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Optimal multispecies harvesting in the presence of a nuisance species

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ABSTRACT

Current knowledge of the complex relationships within ecological and economic systems make operationalizing ecosystem approaches within fisheries management difficult. As these approaches are developed, it is important to include non-target species that affect the productivity (as prey) and availability (as predators) of targeted species. This study develops a multispecies bioeconomic model that incorporates ecological and economic interactions to determine the optimal harvest of each species in the presence of a "nuisance" species, which 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. The populations of walleye pollock, Pacific cod, and arrowtooth flounder (a nuisance species) in the Bering Sea/Aleutian Islands region of Alaska are used as a case study. Vessel-and gear-specific profit functions with multi-output production technologies are used, along with estimated multispecies stock dynamics equations, to determine the optimal multispecies quotas and subsidy on the harvest of the nuisance species to maximize the value of this fishery. Ignoring the nuisance species results in a substantially less productive and lower value fishery than optimal joint management. This study highlights the importance of incorporating the impact of non-targeted species in ecosystem-based fisheries management.

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1. Introduction

The Final Recommendations of the Interagency Ocean Policy Task Force has declared that adopting ecosystem-based approaches to management is their number one national priority objective. It states that traditional management “has often lead to disjointed management approaches resulting in loss of resources, economic hardship, and environments at risk” [13]. However, researchers are only beginning to understand the complex ecological linkages between species in an ecosystem and how these linkages are affected by changing environmental conditions such as climate change, ocean acidification, sea ice, eutrophication, changing ocean currents, and pollution. Often overlooked are the complex economic linkages between human activities such as multispecies harvesting, multiple product forms, substitutable or complementary species in consumption, linked global markets, and implementing coastal marine spatial planning.

Moving toward ecosystem approaches requires updating our biological reference points for management from the current notion of single species maximum sustainable yield (MSY) to maximum sustainable ecosystem yield (MSEY) or an ecosystem based version of maximum economic yield (EMEY). These ecosystem approaches should consider the ecological interactions among species as well as the economic interactions among species which occur through combined harvesting of multiple species, how vessel operators allocate effort across multiple species, and whether species are substitutes or complements in output markets. However, actually implementing MSEY or EMEY may be incompatible with current single species-based defined overfishing levels and rebuilding plans and may require additional management flexibilities to fully incorporate these ecosystem approaches.

While not completely understood, the ecological interactions among species have been studied for many years [10,36]. However, these studies are not often used to set harvest levels because they lack the detail and robustness of current single species stock assessments. New multispecies stock assessment models are currently being developed, and should improve our understanding of the way multiple species grow, reproduce, and interact with one another [19,21,22,26,48].

Similarly, while every fishery is different, there is a large literature in economics exploring the multiproduct nature of vessels' production of multiple fish species ([11,27,34,39–42]). However, these studies tend to ignore the impact that non-targeted species can have on both the ecological and economic outcomes in multispecies systems. The role of non-targeted species in economic models has largely been relegated to bycatch and discards [38,7], or used as constraints on the harvest of the target species via bycatch quotas [1]. There is also an extensive literature on predator-prey systems where both species are harvested simultaneously [15,31,8],

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the predator species is harvested ([37,46,50], the prey species is harvested [18,24], or some combination of the two species are harvested independently [43]. With the exception of [16], which explores conditions in a predator-prey system where the predator could be optimally harvested to extinction, none of these studies explicitly examine the impact of a nuisance species that negatively affects the growth of the other species in the ecosystem while also having little harvest value of its own.

The empirical application follows [25], and uses walleye pollock (*Gadus chalcogramma*), Pacific cod (*Gadus macrocephalus*), and arrowtooth flounder (*Atheresthes stomias*), hereafter referred to as pollock, cod, and arrowtooth, respectively, in the Bering Sea/Aleutian Islands (BSAI) region of Alaska as a case study. The pollock fishery is the largest in North America by volume, and represents over 40% of global whitefish production [20,4], averaging 1.23 million tons and an ex-vessel value of $380 million over the period 2005–2009 [17]. Pacific cod has the second largest groundfish harvest in the BSAI, averaging 0.183 million tons and an ex-vessel value of $148 million over the period 2005–2009 [17]. Arrowtooth is a low value species with no dedicated target fishery and is incidentally caught due to joint harvesting technologies by vessels using trawl and longline gear and is largely discarded when caught.

Arrowtooth is proposed as a potential nuisance species in the BSAI as it is a major predator of pollock, consumes the same prey species as cod, is rarely targeted in the BSAI, and the total harvest is well below the total allowable catch (TAC) [25]. A major reason why arrowtooth has not developed a targeted fishery is that once caught, a parasite attached to the arrowtooth excretes an enzyme which softens the flesh and makes it unpalatable for human consumption [2]. The texture of its flesh has been described as "fish pudding" [30]. However, recently a number of food grade additives have been developed that inhibit the enzymatic breakdown of the flesh, and a small scale targeted fishery has developed in the Gulf of Alaska where arrowtooth flounder is the largest biomass component of the ecosystem [2,47,51]. The actual catch of arrowtooth in the BSAI is only a small fraction of its TAC, and far below the allowable biological catch (ABC). This implies that it is either not profitable to target arrowtooth, or the opportunity cost of harvesting arrowtooth instead of other more valuable species is greater than the expected profit from targeting arrowtooth. Therefore, if arrowtooth is negatively impacting the growth of the two profitably harvested species (cod and pollock), it may be optimal for the fishery manager to subsidize the harvesting of arrowtooth to jointly maximize the value of all three species. In this paper, optimality refers to maximizing the net present value of the harvests of the combined three fisheries and does not consider other ecological or social objectives which would be important to consider in an ecosystem based fisheries management approach.

2. Material and methods

2.1. Three species ecosystem

The stocks of all three species are healthy, and none of them are overfished, nor is overfishing occurring. However, over the period 1990 to 2010, estimates of the pollock and cod population have declined by 21% and 30%, respectively, while estimates of the arrowtooth population have increased by 109%. The ecological interactions between these three species are complex as juvenile pollock, cod, and arrowtooth are all prey for adult pollock, cod, and arrowtooth, and both pollock and cod exhibit some form of cannibalistic behavior [23,29,51]. Currently, pollock is the keystone species in the BSAI ecosystem, while both pollock and cod together have been keystone species in the past [20,3,51]. In 2003, arrowtooth is estimated to have accounted for approximately half of pollock consumption [6]. The decline in pollock stock since the early 1990s is thought to have been caused by increased predation by arrowtooth [20,49,51]. Surprisingly, the pollock stock has declined even as the overall stock of predators for pollock has declined, which is a result of decreases in the cod population [45].

The growth of each species is assumed to follow a simplified multispecies surplus production model as shown in Eq. (1). Annual biomass estimates (x_{iy}) and total catch (h_{iy}) for species i in year y are available for the years 1978 through 2010 from the Stock Assessment and Fishery Evaluation (SAFE) report from the Alaska Fisheries Science Center [20,4,45,49]. All species are assumed to follow a discrete logistic growth function where (r_i) is the intrinsic growth rate for each species, (η_i) is a density dependent factor related to the carrying capacity, and $(\alpha_{i,j})$ is an interaction term between species i and j. The stock dynamics for each species can be expressed as:

$$x_{i,y+1} = (1 + r_i)x_{iy} + \eta_i x_{iy}^2 + \sum_{j\neq i}^{n-1} a_{ij}x_{iy}x_{jy} - h_{iy},\ i = 1, .., n. \tag{1}$$

Estimates of the parameters in Eq. (1) are taken from [25], and are provided in Table 1. As the errors are likely correlated across equations due to the same unobserved environmental, climate, and other factors, [25] uses iterative seemingly unrelated regression (SUR), which is a feasible generalized least squares estimator that converges to the maximum likelihood estimates and provides consistent and asymptotically efficient parameter estimates using the standard assumption that the errors are correlated across equations, but not across observations in each equation [14,52]. The iterated SUR model produces parameter estimates that are consistent in the presence of heteroscedasticity and serial correlation but will produce biased standard errors and, while not implemented here, could be corrected using the techniques described in [35] and [5].

As seen in Table 1, each species' own stock parameters are as expected, leading to classical concave logistic growth curves. Also important is that arrowtooth has a negative and statistically significant impact on the growth of cod and pollock, which is consistent with the proposition that arrowtooth is a nuisance species. The results also suggest that increases in the cod stock increase the growth of arrowtooth, and increases in the pollock stock reduce the stocks of both arrowtooth and cod. As both $a_{cod,plck}$ and $a_{plck,cod}$ are negative, this finding is suggestive of a competing species relationship. Consistent with [23], it is possible that adult cod prey on juvenile pollock and adult pollock prey on juvenile cod. However, as $\alpha_{plck,cod}$ is not statistically significantly different from zero, while $\alpha_{cod,plck}$ is marginally statistically significant at the 10% level, the results suggest that adult pollock predation on juvenile cod is the dominant predator-prey relationship.

2.2. Social planner's optimization

Given that arrowtooth reduces the growth of both cod and pollock, as shown in Table 1, it is possible that it would be economically optimal to subsidize the harvesting of arrowtooth to maximize the harvest of the other two species. To explore the role of a nuisance species on the optimal harvesting of all three species, a multispecies bioeconomic model is set up in two stages. In the first stage, vessels choose their profit maximizing output bundle on each trip (which is constrained by their harvest technology and incorporates joint production across species) and the number of trips to take with each gear type to maximize their annual profits.[1] In the second stage, the social planner chooses the optimal

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[1] The vessel optimization problem is defined in the Appendix.