<u>Optimal Multispecies Harvesting in the Presence of a Nuisance Species</u>

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1. Introduction

The need for ecosystem based fisheries management is well recognized [1,2], 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. Currently, the predominant biological reference point for U.S. fisheries management is the maximum sustainable yield (MSY) of each individual species in an ecosystem. Single species management of multispecies fisheries ignores the ecological relationships among species as well as the technological and economic relationships between species as multiple species are caught jointly or vessels allocate their effort among multiple target species, often to the detriment of the health of the ecosystem, the stocks of fish species, and fishery profits.

While the ecological interactions have long been recognized, multispecies stock assessment models are still relatively new [3]. Likewise, there are numerous studies of the multiproduct nature of firms' production of multiple fish species using dual estimation models [4,5,6,7,8].[1] These studies generally reject input/output separability, which implies that fishing technology should be measured in a disaggregated manner, or risk misspecification of the fishing technology [9]. With the exception of Singh and Weninger [10], previous studies attempting to account for technological interactions within bioeconomic models [11,12] typically assume that only a single composite input

[1] See Jensen [9] for a survey of empirical applications of dual theory in fisheries.

(effort) is used to catch multiple species which implicitly assumes that output is separable from the composite input, which may not be the case in many fisheries.

The role of non-harvested species in economic models has largely been relegated to bycatch and discards [13,14,10], or as constraints on the harvest of the target species via bycatch quotas [15]. However, populations of non-target species also impact the stock dynamics of target species and can lead to changes in optimal harvesting strategies. A type of non-target species that may lead to dramatically different optimal harvesting policies is a nuisance species which is one that lowers the value of the fishery by negatively affecting the growth of the other species in the ecosystem and has little harvest value of its own. This study develops a multispecies bioeconomic model that incorporates biological and technological interactions to determine the optimal effort and stock size for each species in the presence of a nuisance species. Simulations are then run according to optimal policies including and excluding the nuisance species to determine the impact of the nuisance species on fishery profits and stock abundances.

2. Three Species Ecosystem

This study uses the walleye pollock, Pacific cod, and arrowtooth flounder (hereafter referred to as pollock, cod, and arrowtooth respectively) populations in the Bering Sea/Aleutian Islands (BSAI) region of Alaska as a case study. Between 1990 and 2008, estimates of the pollock and cod population have declined by 46% and 39% respectively, while estimates of the arrowtooth population have increased by 105% over the same time period. The biological interactions between these three species can be characterized by both arrowtooth and cod preying on pollock, and cod and arrowtooth competing with one another for food and other resources. As arrowtooth is a low value species, it is possible that increases in the arrowtooth population reduce the value of this multispecies fishery and is an excellent candidate for a nuisance species. Additionally, 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. Given these interactions, this three species system is an ideal candidate to explore the impact of a nuisance species on the profitability of a multispecies fishery.

The pollock fishery in Alaska represents over 40% of global whitefish production, and is the largest fishery (by volume) in the United States, averaging over 1.3 million tons per year since 2000. The pollock fleet in the BSAI generally consists of large catcher vessels and catcher processor vessels, which both catches and processes the fish at sea, using pelagic trawl gear. Cod accounts for the second largest groundfish harvest in the Bering Sea, averaging over 186,000 tons per year since 2000, and is caught by longline, pot, and non-pelagic (bottom) trawl gear by both catcher vessels and catcher processors. Arrowtooth is a low value species that is caught both types of trawls participating in the cod and pollock fisheries and is largely discarded when caught. All three species are managed with a total allowable catch (TAC), with pollock and cod catches approximating their TAC each year. Arrowtooth catches average only 1.6% of the stock and 74% of the TAC over the period 2000-2009, which includes 5 years of TACs set at or below 16,000 tons. The 2009 harvest was 2.5% of the stock, but only 36% of the TAC, as the TAC has been raised to 75,000 tons to potentially allow for increased catch to slow the growth of the stock.

3. Multispecies Stock Dynamics

Stock estimates of each species and the catch on an annual basis is available for the years 1980 through 2009 through the Stock Assessment and Fishery Evaluation (SAFE) report from the Alaska Fisheries Science Center [16]. These stock estimates will be used to parameterize the multispecies stock dynamics equation of each species which are set up as a logistic escapement model, such that:

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

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 for all three species using seemingly unrelated regression for the years 1980-2009.

Parameter estimates are provided in Table 1. Each species own stock parameters are as expected, leading to the classic concave logistic growth curves. However, the interaction terms are not completely as expected. For arrowtooth, the cod stock has a positive and statistically significant impact on growth while the pollock stock has a negative but statistically insignificant impact on growth. Not surprisingly for cod, arrowtooth has a negative and statistically significant impact on growth, while pollock has a positive, but statistically insignificant effect on growth. The interaction terms for pollock are of the expected sign, but both are statistically insignificant. These results suggest that increases in arrowtooth reduce the growth of the cod stock, increases in the cod stock increase the growth of arrowtooth, and increases in arrowtooth reduce the growth of pollock and vice versa. The positive, but statistically insignificant, coefficients between cod and pollock possibly suggests that at different life stages older cod prey on young pollock and older pollock prey on young cod as suggested by Jurado-Molina et al. [17].

Using the parameters from Table 1, Figures 1-3 present a retrospective analysis of the population between 1980 through 2009 comparing the stock assessment model to the multispecies model starting from the same population in 1980 and using the actual harvests over the period. While not exact, the model appears to do a relatively good job approximating the general trends in all three stocks, and should provide reasonable projections for simulating the stock dynamics in the bioeconomic model.

4. Multispecies Harvesting Model

Using data from 2000 to 2008 on all vessels which caught any amount of arrowtooth, cod, or pollock, production functions for each vessel for each of the three species, are estimated. As different sized catcher vessels and catcher processors are likely to have different technologies, the fleet was divided into three classes (*c*), small catcher vessels (less than median catcher vessel size <~80 feet), big catcher vessels (greater than median catcher vessel size> ~80 feet), and catcher processors. Total annual catch of species *i* by a vessel (*v*) in class *c* in year *y*, ($y_{i,y}^{v,c}$) is determined to be a function of effort for species *i* ($e_{i,y}^{v,c}$), the catchability coefficient for that species (q_i^c) and the stock of the species ($x_{i,y}$) plus the bycatch coefficient ($\gamma_{i,j}^c$) times the effort for other species *j* times the stock of species *i*, such that:

(2) $$y_{i,y}^{v,c} = q_i^c e_{i,y}^{v,c} x_{i,y} + \sum_{j \neq i}^{n-1} \gamma_{i,j}^c e_{j,y}^{v,c} x_{i,y} \quad \forall i = 1,...,3; c = 1,...,3.$$

Dividing both sides of equation (2) by $x_{i,y}$, and making a within transformation for each vessel, such that $\overline{e}_{i,y}^{v,c} = e_{i,y}^{v,c} - \frac{1}{T^v}\sum_{y=1}^{T^v} e_{i,y}^{v,c}$ and $\overline{f}_{i,y}^{v,c} = \left(\frac{e_{i,y}^{v,c}}{x_{i,y}}\right) - \frac{1}{T^v}\sum_{y=1}^{T^v}\left(\frac{e_{i,y}^{v,c}}{x_{i,y}}\right)$, the vessel's production function will be estimated via equation (3):

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

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 $\overline{X}_{i,y}^{v,c}$, such that:

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

Instruments included in $\overline{X}_{i,y}^{v,c}$ 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 (3) and (4) are estimated using iterated three stage least squares, and the results are presented in Table 2. As it was determined that there was no trips taken by catcher vessels for which arrowtooth were targeted over the study period, it was assumed that catcher vessels only catch arrowtooth as bycatch, and will not develop a targeted fishery in the future.[2]

The results presented in Table 2 suggest that arrowtooth is caught as bycatch in the cod and pollock fleets for both the small and big catcher vessels. For the catcher

[2] A major barrier for increasing the catch of arrowtooth by catcher vessels is that the flesh degrades in quality very quickly after harvest, so catcher processor vessels which can process their catch almost immediately are much more likely to develop a market for their product than the catcher vessels.

processors, there is no statistically significant impact of cod or pollock effort on arrowtooth harvest which is likely due to the fact that they have some targeted trips, and catch a more substantial amount during those trips than they do as bycatch. For both size classes of the catcher vessels, they appear to catch both pollock and cod when targeting either pollock or cod, but the catchabilities are higher for the own targeted species which suggests that they are targeting one species and not actively avoiding catching the other. For the catcher processors, the catchability for own effort is statistically significant and positive, but for the cross effort between cod and pollock are both negative. This suggests that there is some substitutability of effort between pollock and cod for the catcher processors. An additional day catching cod means one less day catching pollock. This makes sense as these are very big vessels with large fixed capital costs that would like be running as close to full effort as possible to lower their average costs. These parameter estimates, along with those from the stock dynamics equations will be used in the bioeconomic model to determine the optimal amount of effort in the fishery.

5. <u>Bioeconomic Model</u>

The problem that solved here is the maximization of profits from the three species fishery over an infinite horizon subject to the stock dynamics equations of each species. Letting $E_{i,y}^{c} = \sum_{v \in c} e_{i,y}^{c,v}$, $Y_{i,y}^{c}(E,x) = \sum_{v \in c} y_{i,y}^{c,v} = q_i^c E_{i,y}^{c} x_{i,y} + \sum_{j \neq i}^{n-1} \gamma_{i,j}^{c} E_{j,y}^{c} x_{i,y}$ and $Y_{i,y} = \sum_{c=1}^{3} Y_{i,y}^{c}(E,x)$, this problem can be stated as:

$$V(x_0) = \max_{\{E^c_{i,y}\}^{\infty}_{y=1}} \sum_{y=0}^{\infty}\sum_{c=1}^{3}\sum_{i=1}^{3}\left\{\psi_i^c p^c_{i,y} Y^c_{i,y}(E,x) - C^c_i E^c_{i,y}\right\}$$

(5) $$s.t.\, x_{i,y+1} = \theta_i(x_{i,y} - Y_{i,y}) - \eta_i(x_{i,y} - Y_{i,y})^2 + \sum_{j \neq i}^{n-1} \alpha_{i,j}(x_{i,y} - Y_{i,y})(x_{j,y} - Y_{j,y})$$

$$\forall i = 1,\ldots,n;\, y = 0,1,2,\ldots,$$

and $\{x_0, E_0\} = \text{given}$, where $V(x_0)$ is the value function for an initial stock x_0 and ψ_i^c and C_i^c are the profit and cost per unit effort for species *i* by vessel class *c*. To keep the problem tractable and well behaved, the simplifying assumption made here is that there is a constant profit per unit effort in the cod and pollock fisheries, such that $\psi^c_{cod} = \psi^c_{plck} = r = 12.85\%$ and $C^c_{cod} = C^c_{plck} = 0$, where *r* is equal to the average net income rate of the catcher processor vessels taken from [18].[3] For arrowtooth, $\psi^c_{arth} = 1$ and $C^c_{arth} = \bar{C}^c$, where $\bar{C}^c$ is the annual variable cost of vessel class *c* divided by the average number of days that vessel class *c* spends fishing. While this assumption does eliminate the direct stock effect of reducing the marginal cost of effort for cod and pollock, there is an indirect effect of the cod and pollock stock on the shadow value of arrowtooth which affects the optimal harvest of cod and pollock.

After setting up the Bellman equation, the first order necessary conditions for a maximum in year *y* are:

(6) $$\sum_{k=1}^{3}\left\{\psi_i^c p^c_{i,y} q^c_{i,k} x_{k,y} - C^c_i + \sum_{i=1}^{3}\delta\lambda^c_{i,y+1}(-q^c_{k,i} x^c_{i,y})\right\} = 0$$

$$\forall i = 1,\ldots,n;\, c = 1,\ldots,3,$$

(7) $$\Rightarrow \delta\lambda^c_{i,y+1} = \psi^c_i p^c_{i,y} - \frac{C^c_i}{q^c_{i,i} x_{i,y}} + \sum_{j \neq i}^{n-1}\left(\frac{q^c_{j,i} x^c_{i,y}}{q^c_{i,i} x_{i,y}}\right)\left(\psi^c_j p^c_{j,y} - \delta\lambda^c_{j,y+1}\right),$$

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[3] This assumption was made to try to maintain the current ratio of harvests among vessel classes, as quota allocations for pollock and cod are based on the vessel class (catcher vessel or catcher processor). This assumption can be relaxed, and these constraints imposed directly in subsequent analyses.

(8) $$\Rightarrow \pi^c_{i,y}(p_y, q, C, x_y) = \delta\lambda^c_{i,y+1},$$

(9) $$\sum_{c=1}^{3}\sum_{k=1}^{3}\left\{\psi^c_i p^c_{i,y} q^c_{i,k} E^c_{k,y}\right\} + \delta\lambda^c_{i,y+1}(\theta_i - \eta_i x_{i,y} + \sum_{j\neq i}^{n-1}\alpha_{i,j}x_{j,y} - \sum_{c=1}^{3}\sum_{k=1}^{3} q^c_{i,k}E^c_{k,y}) + \sum_{j\neq i}^{n-1}\delta\lambda^c_{j,y+1}\alpha_{j,i}x_{j,y} = \lambda^c_{i,y}$$
$$\forall i = 1,\ldots,n; c = 1,\ldots,3.$$

Multiplying equation (9) the discount rate (δ) and moving it forward in time from *y* to *y*+1 and equating this expression to equation (7), provides the Euler equation for this problem:

(10) $$\psi^c_i p^c_{i,y} - \frac{C^c_i}{q^c_{i,i}x_{i,y}} + \sum_{j\neq i}^{n-1}\left(\frac{q^c_{j,i}x^c_{i,y}}{q^c_{i,i}x_{i,y}}\right)\left(\psi^c_j p^c_{j,y} - \delta\pi^c_{j,y}\right) = \sum_{c=1}^{3}\sum_{k=1}^{3}\left\{\delta\psi^c_i p^c_{i,y+1} q^c_{i,k} E^c_{k,y+1}\right\} + \delta\pi^c_{i,y+1}(\theta_i - \eta_i x_{i,y+1} + \sum_{j\neq i}^{n-1}\alpha_{i,j}x_{j,y+1} - \sum_{c=1}^{3}\sum_{k=1}^{3} q^c_{i,k}E^c_{k,y+1}) + \sum_{j\neq i}^{n-1}\delta\pi^c_{j,y+1}\alpha_{j,i}x_{j,y+1}$$
$$\forall i = 1,\ldots,n; c = 1,\ldots,3,$$

which states that the marginal profit from harvesting species *i* in year *y* should equal the marginal profit from leaving that unit in the sea. Using equation (10), an expression for $E^c_{k,y+1}$ can be derived as a function of current period prices, stock levels, growth parameters, catchability coefficients, and shadow values of the stocks. All of these factors are known to the harvesters at the beginning of period *y*+1, such that:

(11) $$E^c_{i,y+1} = F(p_{y+1}, q, \psi^c, \pi^c_{y+1}, \alpha, x_{y+1}).$$ [4]

Thus, equation (11) determines the optimal effort each period which maximizes the infinite stream of profits from the fishery as a function of current state of the system.

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[4] Explicit solutions for $E^c_{k,y+1}$ and $\pi^c_{i,y}$ are available from the author upon request.

It should be noted that the shadow value of arrowtooth is a function of the profitability of arrowtooth harvest as well as the shadow value of cod and pollock. As arrowtooth has a statistically significant negative impact on the growth of cod, the effort level on arrowtooth that maximizes the profits from the entire three species fishery will be greater than the effort level that maximizes the value of the arrowtooth fishery alone. Using the parameters used in this study, the marginal profit for a unit of effort in the arrowtooth fishery is negative, implying that the optimal harvest rate for the arrowtooth fishery would be equal to zero. Thus, the negative shadow value, or shadow cost, can be regarded as the optimal subsidy required to induce the optimal amount of effort in the arrowtooth fishery to maximize the value of the entire fishery as whole [19]. The following section will simulate the optimal effort levels and stock dynamics for this system, as well as the optimal effort levels for cod and pollock assuming that the harvest of arrowtooth remains constant at the current rate of 2.5%.

6. <u>Simulations</u>

The stock, effort, and harvest were simulated without uncertainty for 100 years into the future using 2008 as a base year and constant real prices and costs. Figures 4,5, and 6 show the difference in stock size and harvest for arrowtooth, cod, and pollock, respectively under the multispecies optimal harvest strategy defined by equation (11), and the optimal harvesting strategy for cod and pollock if arrowtooth was harvested at a constant 2.5% throughout the simulation.

What appears to happen in the optimal policy model is that arrowtooth is initially harvested down to a low level, during which the cod and pollock stocks both realize substantial increases in their populations. As the cod stock increases, the growth of the arrowtooth stock is increased, which then begins to rebound, leading to lower stock levels of cod and pollock. This cycle repeats itself over the simulation approximately every 40 years. The resulting cod and pollock stocks from the optimal strategy are significantly higher than under the constant arrowtooth harvest model since arrowtooth are eating a substantial number of cod in particular. At the end of the 100 year simulation, the cod and pollock stocks are 2.36 and 1.77 times larger, respectively, than their constant arrowtooth harvest rate policy alternatives, while the optimal policy arrowtooth stock has fallen to 49% of the constant harvest policy. It is possible that this level would trigger arrowtooth being defined as overfished and necessitate a rebuilding strategy for arrowtooth, but that possibility is left for future analysis.

It can also been seen in Figures 4, 5, and 6 that the harvest levels are cyclical with the stock under the optimal policy, and are considerably higher than under the constant arrowtooth harvest rate policy. This is not surprising given stocks of cod and pollock are larger under the optimal policy. The optimal total arrowtooth harvest over the simulation is 141 times larger than the constant harvest policy which is a very substantial increase in effort allocated toward arrowtooth. Optimal cod and pollock total harvests are also 7.8 and 3.1 times larger than their respective harvest policies under a constant arrowtooth harvest. This different results in an over 50 trillion dollar net present value increase in the fishery over this 100 year simulation after subtracting the amount of money needed to subsidize the harvesting of arrowtooth. However, this does assume that effort can be increased without increasing the capital stock, which likely is not valid over this time period to increase harvests at this rate. Assuming that increases in capital expenditures are proportional increases in profits, this policy will still result in a substantial profit increase to this fishery.

7. <u>Discussion and conclusion</u>

Using a simple multispecies bioeconomic model, this study shows how the impact of a nuisance species (arrowtooth flounder) can substantially alter the optimal harvest policies for profitable species (Pacific cod and walleye pollock) in a multispecies ecosystem. As arrowtooth negatively impacts the growth of cod, it makes economic sense to subsidize the harvesting of arrowtooth to lower its population to increase the stock of cod and pollock and increase profits from those fisheries.

By ignoring arrowtooth interactions on cod and pollock results in 57% decrease in the stock of cod and a 43% decrease in the stock of Pollock, and 87% decrease in catch of cod and 68% decrease in catch of pollock relative to the optimal policy. The resulting optimal fishery has a net present value of over 50 trillion dollars larger than the fishery with constant arrowtooth harvest rate, after accounting for the subsidy on arrowtooth. Given this large increase in profits resulting from the harvest subsidy on arrowtooth, it is possible to impose a tax on cod and pollock harvests equal to their marginal cost of arrowtooth on the respective fishery, to cover the immediate cost of the subsidy. Analysis on the optimal tax policy to make the subsidy revenue neutral each year is left for future analysis.

There are a number of caveats to these results that should be mentioned before encouraging additional harvests of arrowtooth. A) This is a very basic, reduced form model which has substantial limitations regarding specific production technologies of the vessels and the study lacks data on real profits, but rather is approximating profits with net revenues with some assumptions about the costs of fishing. B) Different gear types may have different production functions, which could impact the catchability coefficients, and optimal harvest policies. C) There is no attempt to model specific regulations specific to these fisheries in the BSAI, such as the allocation of quota across vessel classes. More importantly, there is a 2 million ton per year limit on the total harvest of all managed groundfish species in the BSAI, which is exceeded by the pollock harvest alone in some years in this model. Including this cap on total harvest is left for future analysis. D) The results from this model are one potential explanation for the stock dynamics in this system, but these stock dynamics could change as factors external to the model change. E) It is also possible that increases in arrowtooth have lead to declines in the cod population, but as cod are a top predator in this ecosystem, decreases in the cod population can also lead to increases in other populations which may result in an overall increase in NPV. It is important to note that the adjusting the boundaries of the system can lead to alternative conclusions, so one should be conservative in situations where there are potential factors outside the boundaries influencing the results. Similarly, how the model affects the ecosystem outside its boundaries can lead to alternative conclusions about what is optimal in reality.

While there are substantial limitations as to the direct application of this model to the fishery, it does illustrate how non-target species impact target species not only through bycatch but also through ecosystem interactions, leading to drastically different optimal harvest policies. Future analysis using of this model will include a stochastic stock, catchability, and price component. The model can also be expanded to include a more detailed age structured stock assessment model, as well as a more detailed model of the production technology and profit maximizing behavior by these vessels.

Table 1. Multispecies Stock Dynamics Parameter Estimates

Growth Model	Parameter	Coefficient	Standard Error
Arrowtooth Flounder N=30 R^2=.99	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 R^2=.98	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 R^2=.97	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.

Table 2. Production Function Parameter Estimates

		Arrowtooth Flounder Effort		Pacific Cod Effort		Walleye Pollock Effort	
Growth Model	Harvest Species	Coefficient	Standard Error	Coefficient	Standard Error	Coefficient	Standard Error
Small catcher Vessel Production 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 Production 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 Production 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.

Figure 1. Retrospective analysis of the stock assessment model and multispecies growth model for arrowtooth flounder.

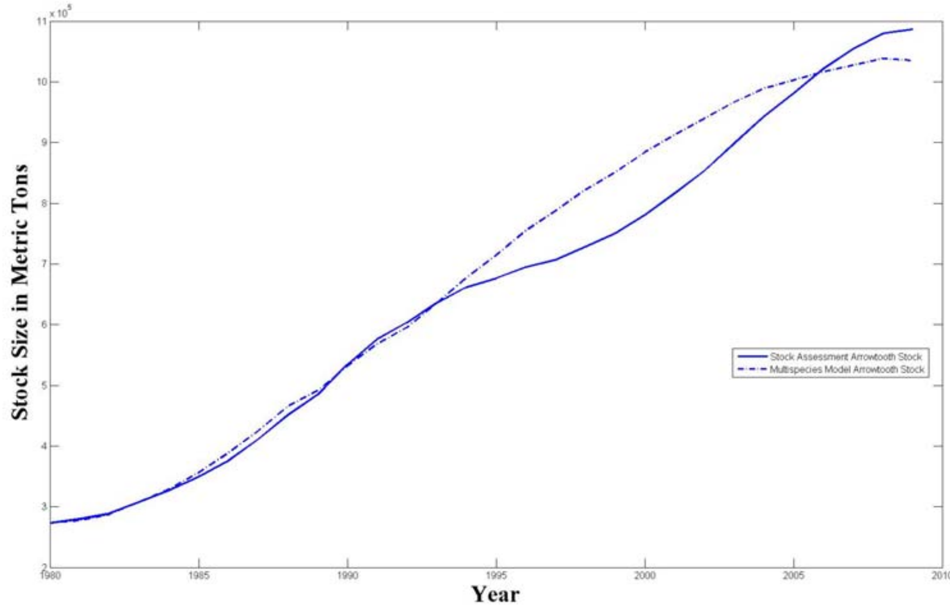


Figure 2. Retrospective analysis of the stock assessment model and multispecies growth model for Pacific cod.

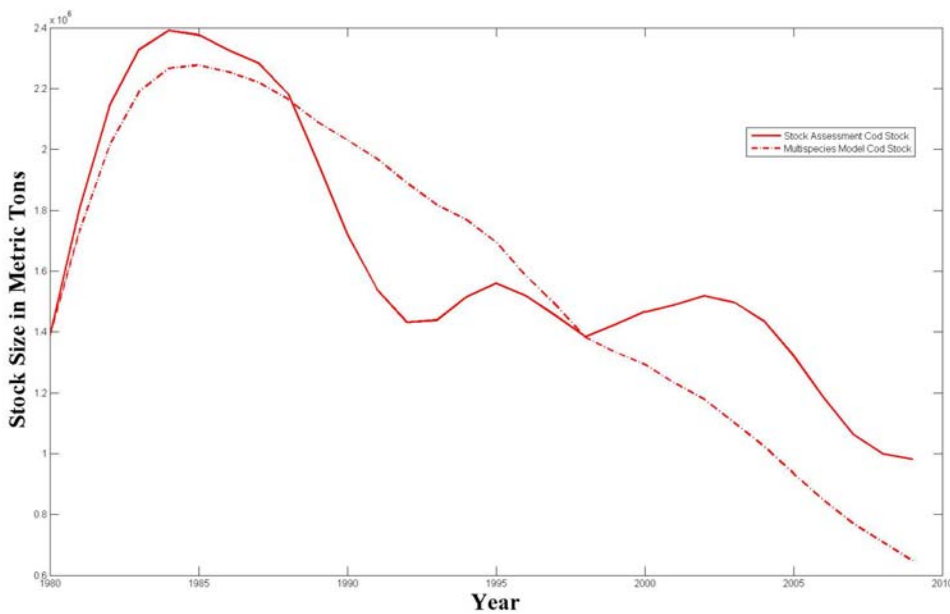


Figure 3. Retrospective analysis of the stock assessment model and multispecies growth model for walleye pollock.

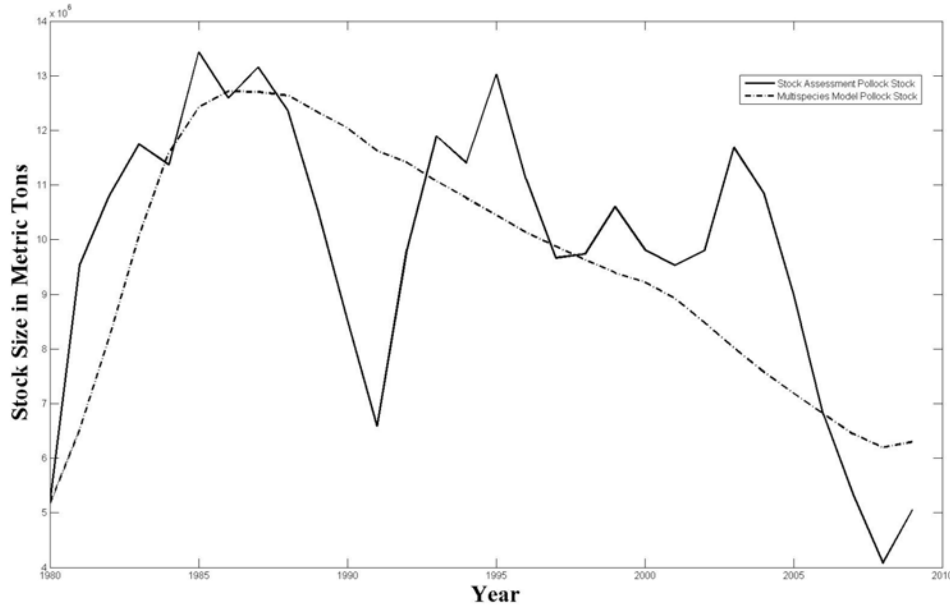


Figure 4. Simulated stock and harvest levels for arrowtooth flounder under the optimal harvest policy for all three species, subsidizing the harvest of arrowtooth, and the optimal harvest policy for cod and pollock for a constant 2.5% harvest rate of arrowtooth.

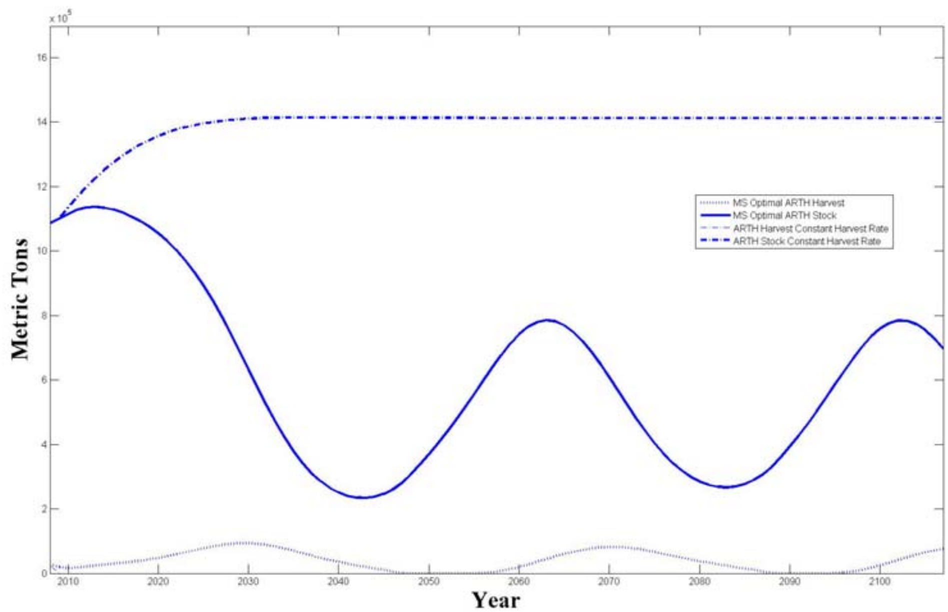


Figure 5. Simulated stock and harvest levels for Pacific cod under the optimal harvest policy for all three species, subsidizing the harvest of arrowtooth, and the optimal harvest policy for cod and pollock for a constant 2.5% harvest rate of arrowtooth.

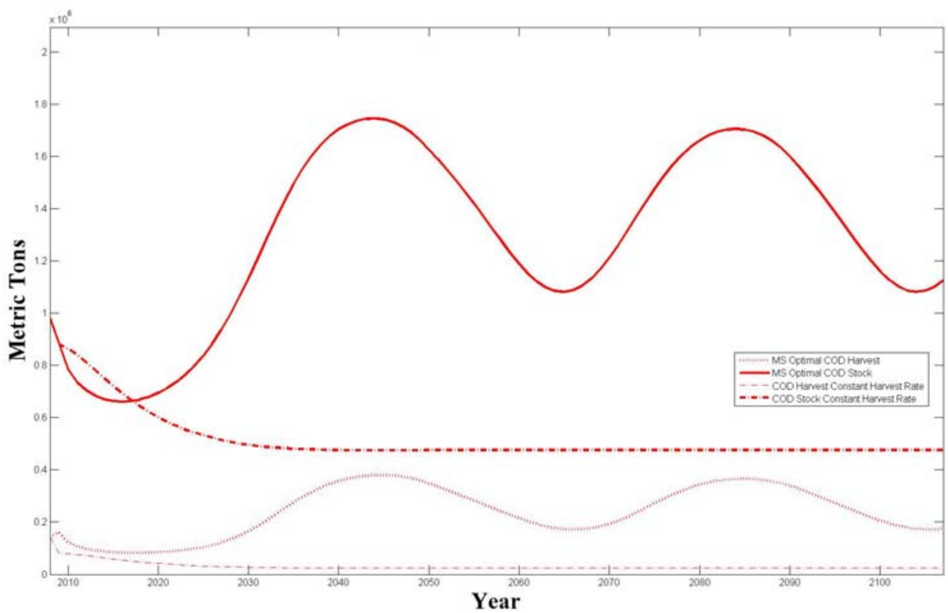
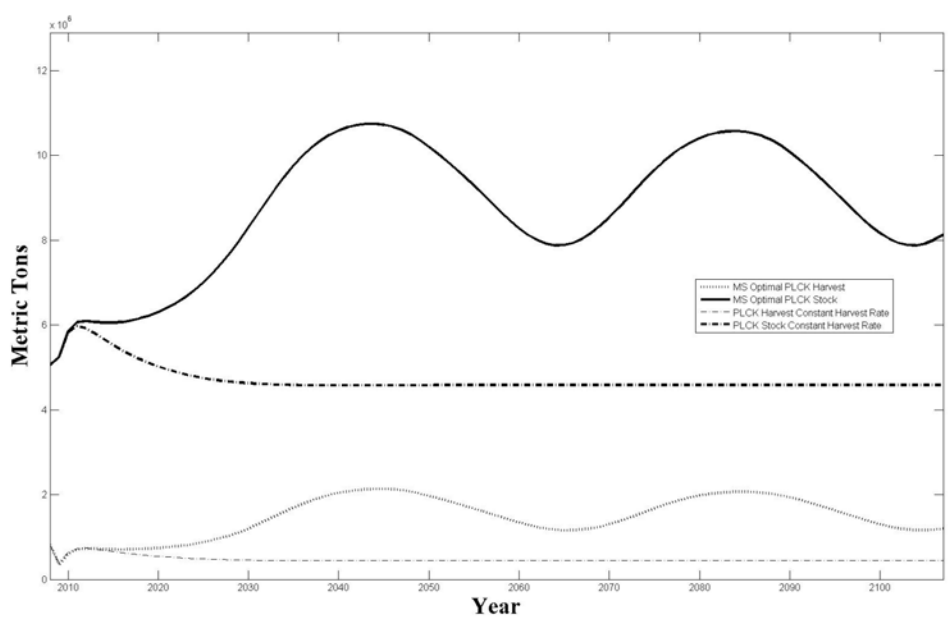


Figure 6. Simulated stock and harvest levels for walleye pollock under the optimal harvest policy for all three species, subsidizing the harvest of arrowtooth, and the optimal harvest policy for cod and pollock for a constant 2.5% harvest rate of arrowtooth.



References:

1. May, R.M., John R. Beddington, Colin W. Clark, Sidney J. Holt, Richard M. Laws, *Management of Multispecies Fisheries.* Science, 1979. **205**(4403): p. 267-277.
2. Pikitch, E.K., C. Santora, E.A. Babcock, A. Bakun, R. Bonfil, D.O. Conover, P. Dayton, P. Doukakis, D. Fluharty, B. Heneman, E.D. Houde, J. Link, P.A. Livingston, M. Mangel, M.K. McAllister, J. Pope, K.J. Sainsbury., *Ecosystem-Based Fishery Management.* Science, 2007. **305**: p. 346-347.
3. Kinzey, D., and Andre E. Punt, *Multispecies and Single-species Models of Fish Population Dynamics: Comparing Parameter Estimates.* Natural Resource Modeling, 2009. **22**(1): p. 67-104.
4. Kirkley, J.E., and Ivar E. Strand, *The technology and management of multi-species fisheries.* Applied Economics, 1988. **20**: p. 1279-1292.
5. Squires, D., *Fishing Effort: It's Testing, Specification, and Internal Strucutre in FIsheries Economics Management.* Journal of Environmental Economics and Management, 1987. **18**: p. 268-282.
6. Squires, D., *Public Regulation and the Strucutre of Production in Multiproduct Industries: An Application to the New Englad Otter Trawl Industry.* Rand Journal of Economics, 1987. **18**(234-247).
7. Squires, D., *Production, Technology, Costs, and Multiproduct Industry Structure: An Application of the Long-Run Profit Function to the New England Fishing Industry.* Canadian Journal of Economics, 1988. **21**: p. 359-378.

8. Squires, D., and James E. Kirkley, *Production Quota in Multiproduct Pacific Fisheries.* Journal of Environmental Economics and Management, 1991. **21**: p. 109-126.

9. Jensen, C.L., *Applications of Dual Theory in Fisheries: A Survey.* Marine Resource Economics, 2002. **17**: p. 309-344.

10. Singh, R., and Quinn Weninger, *Bioeconomies of scope and the discard problem in multiple-species fisheries.* Journal of Environmental Economics and Management, 2009. **58**: p. 72-92.

11. Conrad, J.M., and Richard Adu-Asamoah, *Single and Multispecies Systems: The case of Tuna in the Eastern Tropical Atlantic.* Journal of Environmental Economics and Management, 1986. **13**: p. 50-68.

12. Mesterton-Gibbons, M., *On the Optimal Policy for Combined Harvesting of Independent Species.* Natural Resource Modeling, 1987. **2**: p. 109-134.

13. Arnason, R., *On Catch Discarding in Fisheries.* Marine Resource Economics, 1994. **9**: p. 189-207.

14. Boyce, J.R., *An Economic Analysis of the Fisheries Bycatch Problem.* Journal of Environmental Economics and Management, 1996. **31**: p. 314-366.

15. Abbott, J.K., and James E. Wilen, *Regulation of fisheries bycatch with common-pool output quotas.* Journal of Environmental Economics and Management, 2009. **57**: p. 195-204.

16. Alaska Fisheries Science Center. 2009 North Pacific Groundfish Stock Assessment and Fishery Evaluation Reports for 2010, Bering Sea/Aleutian Islands

Region. Available online at http://www.afsc.noaa.gov/refm/Docs/2009/BSAISafe.pdf.

17. Jurado-Molina J., P. A. Livingston and J. N. Ianelli. Incorporating predation interactions to a statistical catch at-age model for a predator-prey system in the eastern Bering Sea. Canadian Journal of Fisheries and Aquatic Sciences, 2005. 62(8): 1865-1873.

18. The Research Group. Estimating Economic Impacts of Alaska Fisheries Using a Computable General Equilibrium Model. Data Acquisition and Reduction Task Documentation. Report prepared for the National Marine Fisheries Service, Alaska Fisheries Science Center, November 2007.

19. Clark, Colin, W. Mathematical Bioeconomics: Optimal Management of Renewable Resources. John Wiley and Sons, Inc., Hoboken, New Jersey, 1976.