of the US economy with alternative energy availabilities. American Journal of Agricultural Economics, 58: 663–671.

Pew Oceans Commission. 2002. Marine reserves: a tool for ecosystem management and conservation. Pew Oceans Commission, Arlington, VA. http://www.pewtrusts.org (last accessed 10 June 2010).

Sherman, K., and Perkins, H. C. 1971. Seasonal variation in the food of juvenile herring in coastal waters of Maine. Transactions of the American Fisheries Society, 100: 121–124.

Steinback, S. R. 1999. Regional economic impact assessments of recreational fisheries: an application of IMPLAN modeling system to marine party and charter boat fishing in Maine. North American Journal of Fisheries Management, 19: 724–736.

Steinback, S. R., and Thunberg, E. M. 2006. Northeast region commercial fishing input–output model. NOAA Technical Memorandum, NMFS-NE-188.

Transboundary Resources Assessment Committee. 2009. 2009 Stock Assessment, Atlantic Sea Herring. Atlantic States Marine Fisheries Commission, TRAC Status Report, 2009/04. http://www2.mar.dfo-mpo.gc.ca/science/TRAC/rd.html (last accessed 10 June 2010).

Zhu, E., Kim, M., and Harris, T. R. 2009. Input–output analysis, linear programming and modified multipliers. Paper presented at the Southern Agricultural Economics Association Meeting, Atlanta, GA, 31 January–3 February 2009. http://purl.umn.edu/46716 (last accessed 24 June 2009).