Ecosystem Considerations and the Limitations of Ecosystem Models in Fisheries Management: Insights from the Bering Sea

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Abstract

Over the past 10 years there has been increasing criticism of management decisions that are based on single-species approaches and a call for the implementation of ecosystem approaches. The major criticism of single-species models is that they cannot predict changes in community structure. Unfortunately, our experience in modeling the Bering Sea shows that these same criticisms can also be leveled against ecosystem models.

We employed trophic mass-balance models (Ecopath and Ecosim) to examine some possible explanations for the changes that occurred in the Bering Sea between the 1950s and 1980s. We removed fish and mammals

from the modeled system and tracked how other components of the ecosystem responded. Our mass-balance models indicate that neither whaling nor commercial fisheries were sufficient to explain the 400% increase in pollock biomass and other changes that may have occurred between the two time periods. The simulations further suggest that environmental factors, affecting recruitment or primary production, may be more important in determining the dynamics of the Bering Sea ecosystem than predator-prey interactions alone. These findings illustrate that mass balance models that do not account for the impact of climate variability on year-class strength cannot provide reliable estimates of trends in marine fish production. However, our models can show how predation and fishing can affect trophic interactions among species. As such, ecosystem models are a useful scientific tool to identify gaps in understanding and data needs, but are unlikely to ever replace single-species models. They may instead complement and provide parameters to single-species models. Ecosystem models such as ours are still in the early stages of development and will become increasingly more important as a management tool as they begin to incorporate spatial and oceanographic/climatic information.

Introduction

The Magnuson-Stevens Fishery Conservation and Management Act (1996) is the basis of fisheries management in U.S. jurisdictional waters. It maintains that fisheries are to be conserved and maintained to protect the marine ecosystem and to ensure the greatest overall benefit. It further encourages the application of ecosystem principles in fishery conservation and management.

To date, fisheries have not had good tools for understanding how fishing for one species will affect other components of the ecosystem. Fisheries scientists and managers are not yet able to replace single-species approaches with multispecies ecosystem approaches that can reliably predict shifts in species composition, abundance, and productivity. This is changing, however, as people begin to pool their collective knowledge into multispecies and ecosystem models. A number of models have recently been constructed for marine ecosystems around the world (e.g., see contributions in Christensen and Pauly 1993, Pauly and Christensen 1996), and their numbers keep increasing (see http://www.ecopath.org). However, ecosystem modeling is still in its infancy, leaving it unclear to what extent such models can guide ecosystem-based management.

A fundamental question for fisheries concerns how ecosystem models can be used to guide management decisions. Ecosystem models provide information on trophic linkages in a system and have the potential to show how fishing on one species might have unintended effects on other species in a system. Such models were applied to various regions of the North Pacific more than 20 years ago (Laevastu and Larkins 1981, Laevastu

et al. 1982). However, in order to make progress in marine ecosystem management, scientists need to consider more fully how to sufficiently validate these models and communicate the results to managers in a meaningful way that can guide management decisions. This is the challenge we face in our attempt to model the large-scale changes that occurred in the eastern Bering Sea between the 1950s and 1980s.

An Ecosystem Model of the Eastern Bering Sea

We constructed an ecosystem model of the eastern Bering Sea using the Ecopath and Ecosim approach. Ecopath is a software package that describes an ecosystem at steady state using a mass-balance approach (Christensen and Pauly 1992, 1995). It is a relatively simple, but powerful method to model the biomass and fluxes of an ecosystem, and gain some insights into the relationships of the various species in the ecosystem. Ecosim can be applied to the Ecopath files, turning them into fully parameterized simulation models (Walters et al. 1997).

The area we delineated in the eastern Bering Sea encompasses the region covered by the Alaska Fisheries Science Center's bottom trawl surveys of the shelf and slope down to 500 m (Fig. 1). It included a wide range of marine habitats but was treated as a single homogenous area. (A spatially explicit model is being developed using Ecospace software.) Nearshore fauna and the northern portion of the Bering Sea were not considered. We constructed two models: one for the 1950s before large-scale commercial fisheries were under way, and another for the 1980s after many marine mammal populations had declined. Both were annual average models, which means that the biomass and species composition of summer and winter were averaged to provide a year-round annual average.

The main motivation for developing these models was to test the commercial whaling cascade hypothesis (i.e., that pelagic whaling in the eastern Bering Sea in the 1960s set up a chain of events that released prey, reduced predation, and increased the Bering Sea's walleye pollock carrying capacity; Merrick 1995, NRC 1996). How the ecosystem differed between the pre-whaling and post-whaling periods, and how the effects of fishing and whaling altered the dynamics of the Bering Sea were among the questions we posed. We also used the model to consider how changing current fishing quotas for pollock might alter the dynamics of other species in the ecosystem.

A complete description of the model and parameters used is contained in Trites et al. (In press). We split the hundreds of species that make up the Bering Sea ecosystem into 25 groups (Fig. 2). Information gathered from published sources included the numbers or biomass of each group of species living in the Bering Sea; their diets, rates of consumption, and production. The two primary data sources for groundfish biomass estimates were surveys or stock assessments conducted by the Soviet Union during the 1950s and the United States National Marine Fisheries Service
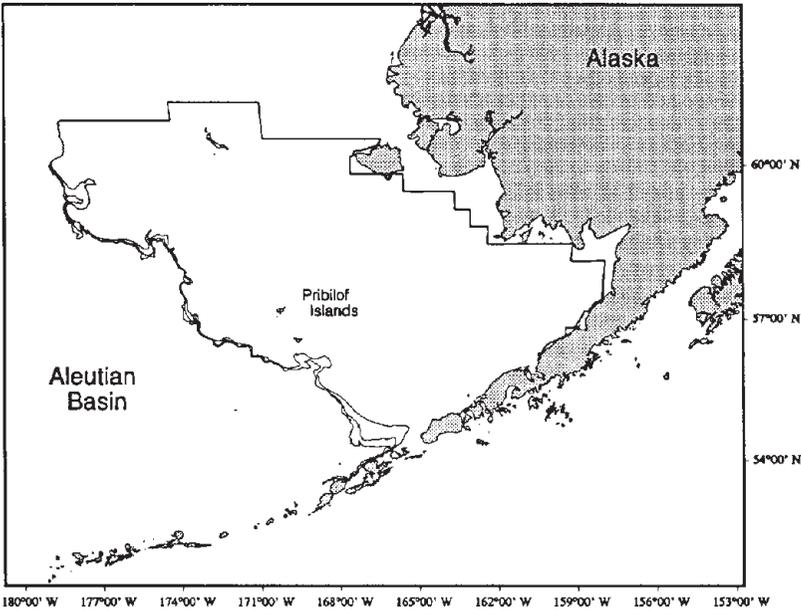
Figure 1.   *The eastern Bering Sea as defined in the ecosystem model. Total area is approximately 500,000 km².*

(NMFS) during the 1980s. Population estimates for marine mammals came from Perez (1990), the NRC (1996) report, and the 1987-1988 Marine Mammal Protection Act annual report (NMFS 1988). Estimates for other species were drawn largely from stock assessments performed by NMFS scientists. Diet data for groundfish come primarily from the groundfish food habits database of NMFS while diet data for marine mammals come primarily from the 1996 NRC report and references therein. Several assumptions were made with respect to the 1950s model. For groups that had no abundance information from that time period, we assumed they had the same biomass as the 1980s period. We also made assumptions about the diet compositions of animals during that time period, particularly assuming that pelagic fish (herring, capelin, and others) were a more important prey than pollock in the 1950s.

The biomass estimates that we input to our mass-balance ecosystem models reflected our assumptions that most of the top predators (trophic level IV) declined from the 1950s to the 1980s (Fig. 3). They included Steller sea lions, seals, sperm whales, deepwater fishes, and other demersal fishes. The only top predators that were assumed to increase were large flatfish such as arrowtooth flounders. At the mid-trophic level (III), baleen whales and pelagic fishes were assumed to decline while small
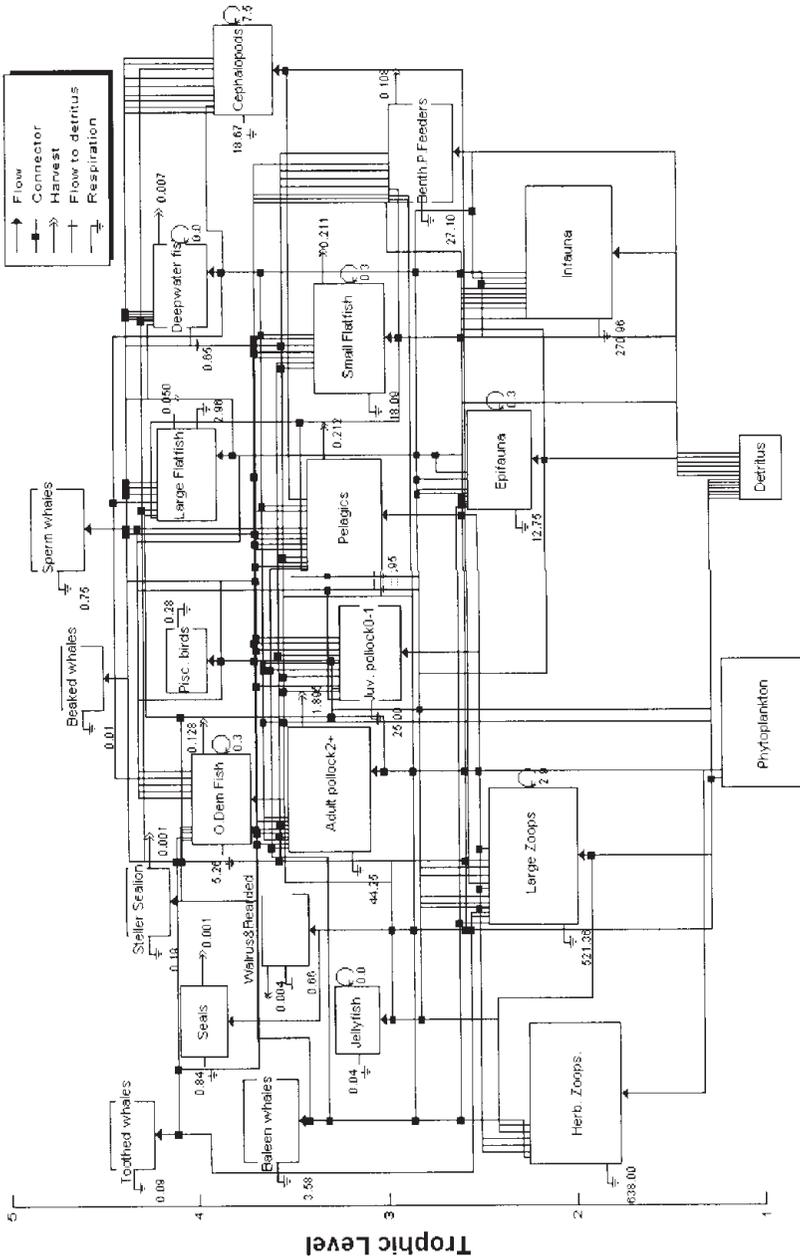
Figure 2. Flow chart of trophic interactions in the eastern Bering Sea during the 1980s. All flows are in t per km² per year. Minor flows are omitted as are all backflows to the detritus.

flatfish, pollock, and walrus and bearded seals were assumed to have increased.

Pollock contributed over 50% of the total flow of energy through trophic level III during the 1980s compared to only 10% during the 1950s. In contrast, pelagic fishes contributed nearly 50% of the flow in the 1950s. At trophic level IV, no one species dominated the flow of energy during the 1950s. However, during the 1980s, large flatfish contributed over 60% of the total energy flow. Large flatfish and adult pollock that dominated the Bering Sea in the 1980s appear to be significant competitors of seals and sea lions. There are also significant overlaps in the diets of pollock and baleen whales.

Our dynamic simulation showed that removing whales from the 1950s model ecosystem had a positive effect on pollock, by reducing competition for food. However, whaling alone was insufficient to explain the 400% increase in pollock biomass that may have occurred between the 1950s and 1980s. Nor could commercial fisheries alone account for the observed changes. The magnitude of changes that occurred in the biomass of all the major groups in the eastern Bering Sea cannot be explained solely through trophic interactions and fishing removals. This suggests a need to examine our assumptions about the state of the Bering Sea in the 1950s, particularly with regard to pollock abundance.

We used our models to test various hypotheses about the effects of whaling, fishing and regime shifts on the Bering Sea (Trites et al., In press). Our models suggest that factors comprising a regime shift may have been at play in altering the Bering Sea between the 1950s and 1980s states, and may have been more important in affecting this northern ecosystem than trophic interactions and fishing removals. Important factors comprising the regime shift could be changes in temperature and/or current patterns that have differential effects on early life history survival of various species. In addition, our assumptions about low pollock abundance and the low importance of pollock in the diet of certain animals in the 1950s may be inaccurate. Shuntov (1972) reported that during the Soviet fishery investigations in the eastern Bering Sea from 1957 to 1964, walleye pollock was one of the most common Bering Sea fishes and was a staple food of large flatfish as well as other fishes.

Our conclusions about the causative factors influencing the shifts in the Bering Sea ecosystem are in contrast to those for the Gulf of Thailand ecosystem. Christensen (1998) found that fishing rates alone could move this tropical ecosystem from one state to another (1960s-1980s: before and after the development of trawl fisheries). Future work to improve the Bering Sea 1950s model should include testing the possibility of a higher dominance of pollock than we assumed.

We examined three pollock fishing scenarios to explore how the Bering Sea ecosystem might be changed from its 1980s state. We considered the effects of reducing the biomass of adult pollock by 50%. We also considered what might happen if pollock were overfished to the point that all
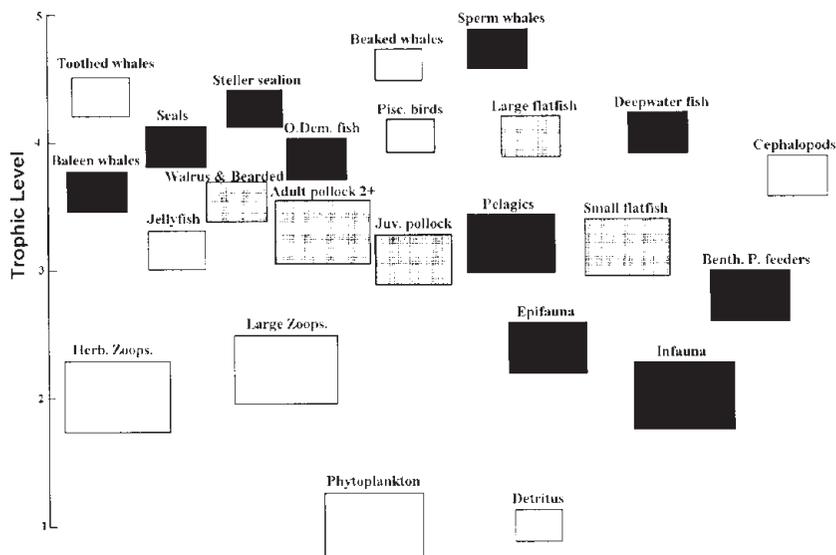
Figure 3. *Trophic levels and relative abundance of species in the eastern Bering Sea during the 1980s. Black boxes indicate groups that had lower estimated abundance in the 1980s than in the 1950s, and shaded boxes show species with higher estimated biomass in the 1980s than in the 1950s. Major flows of energy between the boxes are shown in Fig. 2.*

the juvenile and adult pollock were removed. Obviously, these two scenarios are hypothetical and do not reflect fishing policies that would be considered under the present fishery management regime. Finally, we considered how the Bering Sea ecosystem might look if pollock were not caught at all. All simulations were run over 30 years.

Our model suggests that increased fishing pressure on pollock has only a small effect on the equilibrium estimates of adult biomass due to a continuous replenishment from the juvenile stock (Fig. 4). At certain fishing levels, juvenile pollock may benefit from reduced cannibalism. System-wide effects are minimal, with the biomass changes of individual groups changing from less than 1% to about 30%, because the adult pollock stock does not change appreciably. However, the model predicts that equilibrium biomass levels of seals, sea lions, and piscivorous birds would increase due to an increase in the abundance of juvenile pollock.

Dynamic simulations of overfishing pollock to the point of extinction in the 1980s, predict the decline of seabirds that consume juvenile pollock. However, reducing the adult biomass of adult pollock by 50% would have a positive effect on seals, sea lions, and piscivorous birds because the abundance of juvenile pollock, which they consume, increases as cannibalism

by adult pollock is reduced. This result corroborates the conclusion previously made by Laevastu and Favorite (1988) for Bering Sea pollock: that fishing on the older, cannibalistic portion of the stock might increase juvenile survival and abundance.

Simulations in which pollock fishing is stopped in the 1980s result in a larger adult population and a smaller juvenile pollock population. Reducing the juvenile pollock population has a negative effect on seabirds and a small negative effect on marine mammals.

Success and Failure of the Bering Sea Ecosystem Model

We were unable to move from the assumed state of the Bering Sea in the 1950s to our more certain understanding of the Bering Sea in the 1980s using dynamic simulation of the trophic interactions and fishing removals. Our assessment was that environmental change (which we did not explicitly model) is one explanation for the changes in flatfish and pollock, and the decline of pelagic fishes. Uncertainty in the 1950s state is the other explanation.

We do not know at this point how well our models represent the Bering Sea ecosystem, nor do we have a straightforward means of quantifying the uncertainty of our results. However, we can do further testing to examine our assumptions of the 1950s model. We can also try to project the 1980s model forward in a way that matches present observations. Our models are based on the best available data and have been used in a simple and rigorous modeling framework (Ecopath) that has a number of checks and balances to ensure consistency. Thus, we feel that we can make inferences about some of the general and fundamental properties of the Bering Sea, despite our incomplete knowledge of the past and present. For example, we can identify some of the major flows of energy through the Bering Sea and better understand the trophic relationships of the different species living in the Bering Sea. Our model suggests that the Bering Sea is a system where cascading effects of changing one component tend to be sluggish and may be small compared to the magnitude of change that the environment can cause via its impact on recruitment or primary production. Whether fishing for pollock or other species results in the unexpected changes predicted by our model remains to be verified. It nevertheless highlights the strength of ecosystem approaches to understanding the whole system.

Our conclusions are broad and general and may not be particularly useful to people charged with setting fishing quotas or making other management decisions. However, our models are the first step in a series of models that will come later. Splitting more groups of species into immature and mature stages, and adding habitat and spatial/migratory relationships (Walters et al. 1998) will all improve this model. Ecosystem
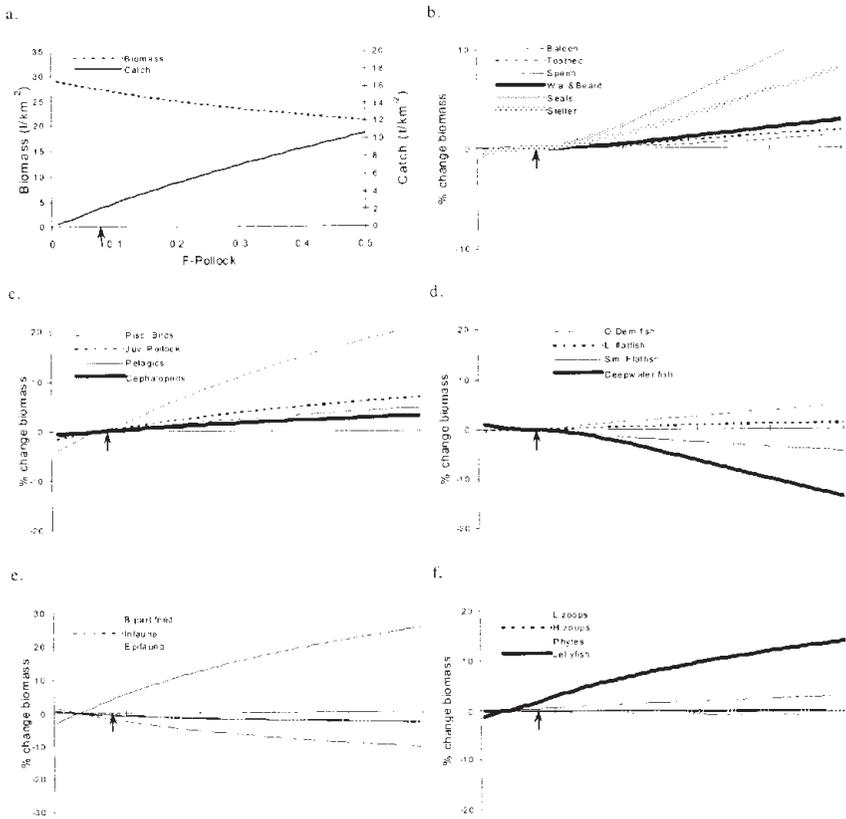
Figure 4.   Equilibrium biomass for Bering Sea species following changes to the fish-
ing mortality of adult pollock in the 1980s model. Arrows mark the in-
stantaneous rate of fishing (F per year) during the 1980s. The top left
panel shows changes in the biomass and catch of baleen whales under
different levels of F. The other five panels show the relative change (%)
that would occur to other species in the ecosystem model to compensate
for changes in the abundance of adult pollock.

models will also need to explicitly consider seasonal and environmental factors influencing carrying capacity and recruitment of dominant species. These are being extensively studied by the National Oceanic and Atmospheric Administration's (NOAA) Fisheries Oceanography Coordinated Investigations program (Kendall et al. 1996) and the Southeast Bering Sea Carrying Capacity program (http://www.pmel.noaa.gov/sebscc/).

Criticisms that have been leveled against single species models can be equally raised against multispecies ecosystem models such as ours. Neither type of model does a particularly good job yet of predicting large decadal shifts in abundance, productivity, or species composition. It is unlikely that ecosystem models will ever replace single-species models. Instead, ecosystem models will likely complement single-species models and provide a context and/or parameters for them. They should prove to be another addition to the scientific and management toolbox.

As a management tool, ecosystem models are not yet very useful. They still need to prove themselves by being able to reconstruct the past or by making realistic predictions about the future. They also need to convey uncertainty. However, as a scientific tool, ecosystem models such as ours are very useful. They can help to identify gaps in understanding and data needs. They can also guide the choice of experiments to highlight our understanding (Walters et al. 1997). Finally, and perhaps most important, they are a tool to bring diverse groups of people together to share their knowledge about small pieces of the ecosystem and increase the collective knowledge about the whole system.

Acknowledgments

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