A Multispecies Bioeconomic Model with Biological and Harvesting Interactions using a Surplus Production Model of Stock Dynamics

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INTRODUCTION

The need for ecosystem based fisheries management is well recognized, but substantial obstacles remain toward implementing these approaches given our current understanding of the biological complexities of the ecosystem along with the economic complexities surrounding resource use. The role of non-harvested species in economic models has largely been relegated to bycatch and discards, or as constraints on the harvest of the target species via bycatch quotas. However, populations of non-target species also impact the stock dynamics of target species and can lead to changes in optimal harvesting strategies.

This study uses the pollock, Pacific cod, and arrowtooth flounder populations in the Bering Sea/Aleutian Islands region of Alaska as a case study. The biological interactions between these three species can be characterized by arrowtooth flounder and Pacific cod both preying on pollock, and by cod and arrowtooth competing with one another for food and other resources. Similarly, a majority of vessels which target pollock over the course of a year also target cod during the same year with arrowtooth being caught as bycatch in both of these fisheries. As arrowtooth flounder are a low value species, which preys on pollock and competes with Pacific cod for resources, increases in the arrowtooth flounder population are found to reduce the value of this multispecies fishery.

METHODS

The multispecies stock dynamics equations of each species are set up as a logistic escapement model, such that:

$$(1) \qquad x_{i,y+1} = \theta_i (x_{i,y} - Y_{i,y}) - \eta_i (x_{i,y} - Y_{i,y})^2 + \sum_{j \neq i}^{n-1} \alpha_{i,j} (x_{i,y} - Y_{i,y})(x_{j,y} - Y_{j,y}) \ \forall i = 1,\ldots,n,$$

where $x_{i,y}$ is the stock of species i in year y, $Y_{i,y}$ is the harvest of species i in year y, θ_i is equal to one plus the intrinsic growth rate, η_i is the density dependent factor related to the carrying capacity, $\alpha_{i,j}$ are the growth interaction parameters, and n = 3 is the number of species included. After using the Prais-Winsten transformation to correct for autocorrelation and appending an error term, equation (1) is estimated using seemingly unrelated regression for the years 1980-2009 and the results are presented in Table 1.

Table 1. Multispecies Stock Dynamics Parameter Estimates

Growth Model	Parameter	Coefficient	Standard Error
Arrowtooth Flounder N=30	θ_{arth}	1.041***	0.0305
	η_{arth}	-4.10E-08*	2.15E-08
	$\alpha_{arth,cod}$	4.85E-08***	1.51E-08
	$\alpha_{arth,plck}$	-1.28E-09	9.80E-10
Pacific Cod N=30	θ_{cod}	1.773***	0.1093
	η_{cod}	-2.87E-07***	4.34E-08
	$\alpha_{cod,arth}$	-4.28E-07***	1.12E-07
	$\alpha_{cod,plck}$	4.25E-09	3.92E-09
Walleye Pollock N=30	θ_{plck}	1.893***	0.3440
	η_{plck}	-5.95E-08***	1.95E-08
	$\alpha_{plck,arth}$	-3.77E-07	2.68E-07
	$\alpha_{plck,cod}$	1.82E-08	1.48E-07

*denotes statistically significant at the 10% level, ** denotes statistically significant at the 5% level, *** denotes statistically significant at the 1% level.

The fleet was divided into three classes (c), small catcher vessels, big catcher vessels, and catcher processors. After making a within transformation, the annual fishery mortality of species i by a vessel (v) in class c, ($\bar{f}_{i,y}^{v,c}$) is determined to be a function of effort for species i ($e_i^{v,c}$), the catchability coefficient for that species (q_i^c) plus the bycatch coefficient ($\gamma_{i,j}^c$) times the effort for other species j times the stock of species i, such that the vessel's production function will be estimated via equation (2):

$$(2) \qquad \bar{f}_{i,y}^{v,c} = q_i^c \bar{e}_{i,y}^{v,c} + \sum_{j \neq i}^{n-1} \gamma_{i,j}^c \bar{e}_{j,y}^{v,c} + \varepsilon_{\bar{f},i}^{v,c} \quad \forall i = 1,\ldots,3; c = 1,\ldots,3.$$

Effort for species i is defined as the total number of days each year on trips when species i comprises the largest share of the catch. As effort is endogenously determined, effort will be instrumented for with $\bar{X}_{i,y}^{v,c}$, such that:

$$(3) \qquad \bar{e}_{i,y}^{v,c} = \bar{X}_{i,y}^{v,c}{}' \beta_i^c + \varepsilon_{\bar{e},i}^{v,c} \quad \forall i = 1,\ldots,3; c = 1,\ldots,3.$$

Instruments included in $\bar{X}_{i,y}^{v,c}$ include lagged effort of all three species, lagged prices of thirteen potential target species, and lagged stock size of each of the three species. The system of equations (2) and (3) are estimated using iterated three stage least squares, and the results are presented in Table 2.

Table 2. Production Function Parameter Estimates

		Arrowtooth Flounder Effort		Pacific Cod Effort		Walleye Pollock Effort	
Vessel Class	Harvest Species	Coefficient	Standard Error	Coefficient	Standard Error	Coefficient	Standard Error
Small Catcher Vessel N=646	Arrowtooth			3.86e-07 ***	6.19E-08	2.01e-07 ***	4.48E-08
	Cod			5.65e-06 ***	1.05E-06	1.93e-06 *	7.60E-07
	Pollock			-1.24e-06 **	4.59E-07	5.78e-06 ***	3.32E-07
Big Catcher Vessel N=858	Arrowtooth			2.83e-07 ***	8.10E-08	1.29e-07 ***	3.14E-08
	Cod			.0000132 ***	8.51E-07	1.96e-06 ***	3.30E-07
	Pollock			6.01e-06 **	1.93E-06	.000019 ***	7.47E-07
Catcher Processor Vessel N=715	Arrowtooth	.0000241 ***	3.56E-06	-1.41E-07	4.03E-07	-7.17E-07	6.66E-07
	Cod	-4.27E-06	7.22E-06	2.99e-06 ***	8.16E-07	-3.99e-06 **	1.35E-06
	Pollock	0.000023	0.0000196	-7.43e-06 ***	2.22E-06	.0000497 ***	3.68E-06

*denotes statistically significant at the 10% level, ** denotes statistically significant at the 5% level, *** denotes statistically significant at the 1% level.

The objective is to maximize the net present value of this fishery over an infinite horizon:

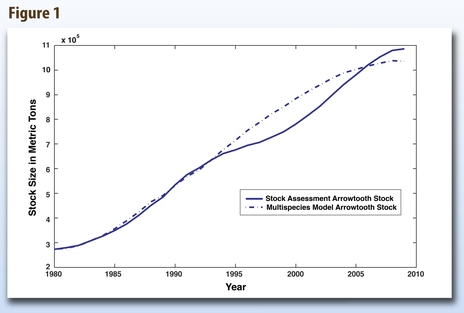
$$\max_{\{E_{i,y}^c\}_{y=1}^{\infty}} \sum_{y=0}^{\infty} \sum_{c=1}^{3} \sum_{i=1}^{3} \left\{ \psi_i^c p_{i,y}^c Y_{i,y}^c(E,x) - C_i^c E_{i,y}^c \right\}$$

subject to the stock dynamics in equation (1), where $p_{i,y}^c$, ψ_i^c, C_i^c, and $E_{i,y}^c$ are the ex-vessel price, and profit and cost per unit effort, and aggregate effort for species i by vessel class c. The model is simulated with the optimal effort by each vessel class for all species as well as the optimal effort on cod and pollock assuming a constant harvest rate on arrowtooth at the current exploitation rate of 2.5%, without uncertainty for 100 years using 2008 as a base year and constant real prices and costs.

RESULTS

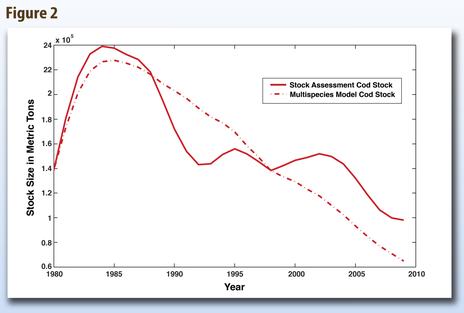
Using the population estimates and catch levels from the 2008 SAFE reports for these three species, Figures 1, 2, and 3 provide a retrospective analysis of the multispecies model relative to the population estimates from the stock assessment for arrowtooth flounder, Pacific cod, and pollock, respectively. They do a relatively good job approximating the general trends in all three stocks. The stock size and harvest level of each species from the simulation results are presented in Figures 4, 5, and 6, respectively. These show that the stocks and harvest levels are cyclical under the optimal policy, which is a result of fishing down the stock of arrowtooth, and both are considerably higher than under the constant arrowtooth harvest rate policy. Thus, to maximize the value of this fishery, substantial harvests of arrowtooth are required to allow the cod and pollock populations to expand and increase the harvest of both species. Some caution is needed in interpreting these results, as this very basic reduced form model has substantial limitations regarding specific production technologies and stock dynamics. Given the economic and ecological uncertainties, it is unclear if the economic gains would be realized in practice.

Figure 1



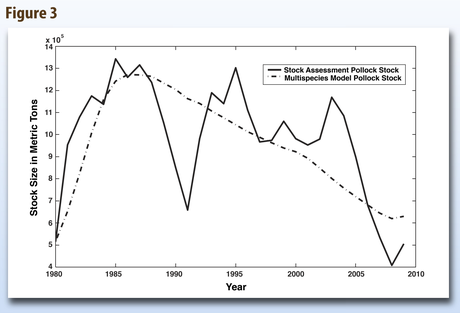
Retrospective analysis of the stock assessment model and multispecies growth model for arrowtooth flounder.

Figure 2



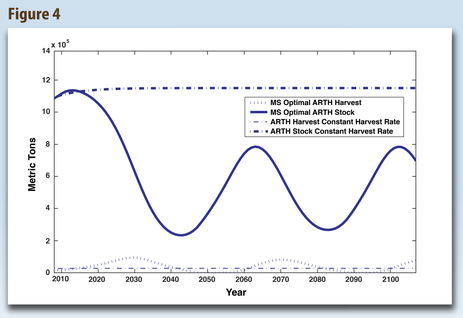
Retrospective analysis of the stock assessment model and multispecies growth model for Pacific cod.

Figure 3



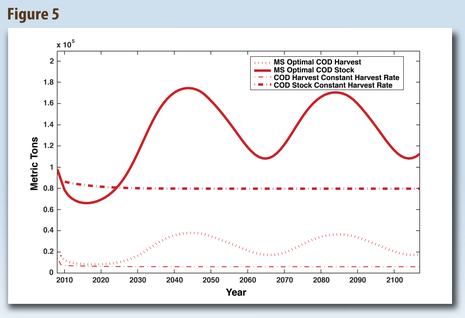
Retrospective analysis of the stock assessment model and multispecies growth model for walleye pollock.

Figure 4



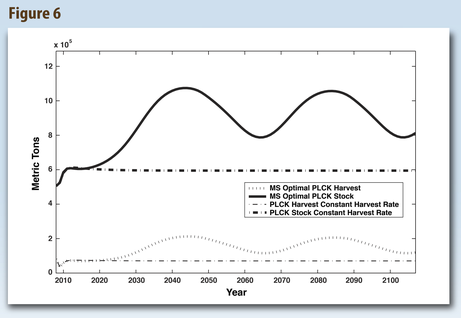
Simulated stock and harvest levels for arrowtooth flounder under the optimal harvest policy for all three species, subsidizing the harvest of arrowtooth, and the optimal harvest policy for cod and pollock for a constant 2.5% harvest rate of arrowtooth.

Figure 5



Simulated stock and harvest levels for Pacific cod under the optimal harvest policy for all three species, subsidizing the harvest of arrowtooth, and the optimal harvest policy for cod and pollock for a constant 2.5% harvest rate of arrowtooth.

Figure 6



Simulated stock and harvest levels for walleye pollock under the optimal harvest policy for all three species, subsidizing the harvest of arrowtooth, and the optimal harvest policy for cod and pollock for a constant 2.5% harvest rate of arrowtooth.

CONCLUSIONS

Using a simple multispecies bioeconomic model, this study shows how the impact of a non-target species (arrowtooth flounder) can substantially alter the optimal harvest policies for two profitable species (Pacific cod and walleye pollock). As arrowtooth negatively impacts the growth of cod, it makes economic sense to subsidize the harvesting of arrowtooth to lower its population which increases the stock of cod and pollock and leads to increased profits from those fisheries. While it is unclear whether or not these stock dynamics would be seen in reality, these target and non-target interactions likely exist in many fisheries and should be considered in any ecosystem based managment scheme.

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