ABSTRACT

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Single species management of multispecies fisheries ignores biological interactions in addition to important technological interactions resulting from the multiproduct nature of firms' production often to the detriment of the health of the ecosystem, the stocks of fish species, and fishery profits. This dissertation solves a dynamic optimization problem of maximizing the net present value from a three species fishery and uses numerical optimization techniques to determine the optimal harvest quota of each species given the biological and technological interactions. The model is then extended to the case of a nuisance species, a species that lowers the value of the fishery by negatively affecting the growth of other species in the ecosystem, and has little harvest value of its own. As approaches for ecosystem-based fisheries management are developed, results demonstrate the importance of focusing not only on the economically valuable species interact, but also on some non-harvested species, as they can affect the productivity and availability of higher value species.

This study uses the arrowtooth flounder, Pacific cod, and walleye pollock fisheries in the Bering Sea/Aleutian Islands region of Alaska as a case study and finds the net present value of the fishery is decreased from $20.7 billion to $8.5 billion dollars by ignoring arrowtooth's role as a nuisance species on the growth of Pacific cod and walleye pollock. The optimal subsidy on the harvest of arrowtooth summed over all years is $35 million dollars, which increases the net present value by $273 million dollars, after accounting for the subsidy.

OPTIMAL MULTISPECIES HARVESTING IN BIOLOGICALLY AND TECHNOLOGICALLY INTERDEPENDENT FISHERIES

By

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List of Acronyms

ABC	Allowable Biological Catch
AFA	American Fisheries Act
AKFIN	Alaska Fisheries Information Network
BSAI	Bering Sea / Aleutian Islands
CAS	Catch Accounting System
CDQ	Community Development Quota
CFEC	Commercial Fisheries Entry Commission
CP	Catcher Processor Vessel
CV	Catcher Vessel
EEZ	Exclusive Economic Zone
EMEY	Ecosystem Maximum Economic Yield
FMP	Fisheries Management Plan
GOA	Gulf of Alaska
MSA	Magnusson-Stevens Act
MSEY	Maximum Sustainable Ecosystem Yield
MSY	Maximum Sustainable Yield
NPFMC	North Pacific Fisheries Management Council
NPV	Net Present Value
PCC	Pollock Conservation Cooperative
SAFE	Stock Assessment and Fishery Evaluation
TAC	Total Allowable Catch
WPR	Weekly Production Report

1. *Background*

1.1 Introduction

The need for ecosystem based fisheries management is well recognized [1-3], but substantial obstacles remain toward implementing these approaches given 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 relationships between species if multiple species are caught jointly or vessels allocate their effort among multiple target species. Ignoring these biological and technological multispecies aspects of fishery management often results in the declining 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 [4]. Likewise, there are numerous studies of the multiproduct nature of firms' production of multiple fish species using dual estimation models [5-9].[1] These studies generally reject input/output separability, which implies that fishing technology should be measured in a disaggregated manner. Aggregating data will result in a misspecification of the fishing technology if the fishing technology rejects input/output separability [10]. With the exception of Singh and Weninger [11], previous studies attempting to account for technological interactions within bioeconomic models [12, 13] typically assume that only a single composite input

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[1] See Jensen 10. Jensen, C.L., *Applications of Dual Theory in Fisheries: A Survey.* Marine Resource Economics, 2002. **17**: p. 309-344. 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 as may not be the case in many fisheries.

These technological interactions among species manifest themselves as bycatch, combined harvesting, multiproduct fishing vessels, economies or diseconomies of scope, and as adjustments to the allocation of effort across species. These technological interactions can have significant impact on the successful management of the fishery. Vessels that exhibit joint production technology cannot produce one target species without also catching other species at the same time and without incurring additional costs. If a vessel's technology is joint in production, policies that fail to take this into account are likely to result in increased discarding or highgrading of exploited species.[2]

As ecosystem based approaches are developed, the impact of non-harvested species should not be overlooked. In economic models, non-harvested species have been included as bycatch and discards [11, 14, 15], or as harvest constraints via bycatch quotas [16]. However, non-harvested species can be predators or prey for the target species and thus impact the stock dynamics of target species. As a result, this likely leads to changes in optimal harvesting strategies for the target species. One example of a non-harvested species that can impact target species harvesting strategies is a nuisance species which lowers the value of the fishery by negatively affecting the growth of the other species in the ecosystem even though it has little harvest value of its own. Chapter 4 explores how a nuisance species impacts the optimal multispecies harvesting in a three species ecosystem, and explores how a subsidy on the nuisance species can increase the net present value of the fishery.

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[2] Highgrading is defined as the practice of discarding legal sized but relatively smaller fish and landing relatively larger fish. This behavior is often a result of a quantity restriction on harvest such as a quota.

This dissertation solves a dynamic optimization problem of maximizing the net present value (NPV) from a three species fishery while estimating the growth and vessel production parameters to determine the optimal harvest quota of three species in the fishery. The theoretical model highlights the importance of both biological and technological interactions when determining optimal quota levels in a multispecies or ecosystem-based management approach. The empirical results demonstrate that some gear types are found to exhibit jointness in production, as well as economies and diseconomies of scope. The numerical optimization results demonstrate that the biological interactions have a substantial impact on the optimal outcome. Diseconomies of scope result in a net cost increase of $233 million dollars for the entire fishery, and a substantial increase in the harvesting of arrowtooth flounder is optimal.

The contribution of this study to the understanding of fisheries economics includes (i) the use of a bioeconomic model that incorporates biological and technological interdependence among species, (ii) examining how single species management differs from multispecies management in terms of net present value and stock abundance, (iii) estimating all of the parameters of the growth and profit equations to allow for comparison of the relative importance of these interactions in multispecies management, and (iv) exploring the role of optimal harvesting of a nuisance species (arrowtooth flounder) in the context of multispecies fisheries management.

1.2 A Three Species Ecosystem

This study uses the walleye pollock, Pacific cod, and arrowtooth flounder (hereafter referred to as pollock, cod, and arrowtooth, respectively) fisheries in the Bering Sea/Aleutian Islands (BSAI) region of Alaska as a case study. Between 1990 and 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% 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. This is a simplification of reality as both pollock and cod have shown cannibalistic behavior towards their young, and juvenile pollock, cod and arrowtooth are all prey for adult pollock, cod and arrowtooth [17-19].

Aydin et al. [20] found for the years 1980-1985 that the two keystone species in the Eastern Bering Sea were pollock and cod, while a more recent study between 1990 and 1993 has shown the role of cod to be in decline, while pollock maintains its central role in the Bering Sea ecosystem [17, 20, 21]. A major predator of pollock is the arrowtooth flounder which was estimated in 2003 to account for approximately half of pollock consumption [22]. The increase in the arrowtooth flounder population and predation upon pollock is believed to be responsible for the decline in pollock stocks since the early 1990s [17, 21, 23]. This decline has occurred even as the total population of pollock predators has decreased over that period, largely due to decreases in the cod population [24]. As Pacific cod and arrowtooth flounder compete for pollock and other prey species, it is not surprising that the recent decline in the cod population has been matched by an increase in the arrowtooth flounder population. The nature of these interactions is estimated empirically in section 3.1 using a reduced form multispecies surplus production model of stock dynamics.

1.3 The Fisheries

There are three different types of vessels operating in these three fisheries utilizing five different gear types. The first type of vessel is motherships that do not catch any fish themselves, but rather act as a floating processor that accepts deliveries from catcher vessels. Second, catcher processors (CPs) both catch and process their catch while at sea and typically take trips lasting a few weeks. Finally, catcher vessels (CVs) catch fish at sea and deliver to onshore processors, motherships, or, occasionally, catcher processors. They typically take trips lasting one day to a week or more. CPs are larger than their equivalent geared CV, and processing their catch onboard allows them to stay at sea longer because their catch has been processed into a more stable form. This also allows them to travel further distances and harvest in less dense species aggregations where the potential for non-target catch is much lower.

This study focuses on ex-vessel revenues and costs of the harvesting of fish, and therefore treats the mothership sector like any onshore processor, excluding them from the analysis. The CP boats tend to be larger in size than the CVs and average 156 feet in length and 938 gross tons in this study, while the CVs average 86 feet in length and 159 gross tons. The extra capacity for the CPs allow them to stay at sea longer than the CVs and travel further to find better fishing areas, which would be unprofitable for the CVs.

Currently, the five gear types used in these fisheries are jig, longline, non-pelagic (bottom) trawl, pot, and pelagic (mid-water) trawl. Pollock is currently only targeted using pelagic trawl gear by both CVs and CPs. Cod is targeted by all gear types except pelagic trawls. Jig harvests of cod are small relative to other gear types and have no CP sector. Therefore jig gear is excluded from the analysis. Both CVs and CPs use the remaining four gear types in various amounts to catch cod as dictated by their gear specific quota allocations. Arrowtooth does not have a target fishery in the BSAI, but is caught incidentally by both CVs and CPs using pelagic and non-pelagic trawl and longline gear.

Each gear type represents a fundamentally different harvesting technology. Longline vessels catch fish by floating a longline of baited hooks anchored to the sea floor. These longlines can be up to a mile in length, and are typically left out at sea for approximately 24 hour soak time before retrieval. Vessels often have multiple longlines in the water at the same time, which are retrieved with a power wench. Pot vessels are similar to longline vessels, but are equipped with metal cages (pots) instead of longlines. These pots are attached to buoys on the surface, and are retrieved after a multiple day soak with a power wench. Location and bait choice determine the mix of catch of both longline and pot vessels. These two vessel types are similar enough that a longline vessel could, with access to enough pots, also be used for crabbing, and vise versa.

Trawl vessels represent a different type of harvesting technology, and it is rare that a vessel would be flexible enough to do both trawling as well as pots or longlines. Trawlers catch fish by towing a cone shaped net, which vary in mesh size, through a dense aggregation of fish. The fish are then brought aboard ship via a large stern (rear) ramp using a very large wench and power drum. Most pelagic trawl nets have doors on the front of the net to hold it open. The non-pelagic trawl nets also have a heavy weighted chain or bar at the bottom of the net opening which is meant to keep the net near the ocean floor. Pelagic trawl vessels are able to adjust their species composition by the use of sonar and other fish finding technologies to target large pollock aggregations and have a low catch rate of non-pollock species relative to the bottom trawls. Bottom trawls use the same fish finding technologies to target individual species, but their target species do not aggregate in large masses above the seafloor like pollock. As their targets, such as cod, live on the ocean floor along with halibut, rockfish, sablefish, and many different flounder species, the bottom trawls are less able to control their species mix.

Once onboard a catcher processor, it does additional processing to its catch. This could be as simple as bleeding the fish, or as complicated as the production in a shorebased processing plant. The CP longine and CP non-pelagic trawl vessels typically only head and gut their catch, and are much less sophisticated than the CP pelagic trawl vessels. The CP pelagic trawl vessels have nearly identical processing equipment to a shorebased processor. After a trawl net is hauled in, it is dumped into a holding tank and the fish are put through a sorter, which sorts the fish by size. The pollock are then put through the filleting machine which able to remove and separate the fillets, roe sacks, and innards with relative accuracy. Depending on the relative price of final products, some of the fillets will be put in the surimi press and processed into surimi. The leftover from the filleting machine will have its oils extracted. The fish oil is retained either for sale or for use in the boiler, depending on the relative prices of fish oil and diesel fuel. After the oil has been captured, the final product will be put through the fish meal line, and will be sold as fish meal. Nearly all, if not all, of a CP pelagic trawl vessel's catch will be transformed into a finished product for sale.

1.3.1. Walleye Pollock

The pollock fishery represents over 40% of global whitefish production, and is the largest fishery in North America by volume [21]. Between 2005 and 2009, the BSAI pollock harvest averaged 1.23 million tons with an average ex-vessel value of $380 million [21, 25, 26]. Pollock are processed into three forms: fillets, whole (head and gutted), and surimi (ground walleye pollock fillets that are used in fish sticks and imitation crab meat among other products). Each form holds a relatively even market share. An important component of the fishery is the production of pollock roe during the pollock A season (January-March). The second or B season, which does not include roe, is open from approximately June through October. Both seasons operate under a total allowable catch (TAC) quota, with 40% of the total annual pollock TAC allocated to the A season and 60% to the B season.

Historically, the walleye pollock fishery was exploited by foreign vessels until the advent of the U.S. Exclusive Economic Zone (EEZ) in 1977 through the passage of the Magnuson-Stevens Fishery Conservation and Management Act of 1976 (MSA) [21, 27]. As a result, U.S. vessels began fishing for pollock in 1980 and were able to catch 99% of the quota by 1987. The fishery remains dominated by domestic vessels. The next major regulatory event was the so-called Inshore/Offshore Decision which affected the fishery after 1992. After 1992, and continuing through 1998, the inshore/offshore TAC is determined by subtracting 4-6 percent for bycatch allowances and 7.5 percent for the community development quota (CDQ) from the TAC for the entire fishery. The remainder of the Bering Sea and Aleutian Islands pollock TAC is allocated 65 percent to the offshore sector (those vessels not delivering to an on-shore processor) and 35 percent to the inshore sector [28].

The passage of the American Fisheries Act (AFA) in 1998 drastically changed the pollock fishery. The CDQ was increased to 10 percent, the offshore allocation was reduced to 50 percent, and foreign flagged vessels were completely removed from the offshore sector. The offshore allocation (50%) was divided with 36.6 percent to catcher processor vessels, 3.4 percent to catcher vessels delivering to catcher processor vessels, and 10 percent to motherships and their catcher vessels [29].

The AFA also provided for the establishment of the Pollock Conservation Cooperative (PCC). As a result, nine cooperatives were formed consisting of one catcher processor cooperative, a single mothership cooperative, and seven catcher vessel cooperatives (one for each on-shore processor).[3] These cooperatives are allocated their share of the TAC based mostly upon the historical harvest of their participant vessels. The process of quota allocation among vessels within a cooperative is unknown, but is a potential area for future research.

1.3.2. Pacific Cod

Pacific cod accounts for the second largest groundfish harvest in the BSAI averaging 0.183 million tons over the period 2005-2009 with an average ex-vessel value of $148 million. Pacific cod is a major predator of pollock in the wild. The Japanese began harvesting Pacific cod via longline in the Bering Sea/Aleutian Islands (BSAI) area in the 1960's for the frozen fish market. In 1964 they began trawling for pollock with Pacific cod as an important bycatch species. On occasion, cod became a target species for these vessels when high concentrations were found during pollock fishing [24]. This fishery was also dramatically impacted by the passage of the MSA in 1976. By 1981 a U.S. and joint venture fishery began operations. While the foreign and joint venture fleet dominated catches until 1989, they were completely displaced by 1991 by the domestic fishery, which currently catches cod with trawl, longline, pot, and jig gear.

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[3] NOAA Regional Office - http://www.fakr.noaa.gov/ram/afa.htm.

The number of seasons and season length for Pacific cod varies by gear type. Fishing with hook and line gear and jig gear is open year round with two and three seasons, respectively. Pot gear has two seasons and is closed during the summer between June 10 and September 1st. Trawl gear has three seasons and is closed during the winter between November 1 and January 20th.

The TAC also varies by gear type. Similar to the pollock fishery, 10.7 percent of the TAC is allocated to the CDQ, and the remaining 89.3 percent is allocated among the gear types. Hook and line catcher vessels receive 2.2%, hook and line catcher processors receive 48.7%, jig vessels receive 1.4%, pot catcher vessels receive 8.4%, pot catcher processors receive 1.5%, trawl catcher vessels receive 22.1%, AFA trawl catcher processors receive 2.3%, and non-AFA catcher processors receive 13.4%. The TAC for each gear type is also allocated differently across seasons, which are not described here.

1.3.3. Arrowtooth Flounder

Arrowtooth is a low value species with no target fishery. It is caught primarily with both types of trawls and longline gear participating in the cod and pollock fisheries and is largely discarded when caught. The average exploitation rate of arrowtooth flounder in the BSAI between 2000 and 2010 was only 1.5% of the stock size, and only 20% of the TAC from 2008 and 2010. Catches averaged almost 13,000 tons between the years 1977 and 2010, but catches are increasing in recent years. The 2010 catch of almost 15,000 tons was less than ten percent the allowable biological catch (ABC) of 156,300 tons, and less than twenty percent of the TAC of 75,000 tons [23]. This outcome is explained by the lack of arrowtooth flounder as a target species and high discard rates that decrease recorded total landed amounts. Amendment 80 to the BSAI fisheries management plan (FMP) was implemented in 2008 and aimed to reduce bycatch in the non-AFA CP non-pelagic trawl fleet. It has resulted in increased retention rates above 75% in 2008-2009, despite averaging of 14% over the period 1985-1999. However, the largest discards of arrowtooth flounder still occur in the Pacific cod fishery and other flatfish fisheries via trawl and longline gear [23].

A major reason why arrowtooth has not developed a targeted fishery is that once landed, a parasite attached to the arrowtooth excretes an enzyme which softens the flesh and makes it unpalatable for human consumption [30]. The texture of its flesh has been described as "fish oatmeal." 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 [17, 30, 31]. As the current catches are far below the current TACs, and are extremely below the ABC, there is a potential to substantially increase the harvesting of arrowtooth in the BSAI if vessels find it profitable. However, at the current time it does not appear to be very profitable, and thus no target fishery exists in the BSAI.

1.3.4. Interactions among Fisheries

Unfortunately for fishery managers, ecological interactions are not the only interactions that need to be taken into account in multispecies fisheries management. Fishing with non-specific gear, such as trawls, results in significant incidental catch of non-target species. Nearly all of the Bering Sea pollock and arrowtooth flounder are caught via trawl, and approximately one third of the Pacific cod catch is caught via trawls [25]. If vessel's harvesting technology exhibits jointness in inputs, this implies that separate production processes for each species do not exist, and vessels cannot alter their portfolio of harvests without costly adjustments. Vessels could also exhibit economies of scope across multiple species where there are cost complementarities in the harvesting of multiple species such that it is cheaper to harvest multiple species than each one individually. However, because some processors (particularly the catcher processor vessels) may be set up for only one species, vessels may prefer to keep harvests as homogenous as possible. It is also possible that the cost of separating multiple species is high, and vessels could exhibit cost anti-complementarities or diseconomies of scope from catching multiple species on any given trip. In these cases, vessels are likely to adjust their harvest among species by targeting different species on different trips in response to relative prices.

In addition to fishing with non-specific gear, some vessels in the BSAI switch gear to alter their expected portfolio of species caught. Over half of the CVs using pelagic gear during the year switch to some other type of gear, mostly non-pelagic gear, during other parts of the year. CPs are much less inclined to switch gear, but a good portion of CPs and CVs fish in both the BSAI and the Gulf of Alaska (GOA) during different parts of the year. There are a number of CVs who also switch between harvesting cod with longlines as well as via pot gear. These vessels are also generally involved in the BSAI crab fisheries using the pot gear during the crab season as well. Other longline vessels also harvest sablefish and halibut, primarily in the GOA, during other parts of the year when they are not targeting cod. Non-pelagic trawl vessels typically target flat fish species (yellowfin and rock sole), rockfish, or Atka mackerel during other times of the year. Generally, the only species caught with pelagic trawls is pollock. If vessels wanted to target other species, they would likely switch to a more effective technology for the other species. The seasonality of these and other fisheries may also provide some incentives for vessels to switch gear and fisheries over the course of a year. Many of the trawl vessels use pelagic gear to harvest pollock and then switch to non-pelagic trawl gear to harvest cod during a particular cod trawl season, but switch back to pelagic gear and harvest pollock during the more valuable pollock A season. The adjustment of effort between these two species is likely to be a function of the relative prices and harvest costs of each species, relative abundance in the BSAI, and quota available to each vessel.

1.4 Theoretical Motivation

Many bioeconomic models, such as those of Quirk and Smith [32] and Silvert and Smith [33], have modeled biological interactions as an externality inflicted by one species on another. Hannesson [34] uses a predator-prey bioeconomic model and is able to derive a condition on the optimal harvest such that the rate of return on investing the additional rent from harvesting a unit of species *i* must be equal to the rate of return on leaving that unit of species *i* in the sea. With the exception of the studies by Singh and Weninger [11], Conrad and Adu-Asamoah [12], and Agar and Suitinen [35], these models focus solely on the biological interactions between species in an ecosystem. By ignoring the technological interactions in a fishery, these models recommend policies that may be ineffective if firms cannot adequately adjust to the new regulations. Squires and Kirkley [9] show that when faced with a trip quota on sablefish, firms cannot sufficiently decrease their catch of sablefish. Firms respond by discarding a large amount of sablefish at sea, thereby eliminating the purpose of the trip quota.

There have been only a few attempts to model empirically both the technological and biological interactions among fish species. Singh and Weninger [11] use a simulation framework to explore the impact of scope economies and multispecies harvesting on discards in a multispecies bioeconomic model. Flaaten [36, 37] and Sumaila [38] ignore the technological interactions among species and simulate these ecosystems based on the available biological information about each species and the interactions among species. The implicit assumption of single species models is that harvests and stocks of one species do not affect the harvests of a different species. However, in many fisheries with combined harvesting of species, this is not true. A perfect example is the pollock, cod, and arrowtooth flounder fishery in the BSAI where these species are fished jointly with the same non-specific gear throughout the year.

This study addresses two shortcomings found in previous fisheries literature. The first is a lack of biological studies on which to base the biological stock dynamics and interaction parameters. This issue is overcome by empirically estimating the growth and interaction parameters simultaneously for all species included in the model. This empirical strategy is a departure from the literature [12, 36, 37, 39-42]. Typical studies estimate bioeconomic models using ordinary least squares estimation techniques, which results in consistent but inefficient estimates if there is correlation across equations. The stock growth equations include growth parameters as well as stock interaction effects between species so that the interaction between species i and species $j = 1,2,\ldots,n-1$ are taken into account. Estimating the equations simultaneously allows the errors to be correlated across equations and the parameters to be estimated more precisely.

By also estimating the naïve model without technological and biological interactions, this empirical strategy allows the calculation of additional benefits gained from multispecies management relative to single species management. Therefore, by more precisely predicting the stock effects of harvesting, a more accurate model of the optimal harvesting of these species can be created to maximize the net present value of these resources. This estimation strategy also allows for a better determination of which interdependencies—biological or technological—have a greater impact on the predictions of the model, the health of the resource stocks, and profits from the fishery.

The second unresolved issue in the previous fisheries literature is that ignoring the behavior of the harvesting sector may lead to perverse outcomes for fishery management [43]. This gap in the literature is addressed by using estimates of a flexible functional form of the firm's technology to determine optimal harvests via a dynamic optimization problem. Vessels are assumed to minimize the cost of harvesting their chosen output bundle. As each gear type represents a different harvesting technology, cost functions and conditional input demand functions are estimated separately for each gear type on each trip using iterated seemingly unrelated regression. Similarly, as CPs and CVs likely have different harvesting technologies for the same gear type, separate cost functions are estimated for each gear type used by each class of vessels. With four gear types for each vessel class, a total of eight cost functions are estimated. The parameters of the vessels' cost functions are used in combination with the growth parameters to determine the optimal harvest quota and stock at each point in time using the bioeconomic model, which is a unique feature of this study.

Using highly disaggregated harvest and cost data in addition to a time series of stock estimates, this study provides better estimates of each vessel's technology than the previous empirical bioeconomics literature. With better estimates of how these multiproduct fishing vessels transform multiple inputs into multiple outputs, the optimal harvests from the bioeconomic model take these interdependencies into account so as to avoid perverse outcomes.

Allowing for biological and technological interactions is also more general than previous approaches, where single species management could be included as a special case if no biological or technological interactions exist in the fishery. However, this study may not include all of the relevant biological and technological interactions occurring in this fishery. Numerous other species are intentionally and unintentionally harvested in this fishery, which are not taken into account. This study can therefore be viewed as a general multispecies fisheries model that can be expanded, conditional on the availability of data, to include other harvested and non-harvested species in an ecosystem-based fisheries management approach. For example, this model could be expanded to examine the role of halibut and salmon bycatch limits on this fishery, which are also of direct policy relevance to fishery managers in Alaska.

1.5 Data

This study uses data from 2006-2009 for all CVs and 2000-2010 for all CPs that had a trip in which arrowtooth, cod, and pollock combined accounted for at least 95% of trip revenue.[4] This requirement eliminated a number of non-pelagic trawl vessel trips in which cod was caught in combination with various flatfish species. This was done to focus only on the three species in consideration for this study. The landings data for the catcher vessels are taken from the Alaska Fisheries Information Network (AKFIN) database of fish tickets. Fish tickets record the landings and value of all species caught (not only the three species of interest here), gear type, starting and ending trip dates, and the location of catch and port of delivery for each vessel trip selling the landings to a processor. The fish tickets are filled out by the processor at the time of sale, and are corrected by the Commercial Fisheries Entry Commission (CFEC) after the season to account for various bonuses that accrue to the catcher vessels such as their pollock roe bonuses.

CPs, however, do not sell their catch to another processor and thus generally do not have fish tickets to record their landings. Therefore, the catcher-processor vessel data are taken from the Catch Accounting System (CAS), which is the official account of vessel catch. The CAS uses information that the CPs submit in their Weekly Production Reports (WPR), which record weekly production statistics, and use accepted product recovery rates and observer information to calculate their weekly catch. These two datasets provide information on all of the revenues from these vessels.

The dataset consists of 177 CVs from 2006-2009 and 94 CPs from 2000-2010, both of which are unbalanced panels. The fewest number of trips taken by CVs in the dataset is 1, and the maximum is 52. The CPs operated a minimum of one week and a maximum of 50 weeks of the year. The total number of usable CV trips is 5,172,

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[4] The first year that the crew size information was collected in the fish tickets was 2006. During that year over 60% of trips did not include crew size on the fish ticket, and were thus excluded from the analysis.

including 179 longline vessel trips, 750 non-pelagic trawl vessel trips, 781 pot vessel trips, and 3,462 pelagic trawl vessel trips. The total number of usable CP weeks is 11,503, including 7,312 longline vessel weeks, 345 non-pelagic trawl vessel weeks, 398 pot vessel weeks, and 3,448 pelagic trawl vessel weeks.

Three datasets include information about vessel characteristics. These datasets come from the State of Alaska, the Federal vessel registration listing, and U.S. Coast Guard vessel registry database. The vessel characteristics from the state of Alaska include length, year built, gross tonnage, net tonnage, horsepower, hold capacity, live hold capacity, refrigeration equipment, and fuel capacity. The Federal vessel registration listing includes length and gross and net tonnage. The Coast Guard vessel registry database includes length, gross and net tonnage, year built, horsepower, and vessel breadth and width. The data from each source are slightly different, presumably due to errors in entering or reporting the data. Therefore, the Coast Guard data are used unless the values for some of the variables appear to the author to be grossly incorrect, in which case values from the State of Alaska are used first, followed by values from the Federal database.

The only variable input used in this study is crew services, which is equal to the crew size times the number of days at sea for a given trip. CPs are assumed to fish for a full 7 day week if they are at sea and submit a WPR. Hourly wage data are taken from the Bureau of Labor Statistics' State Occupational Employment and Wage Estimates Annual survey for the Farming, Fishing, and Forestry Occupations in Alaska and are deflated using the Consumer Price Index for Anchorage, AK.[5] No reliable fixed cost

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[5] Other variable costs considered include fuel costs, but the amount of fuel used is not known. Based on their harvest location and port of delivery, I have a rough idea of the distance they travel on each trip, but I

information on these vessels exist, and therefore, this study does not measure profit, but rather a proxy based on the net operating rent accruing to vessels in the fishery.

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lack a mechanism to link distance traveled with fuel consumed. I have some idea of the annual fuel costs of a very small subset of trawl vessels for 2003-2004, and did some regression analysis linking distance traveled to fuel consumed based on their vessel characteristics, but felt that it would likely be inappropriate to use these regression coefficients to predict fuel consumption outside this small sample with only one gear type. Therefore, I have decided that it would introduce more error by including it in the analysis.

2. Bioeconomic Model

The problem this study solves is maximization of the discounted profits of the pollock, cod, and arrowtooth flounder fisheries in the Bering Sea over a 25 year time horizon with a terminal value function equal to a sustainable harvest at ending stock levels in perpetuity, subject to the species growth equations and quota constraints. This problem is solved in two parts. In the first stage, vessels minimize the cost of their chosen output bundle on each trip, and determine the profit maximizing number of trips to take with each gear type in a year given input and output prices and stock levels. In the second stage, the fishery manager (social planner) determines the optimal annual quotas for each species given technological and biological interdependencies to maximize the net present value of the three-species fishery.

2.1 Vessel Optimization

This section examines the case of a single vessel in a given year, and therefore omits vessel and year subscripts that are added later. Vessels are assumed to maximize their profits over the course of a single year by choosing their optimal portfolio of harvests on each trip t and the optimal number of trips for each gear type. In the case of CPs, a trip represents an operating week of 7-day duration. The number of trips a vessel takes with each gear type is a function of input and output prices, the annual quota for each species, its share of the quota for each species for each gear type, and fixed vessel characteristics. Quota share allocated to each vessel for each gear type is assumed to be exogenous and fixed at the current levels because this is the way the regulator and industry have come to regard the allocation process. However, it is not uniform across vessels, and is generally understood to be based on each vessel’s historical harvest of each species with each gear type. As quota are allocated for each gear type separately, the model assumes the decision of how many trips to take with each gear type in a given year is independent of the number of trips it takes with all other gear types. Therefore, the model focuses on the annual decision of how many trips to take with each gear type rather than focusing on each discrete choice of which gear type to use on a given trip.

This ignores the seasonality of the fishery, as each vessel chooses the optimal number of trips in each year based on annual prices and quota levels, fixed vessel characteristics, and fixed quota shares. Therefore, the model does not address the intra-annual variation in value from the different seasons in the pollock fishery, but rather addresses inter-annual changes in value from the pollock, cod, and arrowtooth fisheries. This model can thus be regarded as a combined count and continuous model, which is found by Smith [44] to provide better in sample and out of sample predictions of macro behavior than a discrete choice model of harvester behavior. Thus, this model is more useful for long term projections of fish populations and profits from harvesting than the impacts of short term management actions.

At the beginning of each year, stocks, quotas, quota shares, and input and output prices throughout the year are assumed known to the decision maker. While a simplification, this is not entirely unrealistic. The stock and quota levels are generally known in November, quota shares generally do not change, and as vessels are allocated quota they are able to contract with processors for the price of their catch throughout the year. While prices may not be known exactly to the vessels, they must make their plans based on the best price information available. The general level of prices is are anticipated to a considerable degree of accuracy based on longer term variation in prices of these species and prices of other comparable global whitefish species.

The conditions facing a given vessel in a given year on trip t, $t = 1,\ldots,T$, are described by

$p_t = (p_{1t},\ldots,p_{nt})$ = a vector of output prices for species $i = 1,\ldots,n$ prevailing at trip t,

w_t = a vector of variable input prices prevailing at trip t,

$x = (x_1,\ldots,x_n)$ = a vector of fish stocks by species $i = 1,\ldots,n$ in the current year,

Z = a vector of fixed vessel characteristics,

$\overline{q} = (\overline{q}_1,\ldots,\overline{q}_n)$ = a vector of aggregate annual quotas by species for the fisheries,

$\omega_g = (\omega_{g1},\ldots,\omega_{gn})$ = a vector of shares of $\overline{q} = (\overline{q}_1,\ldots,\overline{q}_n)$ allocated to an individual vessel by gear type, $g = 1,\ldots,G$,

where p_t, w_t, and x are assumed to be strictly positive. The choices made for each vessel for each trip are described by

z_t = a vector of variable input quantities chosen for trip t,

T_g = number of total trips planned for gear type choice g before switching gear types, g = 1,…,G,

$h_{gt} = (h_{g1t},\ldots,h_{gnt})$ = a vector of harvested quantities of each species $i = 1,\ldots,n$ using gear type g at time t,

where z_t and h_{gt} must be nonnegative. The choices are constrained by gear- and species-specific quotas described by

$q_{g,t+1} = q_{gt} - h_{gt} \geq 0$, $g = 1,\ldots,G$; $t = 1,\ldots,T-1$;

where

$q_{gt} = (q_{1gt},\ldots,q_{ngt})$ = a vector of remaining quotas by species and gear type at time t.

The annual quotas for an individual vessel, i.e., the remaining quota at the beginning of the first time period, is thus represented equivalently in terms of ω_g and $\overline{q}$ such that an individual vessel's annual quotas by species, $i = 1,\ldots,n$, for gear type g are represented by

$$\omega_g * \overline{q} = (\omega_{g1}\overline{q}_1,...,\omega_{gn}\overline{q}_n)$$

where "*" denotes an element-by-element product. Replacing the vector of remaining quotas by species and gear type at time t by

$$q_{gt} = \omega_g * \overline{q} - \sum_{t=1}^{t-1} h_{gt} \ ,$$

the constraints can be rewritten as

$$q_{g,t+1} = \omega_g * \overline{q} - \sum_{t=1}^{t} h_{gt} \geq 0,\ t = 1,...,T-1.$$

The profit maximization problem for a given vessel at any point during the year can thus be expressed as[6]

$$\max_{\substack{h_{g\tau},T_g \\ \tau=t,...,T_g}} \ \pi_{gt} = \sum_{\tau=t}^{T_g} \rho^{\tau} \left\{ p_\tau h_{g\tau} - C_g(h_{g\tau} \mid w_\tau, x, Z) \right\}$$

$$\text{s.t. } q_{g,t+1} = \omega_g * \overline{q} - \sum_{t=1}^{t} h_{gt} \geq 0,\ t = 1,...,T-1,$$

where ρ is the intra-annual discount factor, $h_{lt} \equiv 0$ for all $l \neq g$, and C_g is a cost function for gear type g defined by

$$C_g(h_{gt} \mid w_t, x, Z) = \min_{z_t}\Big(w_t z_t \mid h_{gt} \in H_g(z_t, x, Z) \Big),$$

---

[6] For convenience, transposition is not indicated when vectors are multiplied together as a dot product.

which is assumed convex in h_{gt}, concave, non-decreasing, and linearly homogeneous in w_t, and twice continuously differentiable in both. Define $H_g(z_t, x, Z)$ as the harvest possibilities set for gear type g, which is assumed to be closed, bounded, non-empty, convex, and is contained in the positive quadrant for (x,z_t).

The Lagrangian of this optimization problem is

$$\max_{\substack{h_{g\tau}, T_g \\ \tau=t,\dots,T_g}} L_{gt} = \sum_{\tau=t}^{T_g} \rho^{\tau} \left\{ p_\tau h_{g\tau} - C_g(h_{g\tau} \mid w_\tau, x, Z) + \rho\mu_{\tau+1}\left(\omega_g * \overline{q} - \sum_{t=1}^{t} h_{gt} - q_{g\tau+1} \right) \right\}, \quad (1.1)$$

where μ_t is a vector of the Lagrangian multipliers for the constraints that harvests must be less than or equal to unused quota allocations by species and gear type. Maximizing the Lagrangian produces optimal choices $h^*_{gt} = h_g(p, w, x, Z, \overline{q}, \omega_g)$, and $T^*_g = T_g(p, w, Z, \overline{q}, \omega_g)$, and an optimal value of the Lagrangian $L^*_{gt} = L_{gt}(T^*_g, h^*_{gt}, \dots, h^*_{g,T^*_g})$ where $p = (p_t, \dots, p_{T^*_g})$ and $w = (w_t, \dots, w_{T^*_g})$.

Assuming that the optimal number of trips a vessel takes with each gear type, T^*_g, is continuous rather than discrete and further assuming an interior solution, the first order conditions with respect to the harvest of species i with gear type g at time τ and the number of trips with gear type g can be expressed as

$$\frac{\partial L_{gt}}{\partial h_{ig\tau}} = \left(\frac{\partial L_{gt}}{\partial T_g} \frac{\partial T_g}{\partial h_{ig\tau}} \right) + \rho^{\tau} \left\{ p_{i\tau} - \frac{\partial C_g}{\partial h_{ig\tau}} - \rho\mu_{i,\tau+1} \right\} = 0, \quad (1.2)$$

$$\frac{\partial L_{gt}}{\partial T_g} = \rho^{T_g} \left\{ p_\tau h_{gT_g} - C_g(h_{gT_g} \mid w_{T_g}, x_{T_g}, Z) + \rho\mu_{T_g+1}\left(\omega_g * \overline{q} - \sum_{t=1}^{T_g} h_{gt} - q_{gT_g+1} \right) \right\} = 0. \quad (1.3)$$

Rearranging equation (1.2) using equation (1.3) implies:

$$\rho\mu_{i,\tau+1} = p_{i\tau} - \frac{\partial C_g}{\partial h_{ig\tau}} \tag{1.4}$$

Using the envelope theorem, the marginal profit for an increase in the stock of species *i* and the marginal profit for an additional unit of aggregate quota for species *i* can be expressed as:

$$\frac{\partial L_{gt}}{\partial x_i} = -\sum_{\tau=t}^{T_g} \rho^{\tau} \frac{\partial C_g}{\partial x_i} \tag{1.5}$$

$$\frac{\partial L_{gt}}{\partial \overline{q}_i} = \omega_{gi} \sum_{\tau=t}^{T_g} \rho^{\tau+1} \mu_{i,\tau+1} \tag{1.6}$$

Using equations (1.4) and (1.6) implies:

$$\frac{\partial L_{gt}}{\partial \overline{q}_i} = \omega_{gi} \sum_{\tau=t}^{T_g} \rho^{\tau} \left\{ p_{i\tau} - \frac{\partial C_g}{\partial h_{ig\tau}} \right\}. \tag{1.7}$$

For purposes of social optimization, the optimal profit from the above annual vessel maximization problem using gear type *g* is denoted by

$$\pi_g^*(p, w, x, Z, \overline{q}, \omega). \tag{1.8}$$

2.2 Social Planner Optimization

In the second stage, the social planner takes vessel profit maximizing behavior as given and chooses the optimal annual quotas in each year $(\overline{q}_y)$ to maximize the net present value of the fishery where *y* indexes years. In a given year, the social planner aggregates over all vessels, $v = 1,\ldots,V_g$, and all gear types, $g = 1,..,G$, where V_g denotes the total number of vessels which have the potential to use gear type *g*. The number of potential vessels for each gear type is fixed for all years of the model, and assumed equal to the number of vessels that have used respective particular types of gear in the past. The social planner determines quotas based on

$R(x_{1y},\ldots,x_{ny})$ = a vector of surplus production (logistic) growth functions for each species, i=1,…,n,

$I(x_{1y},\ldots,x_{ny})$ = a vector of ecological interaction functions that determine how species interact in the ecosystem, i.e., predator, prey, competitive, symbiotic, etc., for each i=1,…,n,

as well as p_y, w_y, x_y, Z_v, and ω_{vg} where y subscripts are added to index years and v subscripts are added to index vessels. Therefore, the maximized annual profit by gear type g for each vessel v in year y is denoted as

$$\pi^*_{vgy}(p_y, w_y, x_y, Z_v, \bar{q}_y, \omega_{vg}) .$$

Aggregating over all gear choices for a given vessel defines each vessel's maximized annual profit as

$$\pi^*_{vy}(p_y, w_y, x_y, Z_v, \bar{q}_y, \omega_v) = (\pi^*_{v1y}, \ldots, \pi^*_{vGy}) ,$$

where $\omega_v = (\omega_{v1}, \ldots, \omega_{vG})$ is a vector of quota shares for each gear type for vessel v. Total annual profits can be represented by aggregating the annual profits for each gear as

$$\pi^*_y(p_y, w_y, x_y, Z, \bar{q}_y, \omega) = \sum_{v=1}^{V} \pi^*_{vy} ,$$

where V is the total number of all vessels, and $Z = (Z_1, \ldots, Z_V)$ is the vector of fixed vessel characteristics for all vessels.

The optimal values of harvest on each trip for vessel v in year y comes from the maximization of the Lagrangian in equation (1.1) is defined as the vector

$$h^*_{vgty} = h_{vgt}(p_y, w_y, x_y, Z_v, \bar{q}_y, \omega_{vg}) .$$

Similarly, maximization of the Lagrangian in equation (1.1) defines the optimal number of trips taken by vessel *v* with gear type *g* in year *y* represented by

$$T^*_{vgy} = T_{vg}(p_y, w_y, Z_v, \bar{q}_y, \omega_{vg}) . \tag{1.9}$$

Therefore, define the vector of optimal total harvest by species in year *y* as

$$h_y = \sum_{v=1}^{V_g} \sum_{g=1}^{G} \sum_{t=1}^{T^*_{vgy}} h_{vgty} .$$

From the individual vessel's problem, the vector of optimal total harvests is equal to the annual quota less the unused quota left over after the last trip, such that:

$$h_y = \sum_{v=1}^{V_g} \sum_{g=1}^{G} \left(\omega_{vg} * \bar{q}_y - q_{vg,T^*_{vgy}+1} \right) = \bar{q}_y - \sum_{v=1}^{V_g} \sum_{g=1}^{G} q_{vg,T^*_{vgy}+1} ,$$

where $q_{vg,T^*_{vgy}+1}$ is the vector of quota for gear type *g* remaining after vessel *v* takes its final trip in year *y* with gear type *g*. For this analysis, quota constraints for each species are assumed to be binding in each year $(q_{vg,T^*_{vgy}+1} = 0 \,\forall\, v = 1,...,V^g, g = 1,...,G)$, which is certainly the case in the pollock and cod fisheries, but is not likely to hold for the arrowtooth flounder fishery. The role of the arrowtooth flounder quota, harvests, and a potential subsidy on its harvests are examined in chapter 4.

The problem of maximizing the total discounted profits of this three species fishery over a 25 year time horizon for the fishery manager can be written as follows:

$$\underset{\bar{q}_y}{Max} \sum_{y=1}^{Y} \theta^y \left\{ \pi^*_y(p_y, w_y, x_y, Z, \bar{q}_y, \omega) \right\} + TV(\bar{p}, \bar{w}, x_Y, Z, \bar{q}_{Y+1}, \omega) , \tag{1.10}$$

subject to the growth of each species,

$$x_{i,y+1} = x_{iy} + R_i(x_{iy}) + I_i(x_y) - \bar{q}_{iy}, \quad i = 1,...,n, \tag{1.11}$$

where $\theta = 1/(1+\delta)$ is the discount factor, δ is the discount rate, *Y* = 25 years, $\bar{p}$ and $\bar{w}$ are the mean output and input prices for the five years preceding the steady state, the vector of quotas in the terminal period is equal to the vector of steady state growth for each species in the terminal period, $\overline{q}_{Y+1} = (R_i(x_{iY}) + I_i(x_Y), ..., R_n(x_{nY}) + I_n(x_Y))$, and $TV(\overline{p}, \overline{w}, x_Y, Z, \overline{q}_{Y+1}, \omega)$ is the terminal value function. The growth equations imply that the stock of species *i* in the following year is a function of the stock *i* in the current year, the density-dependent growth as a function of the current stock level, the growth from ecological interactions which is a function of the current stock of all species, and the annual quota for species *i* which is assumed to be completely harvested.

At the end of the time horizon, input and output prices, $\overline{w}$ and $\overline{p}$ respectively, are set to their mean of the five years prior to the steady state to reduce the dependence of the terminal value function on the stochastic elements which determine prices in each period. The terminal value function is equal to the rent from harvesting sustainable harvest levels for each species at the terminal stock value in perpetuity. Setting $x_{i,Y+1} - x_{i,Y} = 0$ and solving for the harvest:

$$h_{i,Y+1} = \overline{q}_{i,Y+1} = R_i(x_{iY}) + I_i(x_Y) \ , \tag{1.12}$$

where $h_{i,Y+1}$, represents the harvest of species *i* at the end of the time horizon. The terminal value function is then equal to:

$$TV(\overline{p}, \overline{w}, x_Y, Z, R_i(x_{iY}) + I_i(x_Y), \omega) = \frac{\theta^{Y+1}}{\delta} \left\{ \pi_Y^*(\overline{p}, \overline{w}, x_Y, Z, \overline{q}_{Y+1}, \omega) \right\}. \tag{1.13}$$

The Lagrangian expression for the problem is thus

$$\begin{aligned} L^{SP} = \sum_{y=1}^{Y} \theta^y & \left\{ \begin{aligned} & \pi_y^*(p_y, w_y, x_y, Z, \overline{q}_y, \omega) + \\ & \sum_{i=1}^{n} \theta \lambda_{i,y+1} \left[x_{iy} + R_i(x_{iy}) + I_i(x_y) - \overline{q}_{iy} - x_{i,y+1} \right] \end{aligned} \right\} + \\ & \frac{\theta^{Y+1}}{\delta} \left\{ \pi_Y^*(\overline{p}, \overline{w}, x_Y, Z, R_i(x_{iY}) + I_i(x_Y), \omega) \right\} \end{aligned} \tag{1.14}$$

where the λ_{iy} are Lagrangian multipliers for the stock constraints. The first-order necessary conditions for a maximum are:

$$\frac{\partial L^{SP}}{\partial \bar{q}_{iy}} = \theta^{y}\left\{\frac{\partial \pi_{y}^{*}}{\partial \bar{q}_{iy}} - \theta\lambda_{i,y+1}\right\} = 0,\ \ i = 1,\ldots,n, \tag{1.15}$$

$$\frac{\partial L^{SP}}{\partial x_{iy}} = \theta^{y}\left\{\frac{\partial \pi_{y}^{*}}{\partial x_{iy}} + \theta\lambda_{i,y+1}\left[1 + \frac{dR_i}{dx_{iy}} + \frac{\partial I_i}{\partial x_{iy}}\right] + \sum_{j\neq i}^{n-1}\theta\lambda_{j,y+1}\left[\frac{\partial I_j}{\partial x_{iy}}\right]\right\} - \theta^{y}\lambda_{iy} = 0, \tag{1.16}$$
$i = 1,\ldots,n, i \neq j,$

$$\frac{\partial L^{SP}}{\partial \lambda_{i,y+1}} = \theta^{y+1}\left\{x_{iy} + g_i(x_{iy}) + I_i(x_y) - \bar{q}_{iy} - x_{i,y+1}\right\} = 0,\ i = 1,\ldots,n. \tag{1.17}$$

Rearranging, and simplifying the first order necessary conditions obtains

$$\frac{\partial \pi_{y}^{*}}{\partial \bar{q}_{iy}} = \theta\lambda_{i,y+1},\ \ i = 1,\ldots,n, \tag{1.18}$$

$$\frac{\partial \pi_{y}^{*}}{\partial x_{iy}} + \theta\lambda_{i,y+1}\left[1 + \frac{dR_i}{dx_{iy}} + \frac{\partial I_i}{\partial x_{iy}}\right] + \sum_{j\neq i}^{n-1}\theta\lambda_{j,y+1}\left[\frac{\partial I_j}{\partial x_{iy}}\right] = \lambda_{iy},\ \ i = 1,\ldots,n;\ i \neq j; \tag{1.19}$$

$$x_{i,y+1} - x_{iy} = R_i(x_{iy}) + I_i(x_y) - \bar{q}_{iy},\ i = 1,\ldots,n. \tag{1.20}$$

Substituting $\theta\lambda_{j,y+1} = \dfrac{\partial \pi_{y}^{*}}{\partial \bar{q}_{jy}}$ in the left hand side of equation (1.19) obtains:

$$\frac{\partial \pi_{y}^{*}}{\partial x_{iy}} + \left[\frac{\partial \pi_{y}^{*}}{\partial q_{iy}}\right]\left[1 + \frac{dR_i}{dx_{iy}} + \frac{\partial I_i}{\partial x_{iy}}\right] + \sum_{j\neq i}^{n-1}\left[\frac{\partial \pi_{y}^{*}}{\partial q_{jy}}\right]\left[\frac{\partial I_j}{\partial x_{iy}}\right] = \lambda_{iy},\ i = 1,\ldots,n,\ i \neq j. \tag{1.21}$$

Moving equation (1.21) forward from year *y* to year *y*+1,

$$\frac{\partial \pi_{y+1}^{*}}{\partial x_{i,y+1}} + \left[\frac{\partial \pi_{y+1}^{*}}{\partial q_{i,y+1}}\right]\left[1 + \frac{dR_i}{dx_{i,y+1}} + \frac{\partial I_i}{\partial x_{i,y+1}}\right] + \sum_{j\neq i}^{n-1}\left[\frac{\partial \pi_{y+1}^{*}}{\partial q_{j,y+1}}\right]\left[\frac{\partial I_j}{\partial x_{i,y+1}}\right] = \lambda_{i,y+1}, \tag{1.22}$$
$i = 1,\ldots,n;\ i \neq j;$

and substituting equation (1.22) on the right hand side of equation (1.18) thus implies

$$\frac{\partial \pi_y^*}{\partial \overline{q}_{iy}} = \theta \frac{\partial \pi_{y+1}^*}{\partial x_{i,y+1}} + \theta \left[\frac{\partial \pi_{y+1}^*}{\partial q_{i,y+1}} \right] \left[1 + \frac{dR_i}{dx_{i,y+1}} + \frac{\partial I_i}{\partial x_{i,y+1}} \right] + \theta \sum_{j \neq i}^{n-1} \left[\frac{\partial \pi_{y+1}^*}{\partial q_{j,y+1}} \right] \left[\frac{\partial I_j}{\partial x_{i,y+1}} \right]. \tag{1.23}$$

$$i = 1,...,n.$$

Equation (1.23) is the multi-species Euler equation including both biological and technological interactions between species, which states that the marginal profit from an additional unit of quota for species *i* (the left hand side) should be equal to the discounted marginal profit of an additional unit of quota for species *i* next period (the right hand side). The first term in brackets on the right hand side is the discounted marginal profit from an additional unit of species *i* next period on next period profits. The second term in brackets on the right hand side is the discounted marginal value of an additional unit of quota (which is assumed to be equal to the marginal value of an additional unit harvested) next period times the marginal growth rate of the stock that was allowed to grow from year *y* to *y*+1. The third term represents the impact of the unharvested unit interacting with the other species for an additional period that may lead to increases or decreases in the stock of other species, which is multiplied by the marginal profit of harvesting those species next period.

Assuming a steady state $\left(\lambda_{i,y+1} - \lambda_{iy} = x_{i,y+1} - x_{iy} = 0 \ \forall \ i, y\right)$, the first order conditions can be rewritten as

$$\theta \lambda_i = \frac{\partial \pi_y^*}{\partial \overline{q}_i}, \ i = 1,...,n, \tag{1.24}$$

$$\theta \lambda_i = \frac{\frac{\partial \pi_y^*}{\partial x_i} + \sum_{j \neq i}^{n-1} \frac{\partial \pi_y^*}{\partial \overline{q}_j} \frac{\partial I_j}{\partial x_i}}{1 - \theta \left(1 + \frac{dR_i}{dx_i} + \frac{\partial I_i}{\partial x_i} \right)}, \ i = 1,...,n; \ i \neq j; \tag{1.25}$$

$$\overline{q}_i = R_i(x_i) + I_i(x), \quad i = 1,\dots,n. \tag{1.26}$$

Setting equation (1.24) equal to equation (1.25) results in a modified multispecies golden rule for these fisheries:

$$\frac{\partial \pi_y^*}{\partial \overline{q}_i} = \frac{\dfrac{\partial \pi_y^*}{\partial x_i} + \sum_{j \neq i}^{n-1} \dfrac{\partial \pi_y^*}{\partial \overline{q}_j} \dfrac{\partial I_j}{\partial x_i}}{1 - \theta\left(1 + \dfrac{dR_i}{dx_i} + \dfrac{\partial I_i}{\partial x_i}\right)}, \forall i = 1,\dots,n, i \neq j, \tag{1.27}$$

Equation (1.27) states that the marginal profit from an additional unit of quota for species *i* (the left hand side) should be equal to the marginal profit from leaving that unit of species *i* in the sea (the right hand side). The first term in the numerator on the right hand side is the marginal profit from increasing the stock next period through lower harvesting costs. As the profit function represents the profit from the harvest of all three groundfish species, the derivatives of the profit function incorporate the technological interactions between species in the firm's profit maximizing behavior. The other terms in the numerator each represent the marginal profit of an additional unit of quota for species *j* times the marginal interaction effect of not harvesting another unit of species *i* on species *j*. The numerator on the right hand side is weighted by how the net growth rate of species *i* is related to the discount rate.

The envelope conditions of the individual vessel's problem from equations (1.5) and (1.7) can be rewritten to include vessel subscripts as

$$\frac{\partial L_{vgt}}{\partial x_i} = -\sum_{\tau=t}^{T_{vg}} \rho^{\tau} \frac{\partial C_{vg}}{\partial x_i},$$

$$\frac{\partial L_{vgt}}{\partial \overline{q}_i} = \omega_{vgi} \sum_{\tau=t}^{T_{vg}} \rho^{\tau} \left\{ p_{i\tau} - \frac{\partial C_{vg}}{\partial h_{ivg\tau}} \right\},$$

where L_{vgt} is the Lagrangian for vessel *v* using gear type *g* at time *t* and C_{vg} is vessel *v*'s cost function for gear type *g*. The optimal annual profits for the fishery (π_y^*) is equal to the optimal Lagrangian value in a given year aggregated over all vessels, gear types and trips (L_{vgty}^*), which can be represented as

$$\pi_y^* = \sum_v^{V_g} \sum_{g=1}^{G} \sum_{t=1}^{T_{vgy}^*} L_{vgty}^* .$$

Therefore, the envelope conditions can be rewritten in disaggregated form as

$$\frac{\partial \pi_y^*}{\partial x_{iy}} = -\sum_v^{V_g} \sum_{g=1}^{G} \sum_{\tau=t}^{T_{vgy}^*} \rho^\tau \frac{\partial C_{vg}}{\partial x_{iy}},$$

$$\frac{\partial \pi_y^*}{\partial \overline{q}_{iy}} = \sum_v^{V_g} \sum_{g=1}^{G} \omega_{vgi} \sum_{\tau=t}^{T_{vgy}^*} \rho^\tau \left\{ p_{i\tau} - \frac{\partial C_{vg}}{\partial h_{ivg\tau y}} \right\}.$$

Ignoring the year subscripts and substituting these expressions into equation (1.27) results in a true multispecies golden rule for any fishery that exhibits biological and technological interactions:

$$\sum_v^{V_g} \sum_{g=1}^{G} \omega_{vgi} \sum_{\tau=t}^{T_{vg}^*} \rho^\tau \left\{ p_{i\tau} - \frac{\partial C_{vg}}{\partial h_{ivg\tau}} \right\} = \frac{-\sum_v^{V_g} \sum_{g=1}^{G} \sum_{\tau=t}^{T_{vg}^*} \rho^\tau \frac{\partial C_{vg}}{\partial x_i} + \sum_{j \neq i}^{n-1} \frac{\partial I_j}{\partial x_i} \left(\sum_v^{V_g} \sum_{g=1}^{G} \omega_{vgi} \sum_{\tau=t}^{T_{vg}^*} \rho^\tau \left\{ p_{i\tau} - \frac{\partial C_{vg}}{\partial h_{jvg\tau}} \right\} \right)}{1 - \theta \left(1 + \frac{dR_i}{dx_i} + \frac{\partial I_i}{\partial x_i} \right)}, \quad (1.28)$$

$$i = 1, \ldots, n;\ i \neq j.$$

Equation (1.28) is the fully specified multispecies golden rule for this fishery which includes both the biological and technological interdependencies between different species harvested by any number of vessel classes and gear types. The term on the left hand side is the marginal profit per trip weighted by the quota share allocated to each vessel and gear type and aggregated over all vessels, trips and gear types. On the right hand side, the first term is the marginal cost reduction for a change in the stock of species *i* aggregated over all vessels, trips and gear types. The second term in the numerator is the marginal profit per trip weighted by the quota share allocated to each vessel and gear type aggregated over all vessels, trips, and gear types from an additional unit of quota for species *j* times the marginal interaction effect of an additional unit of species *i* on the stock of species *j*.

Solving equation (1.28) for the discount rate results in the most general version of what Conrad [45] and others call the "fundamental equation of renewable resources":

$$\delta = \frac{\left(1 + \frac{dR_i}{dx_i} + \frac{\partial I_i}{\partial x_i}\right)}{1 - \frac{\left(-\sum_{v}^{V_g}\sum_{g=1}^{G}\sum_{\tau=t}^{T_{vg}^*}\rho^{\tau}\frac{\partial C_{vg}}{\partial x_i} + \sum_{j\neq i}^{n-1}\frac{\partial I_j}{\partial x_i}\left(\sum_{v}^{V_g}\sum_{g=1}^{G}\omega_{vgi}\sum_{\tau=t}^{T_{vg}^*}\rho^{\tau}\left\{p_{i\tau} - \frac{\partial C_{vg}}{\partial h_{jvg\tau}}\right\}\right)\right)}{\sum_{v}^{V_g}\sum_{g=1}^{G}\omega_{vgi}\sum_{\tau=t}^{T_{vg}^*}\rho^{\tau}\left\{p_{i\tau} - \frac{\partial C_{vg}}{\partial h_{ivg\tau}}\right\}}} - 1, \qquad (1.29)$$

$$i = 1,\ldots,n;\ i \neq j.$$

Equation (1.29) is the fundamental equation of multi-species renewable resources, where the single species case is included as a special case. Equation (1.29) states that the discount rate should be equal to the marginal net growth rate of the biological resource (the numerator) divided by the marginal stock effect, which measures the value of a marginal unit of stock relative to the marginal value of quota [46]. This equality states that a dollar invested in the fish stock (the right hand side) should achieve the same rate of return as a dollar invested elsewhere in the economy (the left hand side).

Revisiting equation (1.23), the multispecies Euler equation, and substituting the derivatives of the profit function with respect to $\overline{q}_{iy}$, $\overline{q}_{i,y+1}$ and $x_{i,y+1}$ yields

$$
\begin{aligned}
&\sum_{v}^{V_g}\sum_{g=1}^{G}\omega_{vgi}\sum_{\tau=t}^{T^*_{vgy}} \rho^{\tau}\left\{p_{i\tau}-\frac{\partial C_{vg}}{\partial h_{ivg\tau y}}\right\}= \\
&\qquad -\theta\sum_{v}^{V_g}\sum_{g=1}^{G}\sum_{\tau=t}^{T^*_{vg,y+1}}\rho^{\tau}\frac{\partial C_{vg}}{\partial x_{i,y+1}} \\
&\qquad +\theta\left[\sum_{v}^{V_g}\sum_{g=1}^{G}\omega_{vgi}\sum_{\tau=t}^{T^*_{vg,y+1}}\rho^{\tau}\left\{p_{i\tau}-\frac{\partial C_{vg}}{\partial h_{ivg\tau,y+1}}\right\}\right]\left[1+\frac{dR_i}{dx_{i,y+1}}+\frac{\partial I_i}{\partial x_{i,y+1}}\right] \qquad (1.30) \\
&\qquad +\theta\sum_{j\neq i}^{n-1}\left[\sum_{v}^{V_g}\sum_{g=1}^{G}\omega_{vgi}\sum_{\tau=t}^{T^*_{vg,y+1}}\rho^{\tau}\left\{p_{j\tau}-\frac{\partial C_{vg}}{\partial h_{jvg\tau,y+1}}\right\}\right]\left[\frac{\partial I_j}{\partial x_{i,y+1}}\right], \\
&i=1,\ldots,n,
\end{aligned}
$$

Equation (1.30) has the same interpretation as equation (1.23). That is, the marginal profit from increasing the quota today (harvesting today) should be equal to the discounted value of increasing the quota (harvesting) next period, where the technological interdependencies between species are made more explicit.

The multispecies golden rule determines whether a unit of species *i* should be harvested or left in the ocean to grow until next period. It is interesting to note how the optimal quotas differ between equation (1.28) and the single species version of the golden rule. If there are complementarities (anti-complementarities) in the production of these three species, then the marginal profit from harvest (the left hand side) is larger (smaller) when technological interactions are included than in the single species case.[7] Given the

---

[7] The single species individual vessel problem can be defined as:

$$
\max_{\substack{h_{g\tau},T_g \\ \tau=t,\ldots,T_g}} \pi_{gt}=\sum_{\tau=t}^{T_g}\rho^{\tau}\sum_{i=1}^{n}\Big(p_{i\tau}h_{ig\tau}-C_{ig}(h_{ig\tau}\mid w_{\tau},x_i,Z)\Big)
$$

subject to $q_{ig,t+1}=\omega_{gi}*\overline{q}_i-\sum_{t=1}^{t}h_{igt}\geq 0,\ i=1,\ldots,n,\ t=1,\ldots,T-1$. In the single species case, $-\partial C_{ig}\big/\partial h_{ig\tau}=0$, while if there are cost complementarities, this implies that $-\partial^2 C_{ig}\big/\partial h_{ig\tau}\partial h_{jg\tau}>0$, which means that marginal profits are higher when these species are caught together rather than separately. The reverse is true for cost anti-complementarities, such that $-\partial^2 C_{ig}\big/\partial h_{ig\tau}\partial h_{jg\tau}<0$, which implies that marginal profits are lower when species are caught together.

same underlying technology and convexity of the profit function in the stock, larger (smaller) marginal profits indicate that the optimal steady state stock is greater (less) in the multispecies case including technological interactions than in the single species case. This pattern is consistent for all species that exhibit complementarities in production.

To examine how ecological interactions affect the optimal quotas, consider the case of arrowtooth flounder, which prey on pollock but compete with cod for resources, $\partial I_j \big/ \partial x_{arth} < 0 \ \forall\ j$. Assuming positive profits in the pollock and cod fisheries, this leads to an decrease in the right hand side of equation (1.28), which means that the marginal profit from leaving a unit of arrowtooth in the water is less than the marginal profit from harvesting today. This leads to a lower optimal arrowtooth population than the single species case. As profits are likely positive both in the pollock and cod fisheries, including biological interactions leads to an unambiguous decrease in the optimal arrowtooth flounder population.

Equations (1.28), (1.29), and (1.30) are the fundamental marginal conditions for renewable resource management. Equation (1.28) is the fully specified multi-species golden rule, which for the steady state, indicates that the marginal profit from an additional unit of quota for species *i* should be equal to the marginal profit from leaving that unit of species *i* in the sea. In the steady state, equation (1.29) states that the rate of discount should be equal to the rate of return that is earned by investing in the fish stock. Equation (1.30) states that, even when not in the steady state, the marginal profit from increasing the quota by a unit today should be equal to the discounted value of increasing the quota by a unit next period. These three equations state the fundamental marginal conditions that must be satisfied for optimal renewable resource management: (i) the value of harvest today should be equal to the value of harvest tomorrow, (ii) the value of a unit harvested is equal to the value of a unit left in the sea, and (iii) the rate of return earned on the fish stock is equal to the rate of return earned elsewhere in the economy. Chapter 3 focuses on empirically estimating the multispecies stock dynamics and vessel technology using numerical optimization techniques to determine the optimal quotas in this multispecies fishery.

3. Optimal Multispecies Harvesting in Biologically and Technologically Interdependent Fisheries

3.1 Estimation of the Biological Stock Dynamics

Stock estimates of each species and the catch on an annual basis are available for the years 1978 through 2010 through the Stock Assessment and Fishery Evaluation (SAFE) report from the Alaska Fisheries Science Center [21, 23, 24, 26]. The growth of each species is assumed to follow a discrete logistic function. The parameters to be estimated are the intrinsic growth rate for each species (r_i), a density dependent factor related to the carrying capacity (η_i), and the two interaction parameters between species $(\alpha_{i,j})$. The two interaction parameters are assumed to be equal to zero in the single species estimation. The functional form comes from equation (1.11) in the bioeconomic model, such that the surplus production growth function for species *i* is defined as $R_i\left(x_{iy}\right) = r_i x_{iy} + \eta_i x_{iy}^2$, *i*=1,…,*n*, and the interaction function is defined as $I_i(x_y) = \sum_{j\neq i}^{n-1} a_{ij} x_{iy} x_{jy}$, *i*=1,…,*n*,

implies that the stock dynamics can be expressed mathematically as:

$$x_{i,y+1} = (1+r_i)x_{iy} + \eta_i x_{iy}^2 + \sum_{j\neq i}^{n-1} a_{ij} x_{iy} x_{jy} - h_{iy},\ i = 1,..,n. \tag{2.1}$$

The same unobserved environmental, climate, and other factors that impact the growth of pollock likely also impact the growth of cod and arrowtooth flounder, which implies that the errors are correlated across growth equations. Therefore, this system of three equations is estimated with iterative seemingly unrelated regression, which 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. After appending an error term, equation (2.1) is estimated for all three species using seemingly unrelated regression for the years 1978-2010.

Parameter estimates of equation (2.1) are provided in Table 1. Each species' own stock parameters are as expected, leading to classical 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 marginally statistically significant (at the 10% level) impact on growth. Interestingly, the coefficient on the quadratic term (η_i) for arrowtooth is not statistically significant. This is likely due to the fact that the estimate of the stock has never declined for as long as data are available. Therefore little curvature is evident to identify the coefficient on the quadratic term. For cod, arrowtooth has a negative and statistically significant impact on growth, while pollock has a negative and marginally statistically significant (at the 10% level) effect on growth. The interaction terms for pollock are of the expected sign, with arrowtooth having a statistically significant negative impact on pollock growth, while cod has a negative but statistically insignificant impact.

These results suggest that increases in arrowtooth reduce the growth of the cod and pollock stocks, increases in the cod stock increase the growth of arrowtooth, and increases in pollock reduces the stocks of both arrowtooth and cod. The negative coefficients between pollock and cod ($a_{cod,plck}$ and $a_{plck,cod}$) suggest a competing species relationship. It is possible that the relationship between species changes at different life stages such that older cod prey on young pollock and older pollock prey on young cod as suggested by Jurado-Molina et al. [19]. As the coefficient on the cod/pollock interaction term for the pollock stock ($a_{plck,cod}$) is not statistically significant, while the cod/pollock interaction term is marginally statistically significant at the 10% level for the cod stock ($a_{cod,plck}$), this suggests that the adult pollock predation on cod juveniles is the dominant predator-prey relationship.

The multispecies model is compared with a single species model, which estimates the same growth function from equation (2.1), setting $a_{i,j} = 0 \; \forall \; i, j$, such that:

$$x_{i,y+1} = (1 + r_i^{ss})x_{iy} + \eta_i^{ss} x_{iy}^2 - h_{iy}, \; i = 1,..,n \; . \qquad (2.2)$$

Table 2 presents the single species parameter estimates of equation (2.2), which is estimated via constrained linear regression independently for each species, constraining the coefficient on the harvest to be equal to one. Similar to the multispecies model, the estimated coefficients imply a standard concave logistic growth curve. Interestingly, the multispecies intrinsic growth rates (r_i) are larger for cod and pollock, but smaller for arrowtooth. One possible explanation for this phenomenon would be if arrowtooth is relatively more dependent on prey availability than cod and pollock. The coefficients in Table 2 also imply that the implied carrying capacity, $-r_i / \eta_i$, is larger for the single species model than the multispecies model for cod and pollock, but is over ten times smaller for arrowtooth.

Using the parameters from Table 1 and Table 2, Figures 1-3 present a retrospective analysis of the population between 1978 through 2010 comparing the stock assessment model to the predicted values from the multispecies and single species models using the actual harvests over the period. While not exact, both models appear to do a relatively good job of approximating the general trends in all three stocks, and should provide reasonable projections for simulating the stock dynamics in the bioeconomic model. The multispecies model for all three species is superior to the single species models relative to the stock assessment models as measured by comparing the sum of squared errors between the stock assessment model and the multispecies or single species models. The multispecies model outperforms the single species models for arrowtooth, cod, and pollock by 21, 20, and 6 percent, respectively.

While these estimates may not provide substantially different stock estimates in the retrospective analysis, Figures 4-6 show that the underlying growth functions are fundamentally different between the single and multispecies models. For the multispecies model, the other species are assumed to be at their mean stock size for the study period, 1978-2010. As discussed above, the single species models underestimate cod and pollock growth but overestimate arrowtooth growth at low stock levels. These figures show that the cod and pollock carrying capacity are also larger in the single species model, while arrowtooth carrying capacity is smaller for the single species model than the multispecies model. These two features imply that the maximum sustainable yield (MSY) for cod and pollock are achieved at lower stock levels in the multispecies model than in the single species model. However, the MSY for arrowtooth is larger in the multispecies model than the single species model.

These differing growth equations can have substantially different impacts on the dynamics in this system as arrowtooth has a substantial impact on the growth of cod and pollock in the multispecies model. As each stock is linked in the multispecies model, and therefore each species' growth is a function of the stock size of each other species, substantial increases in the stock of arrowtooth can reduce the growth of the two profitable species in this ecosystem. If the multispecies model is the 'true' model, then using the single species model for cod and pollock management decisions will result in quotas which are too high, and likely lead to stock depletion. Also, using the single species model for arrowtooth will cause overly conservative quotas to be set, which will allow the stock of arrowtooth to increase leading to further depletion of the cod and pollock stocks. The impact of multispecies and single species biological growth functions on the optimal solution is explored in section 3.5.

3.2 Estimation of Vessel Profits

Vessels are assumed to maximize profits each year according to their profit maximization problem from section 2.1, where vessels choose their optimal harvests on each trip, and the optimal number of trips to take with each gear type for the year. The differences in vessel type, crew size, and onboard equipment between catcher vessels and catcher-processors likely lead to different profit maximizing behavior. Similarly, as different gear types can expect to harvest a different portfolio of catches, each gear type is a fundamentally different harvesting technology. Therefore, the sample is stratified by the four major gear types used in these fisheries (longline, non-pelagic trawl, pot, and pelagic trawl) for each class of vessel (CV and CP) for a total of eight gear types for estimation. From section 2.1, a vessel's annual profits from gear type *g* can be expressed as: $\pi^*_{vg}(p,w,x,Z,\overline{q},\omega)=\sum_{\tau=t}^{T^*_{vg}}\rho^{\tau}\left\{p_{\tau}h^*_{vg\tau}-C_{vg}(h^*_{vg\tau}\mid w_{\tau},x,Z)\right\}$, which is the sum of trip level profits (in braces), discounted by the intra-annual discount rate ρ, and summed over all trips with gear type *g*.

Empirically, estimation of the vessel's annual profits is split in two parts using data from 2006 to 2010 for CVs and 2000 to 2010 for CPs that caught any amount of arrowtooth, cod, or pollock.[8] First, the vessel-class-trip level cost functions, $C_{vg}(h^{*}_{vg\tau} \mid w_{\tau}, x, Z)$, are estimated using a flexible functional form for each gear type. Subsequently, each vessel's trip level data is aggregated to the annual level, and the number of trips a vessel takes with each gear type is estimated, assuming the number of trips taken follows a Poisson distribution.[9]

3.2.1. Estimation of the Trip Level Cost Function

A number of inputs in the production of fish are fixed at the vessel level, such as vessel characteristics and the population of each species, which suggests a restricted cost function is most appropriate for estimation. Ignoring the time and vessel subscripts, let C_{vg} be a quadratic approximation to the restricted cost function for vessel *v* using gear type *g*:

$$C_{vg} = \alpha_{g,0} + \sum_{i=1}^{2n+M+k} \alpha_{g,\mathbf{X}_i} \mathbf{X}_{ivg} + \tfrac{1}{2} \sum_{i=1}^{2n+M+k} \sum_{j=1}^{2n+M+k} \alpha_{g,\mathbf{X}_i\mathbf{X}_j} \mathbf{X}_{ivg} \mathbf{X}_{jvg},\ v = 1,..,V_g;\ g = 1,...,G; (2.3)$$

where $\mathbf{X}_{vg} = [w, h_{vg}, x, Z_v]$, and $\mathbf{X}_{ivg}$ represents the *i*th column of the $\mathbf{X}_{vg}$ matrix. Define V_g to be the number of observations using gear type *g*, *w* is a V_g by *M* matrix of variable input prices, h_{vg} is an V_g by *n* matrix of harvest quantities, *x* is an V_g by *n* matrix of given stock levels of the species of interest, and Z_v is an V_g by *k* matrix of given vessel characteristics, so $\mathbf{X}_{vg}$ is an V_g by $2n + M + k$ matrix. Using Shephard's Lemma, the derivative of the cost function with respect to the *m*th input price is equal to the conditional input demand:

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[8] The shorter time series for CVs is due to the fact that crew size was not collected in the data prior to 2006.

[9] Only vessels that have used a particular gear type between 2006 and 2009 for CVs or 2000 and 2010 for CPs are included in the estimation of the number of trips with that gear type. All other vessels are assumed to have taken zero trips with that gear type.

$$\frac{\partial C_{vg}}{\partial w_m} = z^*_{vg,w_m} = \alpha_{g,w_m} + \sum_{j=1}^{2n+M+k} \alpha_{g,w_m\mathbf{x}_j} \mathbf{X}_{ivg} \mathbf{X}_{jvg},\ m = 1,...,M\ . \tag{2.4}$$

The restrictions that must be placed on the parameters to insure symmetry of the cost function are $\alpha_{g,\mathbf{x}_i\mathbf{x}_j} = \alpha_{g,\mathbf{x}_j\mathbf{x}_i}\ \forall\ i = 1,...,n;\ i \neq j;\ g = 1,...,G,$ and the restrictions required for linear homogeneity in input prices are: $\sum_m^M \alpha_{g,w_m} = 1$ and $\sum_m^{2n+M+k} \alpha_{g,w_m\mathbf{x}_i} = 0,\ g =$ 1,…,G. These restrictions assure the convenient theoretical conditions of symmetry and adding up of the cost function. This specification also allows for the testing of a series of hypotheses such as whether production of multiple outputs is joint or whether there are cost complementarities. Estimating the conditional input demand equations in addition to the cost function for each gear type increases the effective degrees of freedom for estimation by imposing cross-equation parameter constraints, and allows for testing hypotheses on the structure of the vessel's technology such as jointness in inputs or economies of scope.

The data used in this study are described in section 1.5. The variable input used as a proxy for vessel effort is the amount of crew services (number of crew multiplied by the trip length in days). The price included in $\mathbf{X}_{vg}$ is an hourly wage for farming, fishing, and forestry occupations in Alaska[10] multiplied by eight hours per day and trip length.[11] Other regressors included in $\mathbf{X}_{vg} = [w; h_{vg}; x; Z_v]$ include the harvest of arrowtooth, cod, and pollock, the annual stock size of arrowtooth, cod, and pollock, and the three given vessel characteristics of length, horsepower, and gross tonnage. After appending an error term for econometric purposes to the cost function and the conditional input demand

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[10] These data are taken from the annual Bureau of Labor Statistics State Occupational Employment and Wage Estimates.

[11] Recall that CPs are assumed to fish a full 7-day week if they are submitting a WPR.

equations and a vessel-gear fixed effect to the cost function, the system of equations (2.3) and (2.4) are estimated using iterated seemingly unrelated regression.

The results are presented in Table 3 for CVs and Table 4 for CPs. Coefficients with no estimate in Tables 3 and 4 were excluded from the estimation. CV longline, CV pot, and CP pot only catch cod; thus, the stocks and harvests of arrowtooth and pollock as well as their interactions are excluded from the estimation of equations (2.3) and (2.4). For the other gear types, some of the stock interaction terms are excluded due to multicollinearity. With only 4 years of data for the CVs, there are only 4 unique stock values for each species, which vary together. Variation in the data is not sufficient to identify these parameters, causing serious collinearity problems if all interaction terms in equation (2.3) are included. As the CPs have 10 years of usable data, additional, but not all, stock interaction terms can be included. Given a longer time series of data this may be possible.

For CV non-pelagic trawl and CV pelagic trawl, the linear stock variables are included in equation (2.3), but all stock interaction terms are excluded. Therefore, these equations capture only the first-order effects of all three stocks on the cost of harvesting, rather than the effect of the target stock and its interactions. For the CPs, with additional years of data, in addition to the linear stock terms of all three species, the target species interaction terms are also included to allow some flexibility in the stock of the target species. Therefore, for CP longline and CP non-pelagic trawl, the cod stock squared along with the cod stock multiplied by the input price, harvest of all three species, and vessel characteristics are included. CP pelagic trawls are estimated similarly using the pollock stock and its interactions instead of the cod stock.

From Shephard's Lemma, the derivative of the cost function with respect to input prices is equal to the conditional input demand, which implies in Tables 3 and 4 that the coefficients of the conditional input demand equation are those interaction terms that have names beginning with *w*. Coefficient names represent the subscripts of the α coefficients in equation (2.3) and equation (2.4), where coefficient names separated by "," represent cross product terms.

The results in Tables 3 and 4 show that the coefficient on the squared input price term *w,w* is negative for all CV and CP gear types and highly significant for all gear types other than CV longline gear. Thus, the estimated conditional input demand for crew service hours is downward sloping in its own price, as expected. Therefore, all gear types are concave in input prices with the exception of CP longline vessels.

All gear types, with the exception of those assumed to only harvest cod (CV longline, CV pot, CP pot) are found to exhibit some form of jointness in inputs.[12] Jointness in inputs is tested using a Wald test of an equivalence of the coefficients: $\alpha_{\mathbf{g},\mathbf{h}_i\mathbf{h}_j} = \alpha_{g,\mathbf{h}_i}\alpha_{g,\mathbf{h}_j}$ [47]. CV non-pelagic trawl are found to exhibit overall jointness in inputs, CV pelagic trawl exhibit jointness for the harvesting of arrowtooth and for harvesting pollock, as well as overall jointness in inputs. CP longline are found to exhibit both jointness in cod harvest and overall jointness, CP non-pelagic trawl only exhibit jointness in the catch of arrowtooth and cod, and CP pelagic-trawl exhibit weak jointness for arrowtooth harvest and overall jointness (at the 10 percent level) but highly significant jointness for harvesting pollock.

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[12] Results of these tests are available from the author upon request.

As CV trawl vessels are less able to make profitable trips traveling large distances than the CP trawl vessels, it is not surprising that both CV pelagic trawl and CV non-pelagic trawl both exhibit jointness in inputs. As CP trawl vessels are able to travel further distances from port and harvest profitably in less dense aggregations, it is not surprising that they still exhibit jointness, but to a lesser degree than the CV trawls. CP longlines also exhibit jointness which is not surprising given how their gear sits near the sea floor which is home to both arrowtooth and pollock at certain life stages.

The lack of significance some of the species could be a result of crew services serving as a poor proxy for the true costs of harvesting in this fishery. Fuel usage is likely to be an additional large contributor to costs, but this information is not available. This result could also be a result of a lack of reporting of species which were discarded at sea (although vessels are required to record all species harvested). Surprisingly, the non-pelagic trawl gear types did not show as much jointness in inputs as would be expected for bottom trawl gear, which may be a result of excluding other species, particularly flatfish, which are caught when these vessels are targeting cod. Lastly, it is possible that the lack of jointness in inputs is a result of a concerted effort by the North Pacific Fisheries Management Council (NPFMC) to reduce incidental catch of non-target species in their fishery management plans. In particular, the American Fisheries Act (AFA) limits the ability of vessels participating in the pollock fishery from expanding their effort in other fisheries. Similarly, Amendment 80 to the BSAI FMP limits non-AFA CP non-pelagic trawl vessels from expanding their harvesting in other fisheries as well.

Surprisingly, only one vessel-class/gear-type combination exhibits statistically significant cost complementarities, while eight exhibit statistically significant cost anti-complementarities. Cost complementarities (anti-complementarities) between species i and j can be tested using a one sided t-test of whether the coefficient $\alpha_{\mathbf{g},\mathbf{h}_i\mathbf{h}_j}$ is less (greater) than zero. The other six vessel-class/gear-type combinations exhibit no statistically significant cost complementarities. CV pelagic trawls are found to exhibit cost complementarities between arrowtooth and cod as the coefficient on h_{arth},h_{cod} in Table 3 is negative and statistically different from zero, but cost anti-complementarities between arrowtooth and pollock and cod and pollock as the coefficients on h_{arth},h_{plck} and h_{cod},h_{plck} are positive and statistically significant. CV non-pelagic trawls exhibit cost anti-complementarities between cod and pollock and weak anti-complementarities between arrowtooth and pollock. CP longline vessels exhibit cost anti-complementarities between all three species combinations. CP non-pelagic trawls exhibit cost anti-complementarities between cod and pollock. The cost anti-complementarities may be a result of vessels having to expend extra effort separating species when they catch multiple species before they are landed. In the case of the CPs, adjusting processing gear to account for different sized fish of the same species is costly, and accounting for multiple species is likely more costly. As many of these gear types exhibit cost anti-complementarities, harvesting each species separately would be less costly, but with jointness in inputs, the harvesting technology does not allow them to harvest each species separately without incurring additional costs.

The estimated cost functions presented in Table 3 and Table 4 are used to determine the cost of harvesting each vessel's allocated catch. Each vessel's share of the quota is determined by their historical catch between 2007 and 2009 for each gear type such that each gear is allocated its historical percentage of each species so that the shares sum to one. For each gear type, the vessel gear share is determined by each vessel's own historical harvest of each species by gear type. As the cost functions estimated above are trip/week level functions, it is now necessary to estimate the number of trips taken or weeks operated with each gear type during a given year to catch the amount of species for each gear type each vessel is allocated.

3.2.2. Estimation of Total Annual Trips and Operating Weeks

Recall from equation (1.9) that the number of trips or weeks operating in these fisheries is a function of input and output prices, the annual harvest allocated to each vessel/gear combination, the annual TAC level, and fixed vessel characteristics. The number of trips that a CV takes or the number of weeks a CP operates with a particular gear type is assumed to follow a Poisson distribution, such that:

$$\Pr[T_{vgy}^{*} = t] = \frac{\exp^{-\exp(U_{ivg}'\beta_g)} \exp(U_{ivg}'\beta_g)^{t}}{t!} . \tag{2.5}$$

where $U_{ivg} = [p, w, h_{vg}, \bar{q}, Z]$ is a $3n + M + k + 1$ by 1 matrix of regressors and β_g is a $3n + M + k + 1$ by 1 matrix of coefficients. The log likelihood function to maximize is:

$$\ln L(\beta_g) = \sum_{i=1}^{V_g} \left(t_i U_{ivg}'\beta_g - \exp(U_{ivg}'\beta_g) - \ln t_i! \right). \tag{2.6}$$

Maximum likelihood estimates of the β_g coefficients for each gear type are presented in Table 5 for CVs and Table 6 for CPs. As the harvests included in U_{ivg} are gear specific, only the harvests using the same gear are used to determine the number of trips or operating weeks with each gear.

Columns 1, 2, 3 of Table 5 and column 1 of Table 6 show that the price of cod and the quota for cod have a positive and statistically significant impact on the number of trips/weeks taken by CV longline, CV non-pelagic trawl, CV pot, and CP longline gears, which is consistent with these gear types targeting cod. However, columns 2 and 3 of Table 6 do not show a similar pattern for the CP non-pelagic trawls and CP pot gears. CP non-pelagic trawl gear has negative and statistically significant coefficients on cod price and cod quota, while CP pot gear has a positive and statistically significant coefficient on cod price, and a negative but statistically insignificant coefficient on cod quota. In contrast with the CVs, the CPs appear to determine the number of weeks they operate largely based on their annual catch.

Column 4 of Table 5 shows that the CV pelagic trawl vessels are clearly targeting pollock as both pollock price and pollock quota have a positive and statistically significant impact on the number of trips taken. Column 4 of Table 6 shows a slightly different picture for CP pelagic trawls. These vessels are also clearly targeting pollock, but both the price of pollock and annual quota do not have a statistically significant impact on the weeks they operate and, similar to the other CPs, the number of operating weeks is largely a function of the harvest of each species. The statistically insignificant coefficients on the price and quota for pollock for CP pelagic trawl vessels can be explained in a few ways. First, the price used in this study is a vessel’s average price for each species weighted by the proportion of each product form. So vessels may not be responding to the average price, but could be adjusting their harvesting to target smaller fish to process into surimi if the relative price of surimi is high, or to target larger fish to make fillets if their relative price rises. These vessels are also operating within and are allocated quota by their Cooperative, which could make the relationship between annual quota and operating weeks less clear. Also, since the passage of the AFA, these vessels are limited from operating in other fisheries, and may not have many options outside of the pollock fishery. So the number of weeks they operate may vary only by the quota they are allocated to catch by the Co-op.

The estimates for each vessel-class/gear-type combination are used to determine the number of trips each vessel takes over the course of a year in the numerical optimization as a result of changing prices, quotas, and individual annual harvests. Combining the number of trips each vessel takes with each gear type in a year, each vessel's share of the total annual quota for each gear type, and the cost functions associated with their trip level harvest, the model can now calculate the total cost of harvesting any level of output. The following section estimates an inverse demand model for all species jointly to provide estimates of the price impacts of increased harvesting.

3.3 Estimation of the Inverse Demand Model for Outputs

The stocks and harvests of pollock and cod are currently at fairly low levels, and are expected to rebound. Therefore, rather than keep prices constant during the numerical optimization procedure, an inverse demand model was developed for each species to allow the market price of each species to respond to its supply. The price of species i in year y (p_{iy}) is a function of the price of all other species in year $y - 1$ ($p_{j,y-1}$), and the harvest of species i in year y (h_{iy}). The inverse demand model is thus:

$$p_{iy} = \sum_{j=1}^{n} \gamma_j p_{j,y-1} + \gamma_{h_i} h_{iy} + \varepsilon_{iy},\ i = 1,\ldots,n. \tag{2.7}$$

The system of equations (2.7) is estimated with maximum likelihood assuming that the ε_{iy} are normally distributed and contemporaneously correlated but serially independent. As the catch of each species is determined exogenously by the TAC for each species, this demand system will not suffer from simultaneity bias. To the extent that arrowtooth TAC is not fully harvested, simultaneity bias could be a concern, but as arrowtooth is largely sold as a component of fish meal, the bias is likely to be small. The results are presented in Table 7.

The results suggest that all species have a downward sloping demand curve, although the estimated own price coefficient is statistically significant only for arrowtooth. The lack of statistical significance on the coefficient on the catch of cod and pollock in the inverse demand model is likely due to both cod and pollock competing in a largely homogeneous global whitefish market. While Alaska pollock are a substantial portion of the global whitefish market, any reduction in supply can be made up with increased production from other global capture fisheries such as orange roughy and the rebounding stock of Atlantic cod as well as from increasing aquaculture operations for species such as catfish and tilapia. Another potential explanation for the lack of statistical significance for the coefficients on the catch of cod and pollock is that the prices used to estimate equation (2.7) are annual weighted averages over all vessels, ports, and delivery codes. Therefore, it is possible that the aggregation is masking some price variation among different product forms for each species, as the price of fillets could increase at the same time as the price of surimi declines, which would mask any quantity impact on price. The estimates from this inverse demand model are used in the numerical optimization procedure to predict future prices based on previous year's prices and current harvest levels.

3.4 Numerical Optimization

The functional forms used for estimation in chapter 3 prevent an analytical solution to the bioeconomic model developed in chapter 2. Therefore, to examine how stocks, harvests, quotas, and profits evolve over time, numerical optimization methods are relied upon to provide a solution. This also allows a comparison of the optimal multispecies solution to the single species solutions that ignore multispecies biological interactions. This also permits quantification of the cost savings (additions) from cost complementarities (anti-complementarities) in the harvesting of multiple species.

The base model with which alternative models are compared is the multispecies bioeconomic model discussed in chapter 2. Vessels are assumed to maximize their profits each year by choosing the optimal number of trips to take with each gear type and their optimal harvest on each trip given the harvesting technology. Thus, this is the social planner's problem from section 2.2, which is expressed as:

$$\begin{aligned} &\underset{q_{i,y}}{Max} \sum_{y=1}^{Y=25} \theta^{t} \left\{ \pi_{y}^{*}(p_{y}, w_{y}, x_{y}, Z, \bar{q}_{y}, \omega) \right\} + \frac{\theta^{Y+1}}{\delta} \left\{ \pi_{Y}^{*}(\bar{p}, \bar{w}, x_{Y}, Z, \omega) \right\} \\ &s.t.\ x_{i,y+1} = (1 + r_{iy}) x_{iy} + \eta_{iy} x_{iy}^{2} + \sum_{j \neq i}^{n-1} a_{ijy} x_{iy} x_{jy} - h_{iy},\ i = 1, \ldots, n, \end{aligned} \tag{2.8}$$

where the y subscripts on the growth parameters $(r_{iy}, \eta_{iy}, a_{ijy})$ represent a random draw of the stock growth parameters. Due to uncertainty in the underlying stock growth functions and future prices, rather than take these parameters as fixed for each year of the model, a random draw of parameter values $(r_{iy}, \eta_{iy}, a_{ijy})$ is taken from a multivariate normal distribution defined by the estimated parameters and variance/covariance matrix from equations (2.1) and (2.7), respectively.[13] These parameters are assumed to be known to the decision maker when determining the optimal quotas over time.

This problem takes the vessel profit maximization problem from section 2.1 and the optimized vessel profit function from equation (1.8) into account when determining the optimal quotas for each species in each year. The multispecies model is compared with the estimated single species biological model from Table 2, using the same vessel profit functions. The role of technological interactions is explored through the cost savings or additions from multispecies harvesting that come out of the estimated cost functions. The optimal quota levels for each species are chosen for 25 years, after which time the harvest is equal to the steady state harvest levels with the corresponding ending stock levels, such that the stocks of all three species remain constant into the indefinite future. The model is run 100 times for both the multispecies and single species model to determine the distribution of profits, stocks, and optimal quotas under different parameter values. The discount rate is set at $\theta = 0.05$ for all model runs. Results of these numerical optimizations are presented in section 3.5.

3.5 Results

The stocks and harvest of each species for the multispecies model and single species model are presented in Figure 7 and Figure 8, respectively. The model runs begin with the year 2010 to the right of the green vertical line in the figures, with historical stock and harvest information to the left of the green line included for context. The dark solid line in each graph is the median stock size for all simulations, while the dark dashed

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[13] For the single species model, a random draw is taken from a normal distribution defined by parameter and variance/covariance matrix estimated by equation (2.2), which is assumed to be independent of the other species.

line is the median harvest level. The thin solid and dashed lines are the 25th and 75th percentile of the model runs for the stocks and harvests, respectively.

The clear result from Figure 7 is that, in the multispecies model, it is optimal to drive down the stock of arrowtooth to increase the growth of cod and pollock. As arrowtooth is not currently a target fishery in the BSAI, this implies that it is not profitable to harvest arrowtooth; therefore vessels have to take some losses on the harvesting of arrowtooth to allow for increased harvesting of cod and pollock in the long term. For the single species model in Figure 8, arrowtooth is not profitable to target and is only caught as bycatch in the other fisheries which allows the stock to grow unimpeded throughout the model. In the single species model, the stock of cod and pollock vary around their starting values throughout the model run. In contrast, the multispecies model leads to an initial decline in the stock of cod, which increases after the stock of arrowtooth declines toward zero, and a relatively stable population of pollock.

Summary statistics for the multispecies and single species models are presented in Table 8. In the multispecies model, the steady state stock of arrowtooth is extremely low, which allows cod and pollock to have substantially higher steady state harvests in the multispecies model than in the single species model. This increase in steady state harvest in the multispecies model causes the discounted sum of vessel profit functions, or the net present value, from the three species fishery to be over $5 billion dollars greater than the net present value of the single species model which ignores the biological interactions among species. As the cod and pollock fisheries are particularly profitable, the net present value in the multispecies model is $20.7 billion dollars, while the net present value in the single species model is $15.1 billion dollars.

As the estimation of the vessel's cost functions has shown that these vessels largely exhibit cost anti-complementarities, it is not terribly surprising that the technological interactions in the fishery lead to large increases in costs. These costs are \$345 million dollars for the multispecies model \$135 million dollars for the single species model. This implies that the cost anti-complementarities cause a .89% reduction in profits in the single species model, and a 1.7% reduction in profits for the multispecies model.

In general, both models respond to the terminal condition by increasing harvests of cod and pollock in the years immediately prior to the terminal year to lower the steady state stock which increases the steady state growth and therefore steady state harvests and profits. The overall results are qualitatively similar to a model with a 10 year time frame, the additional years used in this study allow for further adjustment toward the steady state. While a longer time frame would lower the impact of the terminal condition on the solution, this study is limited by the current availability of computer power and time to do the analysis.

3.6 Discussion and Conclusion

This study shows that the impact of biological and technological interactions can substantially alter the optimal harvest policies compared with a single species bioeconomic model. The net present value of the three species fishery is over \$20.7 billion dollars in the multispecies model, over \$5 billion dollars more than the net present value of the single species model. This is a function of the interdependence among species that affects other species growth. Because arrowtooth negatively impacts the growth of cod and pollock, substantially increasing the harvest of arrowtooth to decrease its stock is optimal in the multispecies model as it leads to increased growth and therefore greater potential harvests of cod and pollock. The single species model does not incorporate these feedbacks among species, and therefore assumes each species is unaffected by the stock rise or collapse of the others. The vessels in this fishery are also shown to exhibit cost anti-complementarities among species, which implies that harvesting multiple species jointly is more costly than catching them independently. These technological interactions result in a $345 million dollar increase in costs in the multispecies model, and $135 million dollar increase in costs for the single species model.

There are a number of caveats to these results that should be mentioned. A) There are regulations for the BSAI fisheries that may impact the results presented here. First, the reauthorized Magnusson-Stevens act requires mandatory rebuilding strategies if a population, such as arrowtooth in this model, falls below a certain population threshold. Second, there is a 2 million ton per year limit on the total harvest of all managed groundfish species in the BSAI, which is nearly doubled by the optimal pollock harvest alone in some years in this model. Including this cap on total harvest is left for future analysis, and would require examining the tradeoff between all managed groundfish species, not just those included here. B) The results from this model offer a potential explanation for the stock dynamics in this system, but these stock dynamics could change as environmental, climatic, or other factors external to the model change. C) Because arrowtooth and cod are top predators in the ecosystem, it is also possible that declines in the arrowtooth and cod populations could lead to increases in other populations that might increase overall NPV. In other words, 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 remain limitations to a direct application of this model to the fishery, it illustrates how multispecies management differs from single species management as a result of both biological and technological interactions among species. The model can also be expanded to include a more detailed age-structured stock assessment model to further explore the role of age specific predator/prey interactions and age/length-specific harvest mortality, which likely varies by gear type. This work is left for future analysis.

4. *Optimal Multispecies Harvesting in the Presence of a Nuisance Species*

4.1 Introduction

The recently completed Final Recommendations of the Interagency Ocean Policy Task Force has declared that adopting ecosystem based approaches towards management is their number one National Priority Objective. They state that traditional management “has often lead to disjointed management approaches resulting in loss of resources, economic hardship, and environments at risk” [3]. However, research efforts are only beginning to understand the complex ecological linkages between species in an ecosystem and how these are affected by changing environmental conditions such as climate change, as well as the complex economic linkages between human activities such as multispecies harvesting, or 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 need to focus on both the ecological interactions among species as well as the technological interactions which occur through combined harvesting of multiple species and the decision of how vessels allocate effort across multiple species.

While not completely understood, the ecological interactions among species have been studied for many years. However, in the current single species management system, these studies are of limited direct use to set harvest levels because they lack the detail of current stock assessments. New multispecies stock assessment models are currently being developed, and should improve understanding of the way multiple species grow, reproduce, and interact with one another [4].

Similarly, while every fishery is different, there is a large literature in economics exploring the multiproduct nature of vessel's production of multiple fish species using dual estimation methods [5-9]. However, these studies tend to ignore the impact that non-harvested species can have on both the ecological and economic outcomes in multispecies systems. The role of non-harvested species in economic models has largely been relegated to bycatch and discards [11, 14, 15], or as constraints on the harvest of the target species via bycatch quotas [16]. 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 even though it has little harvest value of its own.

Arrowtooth flounder is proposed as a potential nuisance species in the Bering Sea/Aleutian Islands (BSAI) region of Alaska. It is a major predator of pollock, competes with cod for resources, and its harvest averages only a small fraction of its TAC. This chapter extends the model used in previous chapters to solve for both an optimal subsidy on the harvest of the arrowtooth in addition to the optimal quotas for each of the species.

4.2 Social Planner's Optimization

Recalling the social planner's optimization from section 2.2, suppose the social planner again takes vessel profit maximizing behavior as given but chooses both the optimal annual quotas in each year as well as the optimal subsidy (*s*) on arrowtooth harvest to maximize the net present value of the fishery. The fishery manager chooses the optimal annual quota $(\overline{q}_y)$ for all species and subsidy (s_y) on arrowtooth harvest to maximize the profits from the three-species fishery over a 25 year time horizon with a terminal value function equal to the steady state harvest level at the ending stock levels in perpetuity, subject to the stock dynamics equations of each species. This problem can be stated as:

$$\begin{aligned}
&\underset{\overline{q}_y, s_y}{Max} \sum_{y=1}^{Y=25} \theta^t \left\{\pi_y^*(p_y, w_y, x_y, Z, \overline{q}_y, \omega) - s_y h_{arth,y}\right\} + \frac{\theta^{Y+1}}{\delta}\left\{\pi_Y^*(\overline{p}, \overline{w}, x_Y, Z, \overline{q}_{Y+1}, \omega)\right\} \\
&s.t.\ x_{i,y+1} = (1+r_{iy})x_{iy} + \eta_{iy}x_{iy}^2 + \sum_{j\neq i}^{n-1} a_{ijy}x_{iy}x_{jy} - h_{iy},\ i = 1,\ldots,n, \qquad (3.1) \\
&h_{i,Y+1} = (1+\overline{r}_i)x_{iY} + \overline{\eta}_i x_{iY}^2 + \sum_{j\neq i}^{n-1} \overline{a}_{ij}x_{iY}x_{jY},\ i = 1,\ldots,n,
\end{aligned}$$

where ω is each vessel's quota share for each species for each gear type, which is assumed equal to their historical harvesting with each gear type over the period 2008-2010; s_y is a subsidy on arrowtooth, which the fishery manager uses to encourage harvesting of the nuisance species; $\theta = 1/(1+\delta)$ is the discount factor with discount rate δ; $Y = 25$ years; the growth parameters $(r_{iy}, \eta_{iy}, a_{ijy})$ are generated as random draws for each year from a multivariate normal distribution defined by the estimated parameters and variance/covariance matrix from equations (2.1) and (2.7), respectively; and the overbars indicate that in the final period (Y+1) prices are equal to their average level. Let π_{yvg}^* represent the solution of the vessel's problem of maximizing annual profits by choice of harvest and number of trips or operating weeks with each gear type. Summed over all vessels and gear types in a given year, this yields aggregate profit represented as

$$\pi_y^* = \sum_{v=1}^{V_g}\sum_{g=1}^{G}\pi_{vgy}^*.$$

Specifically, the vessel's problem in each year y is

$$\begin{aligned}&\max_{h_{vgt},T_{vg}} \pi_{vg} = \sum_{t=1}^{T_{vg}}\rho^t\left\{\left(p_t+s\right)h_{vgt} - C_{vg}(h_{vgt}\mid w_t,x,Z)\right\}\\ &\text{s.t. } q_{vg,t+1} = \omega_{vg} * \overline{q} - \sum_{t=1}^{t} h_{vgt} \geq 0,\ t=1,\ldots,T-1,\end{aligned} \quad , \tag{3.2}$$

where ρ is an intra-annual discount rate, and $q_{vg,t+1}$ is a vector of the vessel's available quota for each species harvested with gear g available on trip t+1, $\omega_{vg} * \overline{q}$ is a vector of each vessel's total quota allocation of each species to be harvested with each gear type, and T_{vg} is the number of trips taken by vessel v in year y with gear type g. The subsidy on arrowtooth enters into each vessel's profit function after the inverse demand model has determined the current year's price based on the aggregate quantity harvested.

As the functional forms used for estimation do not permit an analytical solution to the bioeconomic model described in equation (3.1), numerical optimization methods are relied upon to determine how optimal stocks, harvests, quotas, profits, and the subsidy on arrowtooth evolve over time. Three different models are compared in section 4.3, the multispecies model of chapter 3, a model ignoring arrowtooth's impact on the system by keeping arrowtooth's harvest at its current percentage of the stock with no subsidy, and an optimized subsidy model that determines the optimal quota of all three species as well as an optimal subsidy on arrowtooth.

4.3 Numerical Optimization

The numerical optimization method solves the maximization problem in equation (3.1) for the optimal quotas for each species and subsidy on arrowtooth for 25 years, at which point the model enters the steady state at the ending stock levels, assuming the harvest is equal to the growth of each species in perpetuity, and prices and growth parameters are equal to their mean from all previous years in the simulation. The social planner is assumed to have perfect foresight, i.e., to know the full draw of random parameters for each year of the simulation when determining the optimal quotas in any year. The model is simulated 100 times for each case: the base multispecies model with no subsidy on arrowtooth, the model with a constant harvest of arrowtooth equal to its average historical rate of harvest (1.5% of the stock), and the full model with a potential subsidy on the harvesting of arrowtooth. These model simulations determine the distribution of profits, stocks, optimal quotas, and subsidy on arrowtooth harvests using the randomly drawn parameter values. The discount rate is assumed to be 0.05 for all models.

The stocks and harvest levels are presented in Figure 7 for the base multispecies model, Figure 9 for the constant harvest rate on arrowtooth model, and Figure 10 for the full model with an arrowtooth subsidy. The model runs begin after 2010, which is to the right of the green vertical line. The historical stocks and harvest levels are included to provide context for the model runs. Median values from all model runs are presented with the solid lines, while the 25th and 75th percentile values are represented by the thin lines. Table 9 presents summary statistics including the stocks, harvests, and net present value estimates from each model.

As was shown in chapter 3 for the base multispecies model, Figure 7 shows that optimal policy greatly increases the harvesting of arrowtooth so that the stock of cod and pollock are allowed to thrive, resulting in a median net present value from the base multispecies model of $20.7 billion dollars. This harvesting strategy results in losses to the vessels harvesting arrowtooth in the initial periods as harvesting arrowtooth is not currently profitable. This is based on the fact that there is no directed target fishery for arrowtooth and vessels with extra capacity and time could easily target arrowtooth if it were profitable. These losses are made up from increased harvesting of cod and pollock throughout the 25-year period as Table 1 shows that the stock of arrowtooth decreases the growth of both cod and pollock.

The model with a constant harvest rate of arrowtooth shown in Figure 9 highlights how ignoring the role of arrowtooth impacts this ecosystem. Keeping the harvest rate of arrowtooth constant at the low current rate results in drastically reduced stocks of both cod and pollock, and a median net present value of only $8.5 billion dollars. Comparing this result to the base multispecies model, ignoring the role of the nuisance species results in a loss of over $12 billion dollars from this three species fishery. In the early years of the model run, it is optimal to harvest a large quantity of cod, because if vessels do not harvest the cod, arrowtooth consume the cod, which provides no value to the fishery. Throughout the rest of the model, both the stock and harvest of cod are very low. The reduced stocks of cod and pollock translate into smaller harvests of cod and pollock in the steady state, but larger harvests of the less valuable arrowtooth.

Not surprisingly, the stock dynamics for the model with an arrowtooth subsidy presented in Figure 10 show a similar pattern to the base multispecies model. However, arrowtooth is harvested more aggressively and approaches a zero stock level by the year 2030 in the subsidy model while the base multispecies model approaches a zero stock level around the year 2035. The more aggressive harvesting of arrowtooth translates to larger steady state harvests of cod and pollock and an increase in the net present value of the fishery of $273 million dollars for an estimated net present value of $20.9 billion dollars. The steady state stock of cod is slightly higher and the steady state stock of pollock is slightly lower in the arrowtooth subsidy model which translates into higher steady state harvests of cod and pollock compared with the base multispecies model.

Table 9 shows that the median discounted subsidy for harvesting arrowtooth summed over the 25 years plus the steady state is $35 million dollars. The median subsidy per pound of arrowtooth harvested is $0.113, which is equivalent to an increase of over 3 times the median price of arrowtooth of $0.032. Therefore, a fairly large increase in the price of arrowtooth is necessary to shift enough effort into the fishery to maximize the net present value of the combined three-species fishery. This large price response could be a result of the lack of a well defined market for arrowtooth in the period used for the inverse demand model. It is possible that the demand response may be more subdued if markets for arrowtooth grow. The price of fish meal has increased substantially in recent years, and arrowtooth is an excellent candidate for additional fish meal production, which may counteract any reduction in the arrowtooth price from the increased quantity on the market.

The subsidy on arrowtooth results in a $273 million dollar increase in the value of the fishery after subtracting the cost of the subsidy. This subsidy could be paid from a lump sum tax on cod and pollock harvests based on the quotas shares of each species, as they are the main beneficiaries of increased arrowtooth harvests. It may also be possible to introduce a per pound tax on the harvest of cod and pollock equal to the marginal cost of a unit of arrowtooth on the marginal profit from harvesting a unit of cod and pollock.

This will likely alter the targeting behavior of vessels at the margin, and therefore is left for future analysis.

Table 9 also shows that there are substantial cost anti-complementarities in this multispecies fishery, which is not surprising given that there are diseconomies of scope found in the estimation of the cost functions. At a value of $345, $76, and $841 million dollars for the base multispecies model, constant harvest rate model, and the subsidy on arrowtooth model, respectively, these are fairly substantial costs incurred by the fishery. But they only result in losses equivalent to 1.7%, 0.89%, and 4.0% of the net present value of each model, respectively.

Similar to the models presented in chapter 3, all models increase the harvest of cod and pollock near the end of the time horizon in response to the terminal condition to lower the steady state stock and therefore steady state profits. These results are also similar to a 10 year time horizon model, and a time horizon longer than 25 years would likely be preferable with sufficient increases in computing power.

4.4 Discussion and Conclusion

Using a 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 and pollock, it makes economic sense to subsidize the harvesting of arrowtooth to lower its population and thus increase the stock of cod and pollock, and consequent profits from those fisheries. The median optimal total discounted subsidy amounts to $35 million dollars, but increases the net present value of the fishery by $273 million dollars net of the cost of the subsidy. Ignoring arrowtooth interactions on cod and pollock results in respective steady state stocks of cod and pollock that are only 5% and 39% as large as the base multispecies model from chapter 3, and steady state harvests that are only 11% and 55% of their base multispecies model values.

A number of caveats must be considered in using the results of this research before encouraging additional harvests of arrowtooth. First, this model uses a reduced form ecological model that has substantial limitations regarding age-structured ecological interactions, as well as gear-specific age selectivities. The model accounts for this uncertainty by allowing the parameters of the growth functions to vary stochastically each year in the model and across model simulations. However, the stock dynamics in the ecosystem could change as factors external to the model change. Examples include changes in biogeochemical cycles, changes in abundance of other important prey species, changes in primary productivity of the ecosystem, and climate change.

Second, the study lacks data on real profits, but rather approximates profits with net revenues with some assumptions about the costs of fishing. Substantial fixed costs for vessel operation are likely, and fuel costs likely impact fishery profits. These costs are excluded from this model because data are not available.

Third, no attempt has been made to model specific regulations specific to these fisheries in the BSAI, such as the 2 million ton per year limit on the total harvest of all managed groundfish species in the BSAI. This limit is exceeded by the pollock harvest alone in some years of the model simulation. Exploring the role of the cap on total harvest is left for future analysis, and is likely to become a major issue among various fishing interests if the pollock stock rebounds as expected. Harvesting arrowtooth to the extent proposed by the model would also likely classify arrowtooth as overfished and necessitate a rebuilding strategy for arrowtooth, but that possibility is left for future analysis.

Finally, because cod are a top predator in this ecosystem, increases in the cod population may lead to decreases in other fish populations, which may result in an overall decrease in NPV outside of these three species alone. An important consideration for multispecies and ecosystem based approaches is that adjusting the boundaries of the system can lead to alternative conclusions, which argues for conservative actions in situations where outside factors potentially influence the results. Similarly, changes in the stock dynamics within the model affect the ecosystem outside the model's boundaries, which can lead to alternative conclusions about optimal management in reality.

While there are substantial limitations as to the direct application of this model to the fishery, it illustrates how non-target species impact target species not only through bycatch but also through ecosystem and technological interactions, leading to drastically different optimal harvest policies. The model can also be expanded to include a more detailed age-structured stock assessment model, gear-specific age selectivities, and improved cost information if it becomes available.

Figures

Figure 1

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

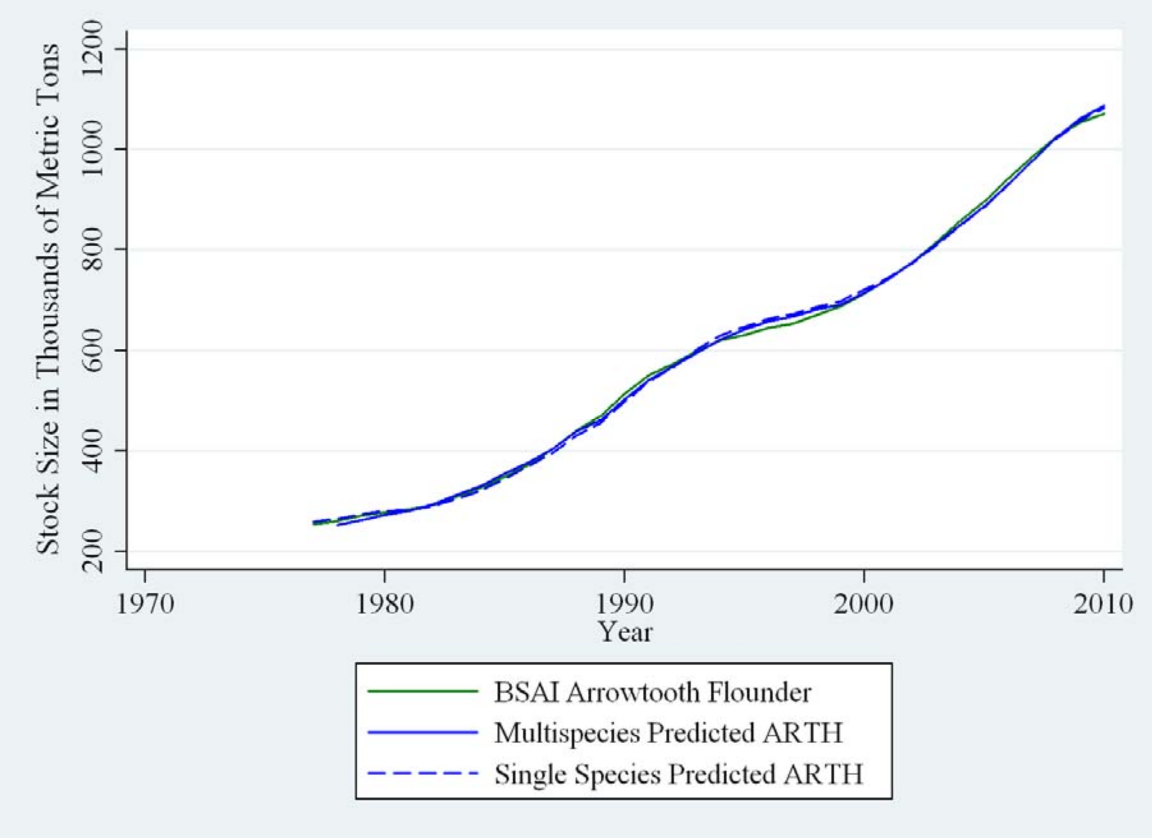


Figure 2

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

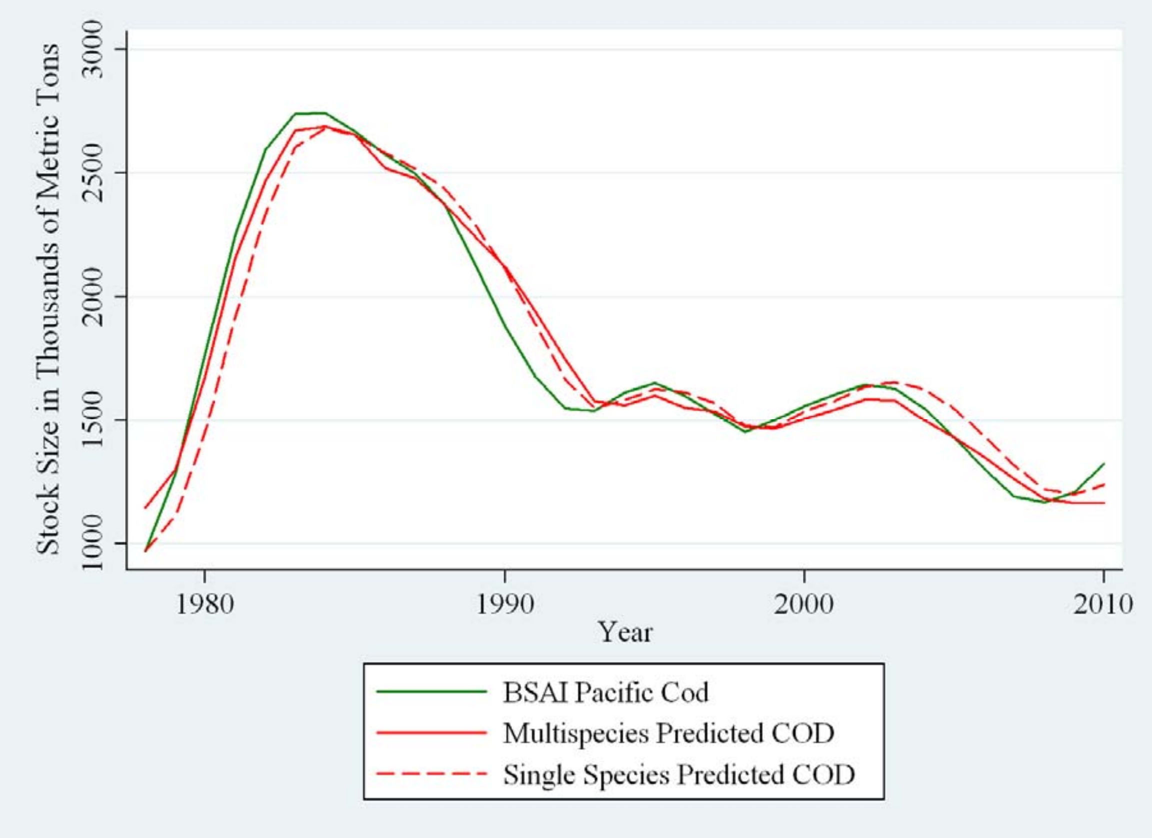


Figure 3

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

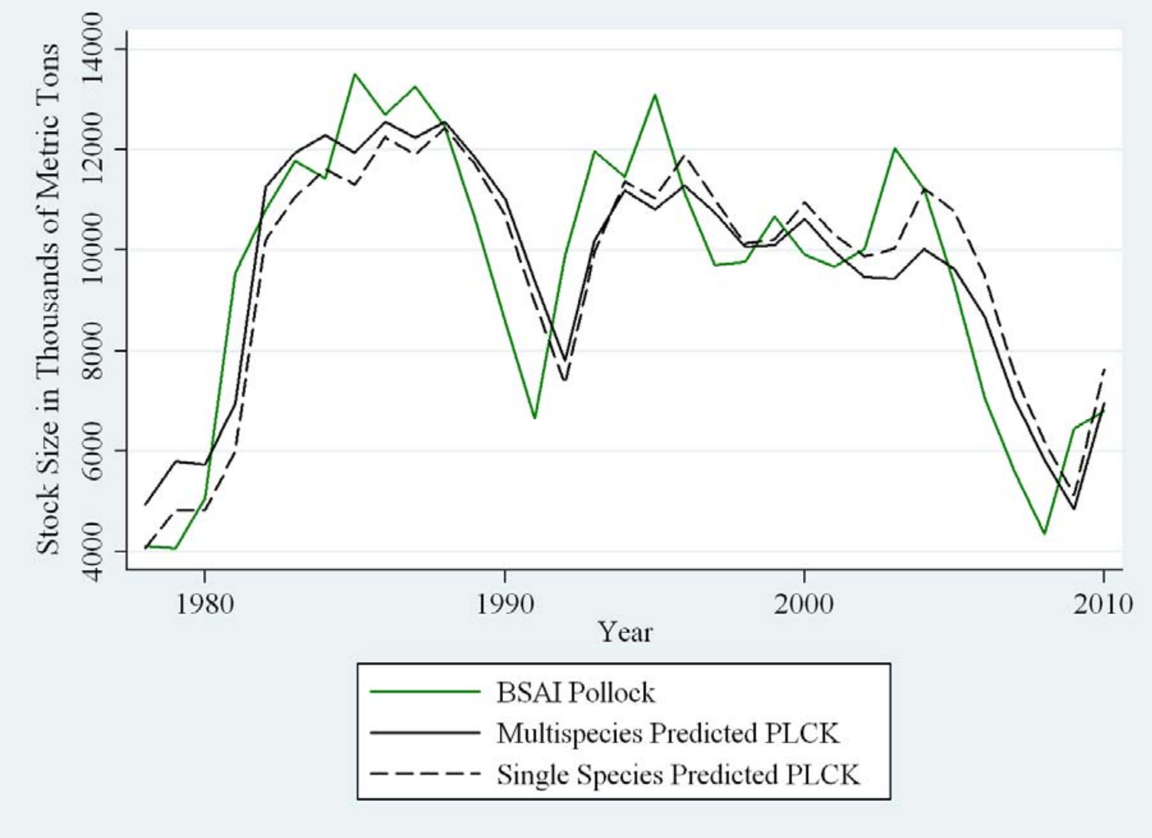


Figure 4

Single and multispecies growth functions for arrowtooth flounder.

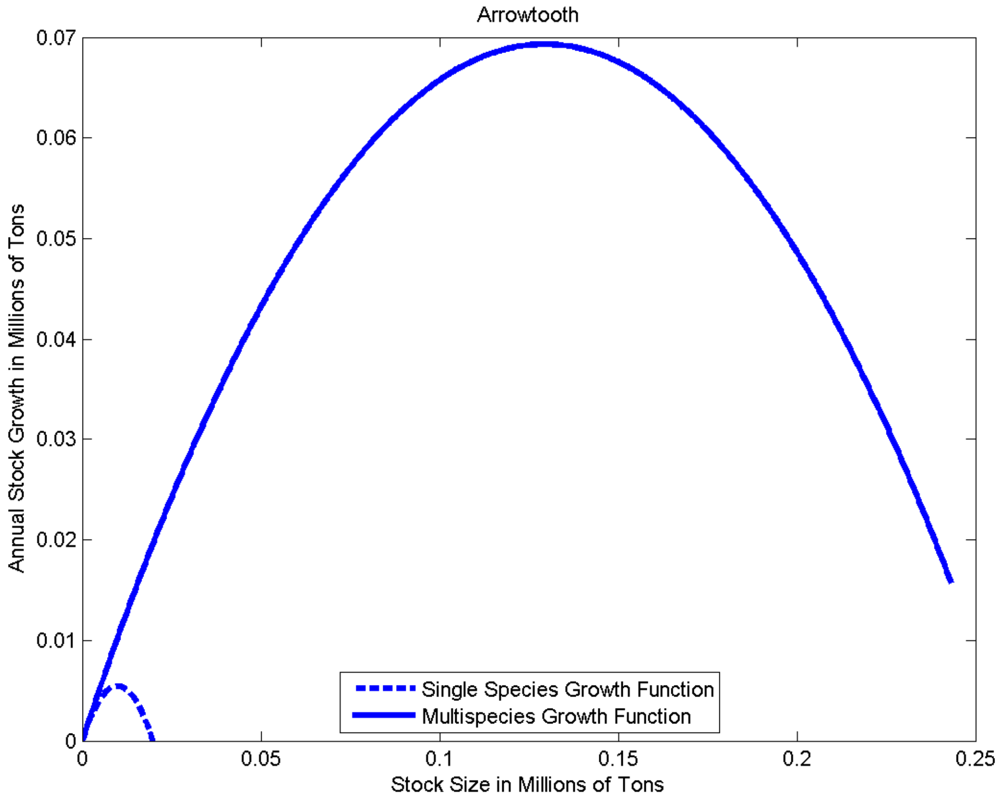


Figure 5

Single and multispecies growth functions for Pacific cod.

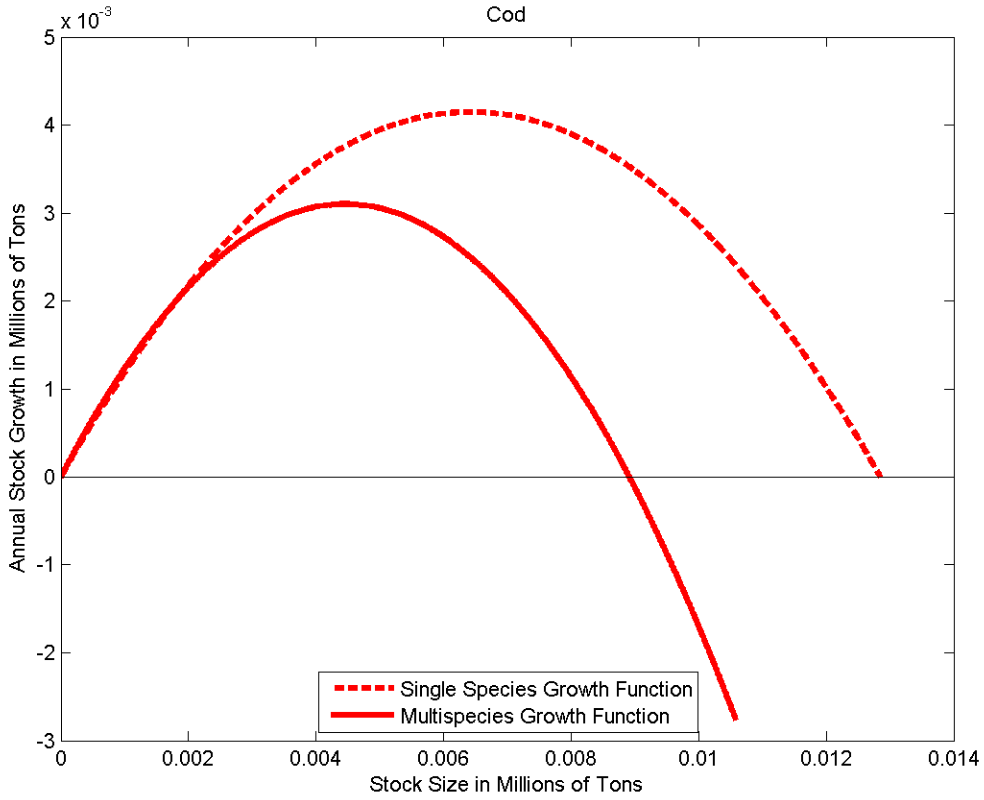


Figure 6

Single and multispecies growth functions for walleye pollock.

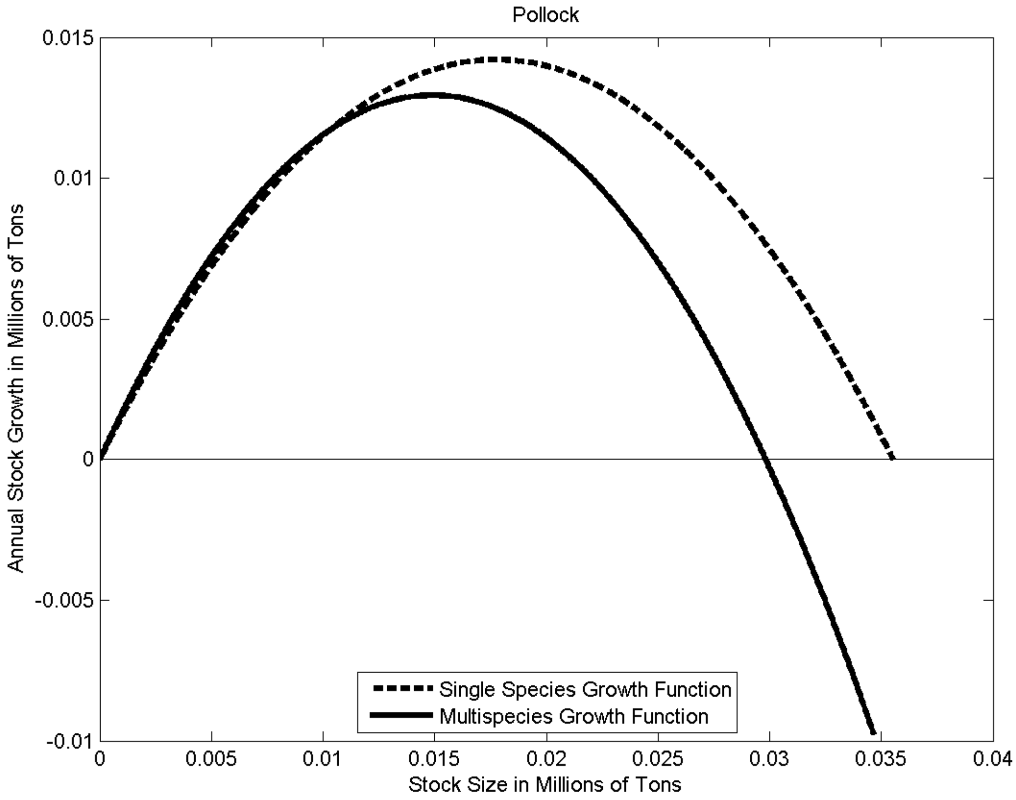
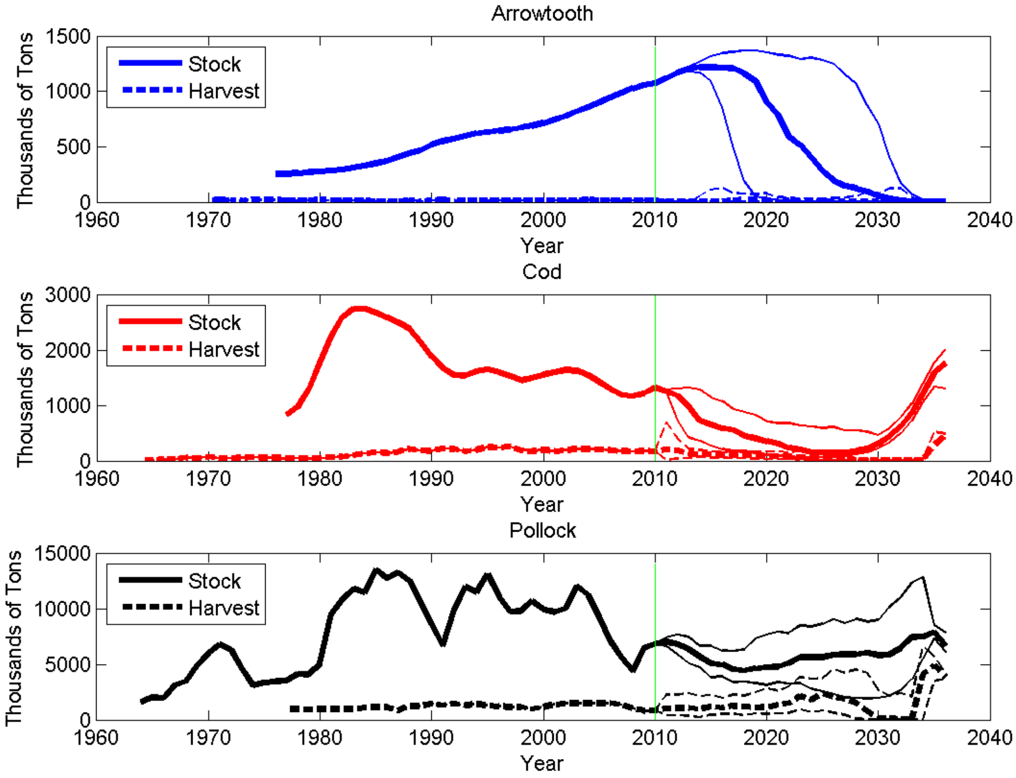


Figure 7

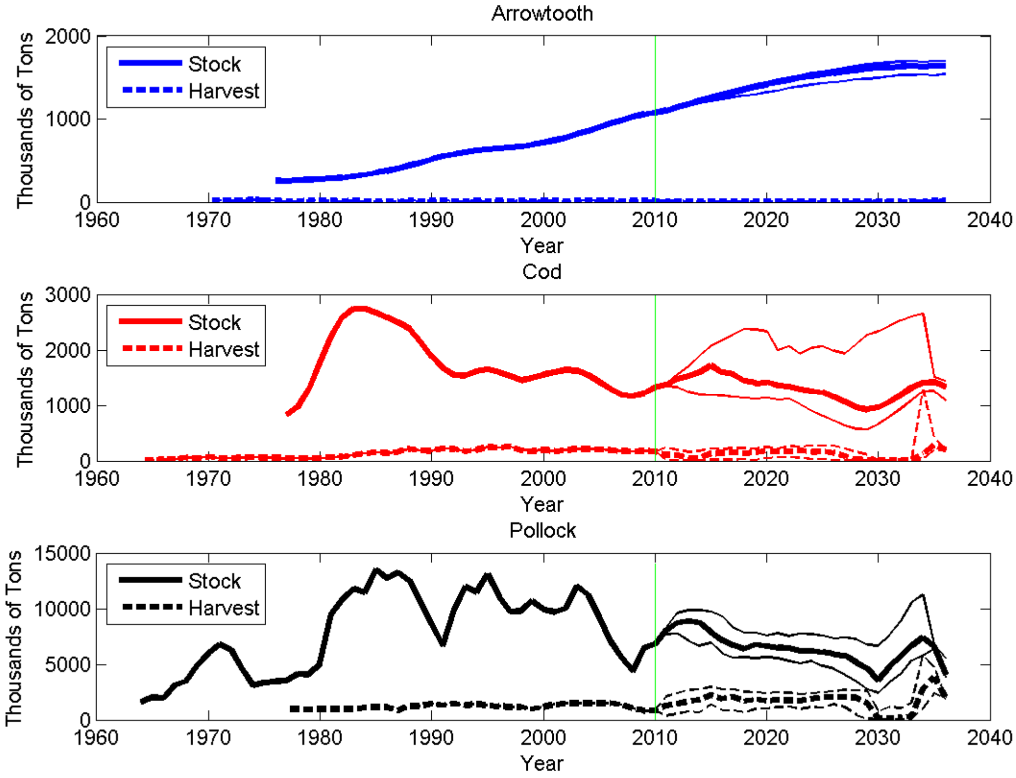
Stocks and harvest from the optimal multispecies model.[a]



[a] The model begins in 2010 (to the right of the green line), and the thin lines represent 25th and 75th percentiles from the model. Historical stocks and harvests are included for context.

Figure 8

Stocks and harvest from the optimal single species model.[a]



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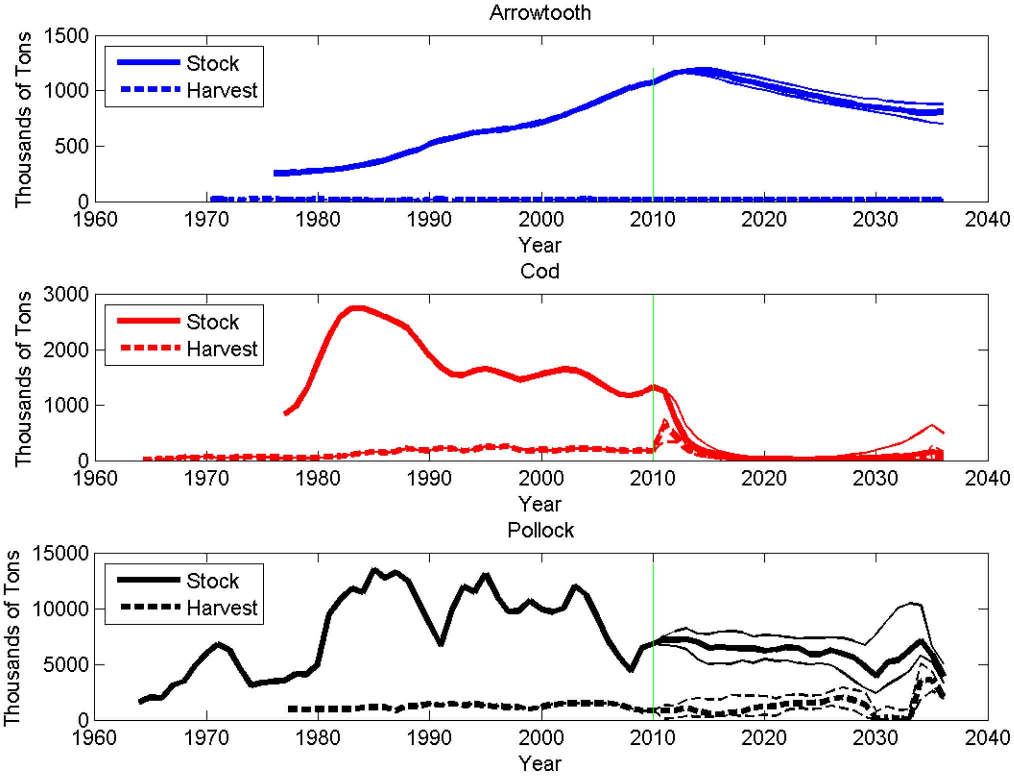
[a] The model begins in 2010 (to the right of the green line), the thick lines are the median model run while the thin lines represent 25th and 75th percentile runs of the model. Historical stocks and harvests are included for context.

Figure 9

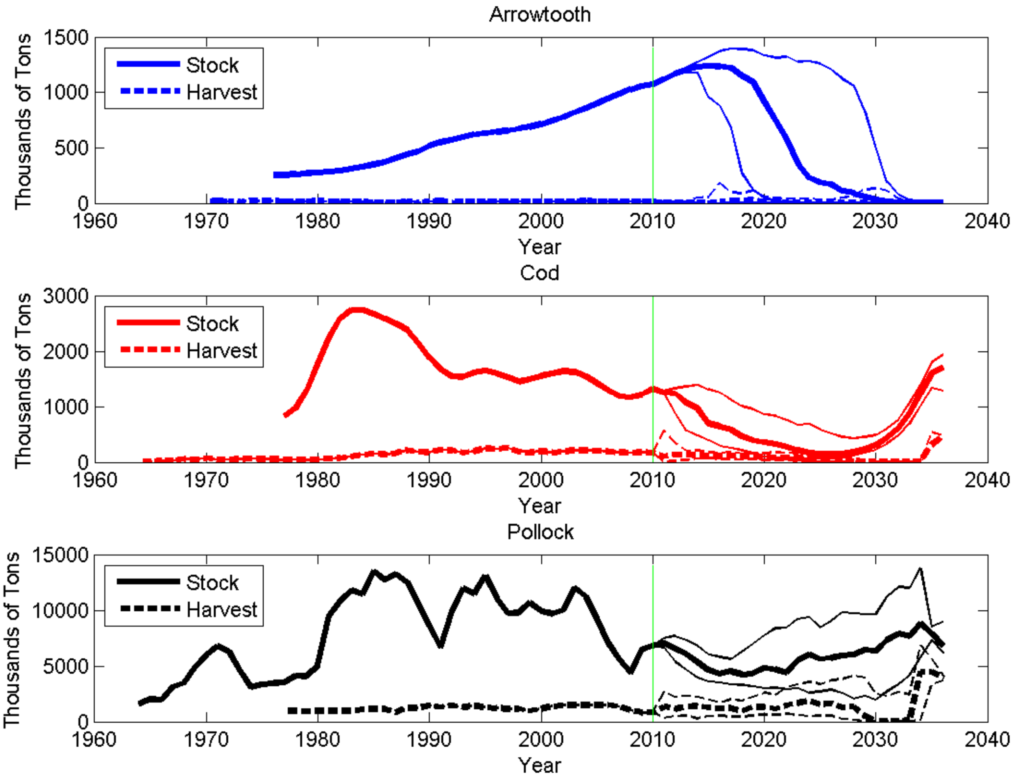
Stocks and harvest from the optimal multispecies model with a constant harvest rate on arrowtooth equal to the historical average (1.5% of the stock).[a]



[a] The model begins in 2010 (to the right of the green line), the thick lines are the median model run while the thin lines represent 25th and 75th percentile runs of the model. Historical stocks and harvests are included for context.

Figure 10

Stocks and harvest from the optimal multispecies model with a subsidy on the harvest of arrowtooth.[a]



[a] The model begins in 2010 (to the right of the green line), the thick lines are the median model run while the thin lines represent 25th and 75th percentile runs of the model. Historical stocks and harvests are included for context.

Tables

Table 1

Multispecies Stock Dynamics Parameter Estimates[a]

Growth Model	Parameter	Coefficient	Standard Error
Arrowtooth Flounder N=33 R^2=.99	r_{arth}	1.0067***	0.0238
	η_{arth}	-0.0041	0.0149
	$\alpha_{arth,cod}$	0.0477***	0.0103
	$\alpha_{arth,plck}$	-0.0019*	0.0011
Pacific Cod N=33 R^2=.99	r_{cod}	1.6539***	0.0815
	η_{cod}	-0.1563***	0.0369
	$\alpha_{cod,arth}$	-0.2749***	0.0733
	$\alpha_{cod,plck}$	-0.0103*	0.0055
Walleye Pollock N=33 R^2=.98	r_{plck}	2.0177***	0.2647
	η_{plck}	-0.0582***	0.0150
	$\alpha_{plck,arth}$	-0.3771*	0.2132
	$\alpha_{plck,cod}$	-0.0324	0.0979

[a] An "*" denotes statistical significance at the 10% level, "**" denotes statistical significance at the 5% level, and "***" denotes statistical significance at the 1% level. Prior to estimation, all variables were rescaled to one millionth of their actual values, thus the resulting coefficient estimates represent a change of one million units. Parameters are defined as follows: *r* represents the intrinsic growth rate, η represents the density dependent factor related to the carrying capacity, and $\alpha_{i,j}$ represents the biological interaction between species *i* and species *j*, where *arth* represents arrowtooth flounder, *cod* represents Pacific cod, and *plck* represents walleye pollock.

Table 2

Single Species Stock Dynamics Parameter Estimates[a]

Growth Model	Parameter	Coefficient	Standard Error
Arrowtooth Flounder N=34	r^{ss}_{arth}	1.102***	0.00989
	η^{ss}_{arth}	-.0557***	.0125
Pacific Cod N=33	r^{ss}_{cod}	1.292***	0.0499
	η^{ss}_{cod}	-.1005***	.0234
Walleye Pollock N=33	r^{ss}_{plck}	1.599***	0.148
	η^{ss}_{plck}	-.045***	.0133

[a] An "*" denotes statistical significance at the 10% level, "**" denotes statistical significance at the 5% level, and "***" denotes statistical significance at the 1% level. Prior to estimation, all variables were rescaled to one millionth of their actual values, thus the resulting coefficient estimates represent a change of one million units. Parameters are defined as follows: r^{ss} represents the intrinsic growth rate and η^{ss} represents the density dependent factor related to carrying capacity, where *arth* represents arrowtooth flounder, *cod* represents Pacific cod, and *plck* represents walleye pollock.

Table 3

Cost function estimates for Catcher Vessels (CVs)[a]

Coefficient	CV Longline	CV Non-Pelagic Trawl	CV Pot	CV Pelagic Trawl
w	1***	1***	1***	1***
h_{arth}		41.6*		39.3***
		(1.96)		(4.21)
h_{cod}	-65.1	11.4***	-21.8***	7.17
	(-1.56)	(21.83)	(-4.39)	(0.88)
h_{plck}		9.07***		3.96***
		(3.48)		(34.24)
x_{arth}		-2052***		-1124***
		(-12.25)		(-14.15)
x_{cod}	-2627	-1930***	19678***	-930***
	(-0.24)	(-4.99)	(4.21)	(-11.00)
x_{plck}		48.1***		19.1***
		(5.39)		(7.16)
Z_{grt}	-11.1	-17.5***	119***	10.4***
	(-0.15)	(-4.84)	(3.78)	(6.91)
Z_{lgth}	106	178***	-562***	37.5***
	(0.35)	(8.30)	(-4.77)	(6.65)
Z_{hp}	-41	-221***	261	-141***
	(-0.07)	(-6.39)	(0.70)	(-3.30)
w,w	-.00121	-.0144*	-.0288***	-.053***
	(-0.22)	(-2.19)	(-5.87)	(-16.65)
w,h_{arth}		.11		.227***
		(1.48)		(3.99)
w,h_{cod}	.858***	.117***	.545***	-.0481
	(8.06)	(24.70)	(30.78)	(-0.85)
w,h_{plck}		.0995***		.0447***
		(5.59)		(48.31)
w,x_{cod}	-.194		-.0757	
	(-1.40)		(-0.60)	
w,Z_{grt}	.213***	.00142	.0467***	.0254***
	(12.04)	(0.27)	(3.98)	(6.13)
w,Z_{lgth}	-.0456	.197***	.153***	.148***
	(-1.41)	(11.64)	(5.60)	(15.89)

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w,Z_{hp}	-.193	-.51***	-.304*	-.344***
	(-1.41)	(-6.30)	(-2.21)	(-9.13)
h_{arth},h_{arth}		.102		.0774
		(0.37)		(0.35)
h_{arth},h_{cod}		.109		-1.86**
		(1.13)		(-2.72)
h_{arth},h_{plck}		.511		.0278**
		(1.26)		(2.59)
h_{arth},Z_{grt}		.168		.106
		(1.01)		(1.52)
h_{arth},Z_{lgth}		-.923*		-.392
		(-2.15)		(-1.95)
h_{arth},Z_{hp}		-.569		-1.18*
		(-0.33)		(-2.02)
h_{cod},h_{cod}	.0366	.000666	-.00326	-.505
	(0.45)	(0.70)	(-1.14)	(-1.86)
h_{cod},h_{plck}		.0606***		.0325***
		(6.04)		(3.98)
h_{cod},x_{cod}	54		17.4*	
	(0.94)		(2.46)	
h_{cod},Z_{grt}	.0424	.00304	-.0179*	.159*
	(0.34)	(1.86)	(-2.00)	(2.52)
h_{cod},Z_{lgth}	-.237	-.0455***	.045*	-.479***
	(-0.48)	(-5.33)	(2.08)	(-3.87)
h_{cod},Z_{hp}	1.24	.00653	.161	-.248
	(0.69)	(0.18)	(1.70)	(-0.62)
h_{plck},h_{plck}		-.00627		.000115
		(-0.78)		(1.74)
h_{plck},Z_{grt}		.0232		.000117
		(1.73)		(0.14)
h_{plck},Z_{lgth}		-.0788		-.00244
		(-1.57)		(-1.20)
h_{plck},Z_{hp}		-.0672		-.0153*
		(-0.49)		(-2.01)
x_{cod},x_{cod}	2053		-17424***	
	(0.26)		(-4.54)	
x_{cod},Z_{grt}	-10.6		12.9	
	(-0.40)		(1.69)	

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x_{cod},Z_{lgth}	.331		3	
	(0.00)		(0.23)	
x_{cod},Z_{hp}	208		69.3	
	(0.64)		(1.13)	
Z_{grt},Z_{grt}	-.116	.0112	.525**	-.00102
	(-0.55)	(1.66)	(2.76)	(-0.37)
Z_{grt},Z_{lgth}	1.18	.568***	-6.76***	-.123***
	(0.44)	(4.75)	(-4.21)	(-3.70)
Z_{grt},Z_{hp}	7.53	-2.46***	25.6*	-.133
	(0.82)	(-4.95)	(2.29)	(-0.42)
Z_{lgth},Z_{lgth}	-2.44	-3.77***	16.3***	-.195
	(-0.35)	(-6.87)	(3.76)	(-1.36)
Z_{lgth},Z_{hp}	-16.4	23***	-80.8	.966
	(-0.48)	(6.46)	(-1.68)	(0.74)
Z_{hp},Z_{hp}	17.1	-51.4***	142	5.6***
	(1.61)	(-6.73)	(1.03)	(3.34)
V	179	750	781	3462
R^2	.883	.869	.875	.889

[a] An "*" denotes statistical significance at the 10% level, "**" denotes statistical significance at the 5% level, and "***" denotes statistical significance at the 1% level. The t statistics are in parentheses. Coefficient names represent the subscripts of the α coefficients in equation (2.3). Names separated by ","denote cross product terms in the cost function. Parameters are defined as follows: *w* represents the daily crew services wage, *h* represents harvest, *x* represents the stock, and Z represents fixed vessels characteristics, where *arth* represents arrowtooth flounder, *cod* represents Pacific cod, *plck* represents walleye pollock, *grt* represents gross tonnage, *lgth* represents length, *hp* represents horsepower, and *V* is the number of observations used to estimate each equation. As the R^2 statistic is not a well defined concept for generalized least squares, the reported R^2 statistic represents the percent of the variance explained by the predictors.

Table 4

Cost function estimates for Catcher Processor Vessels (CPs)[a]

Coefficient	CP Longline	CP Non-Pelagic Trawl	CP Pot	CP Pelagic Trawl
w	1***	1***	1***	1***
h_{arth}	82.7	-44.4**		-936**
	(1.59)	(-3.20)		(-2.69)
h_{cod}	9.96***	-14.9*	-1.03	65.6
	(10.30)	(-2.44)	(-0.20)	(1.59)
h_{plck}	18.5	-6.46		2.04***
	(1.76)	(-0.08)		(3.50)
x_{arth}	-3424***	-3004		-9654***
	(-27.24)	(-1.03)		(-7.51)
x_{cod}	3518***	-75903***	907	28742***
	(6.48)	(-5.51)	(0.30)	(20.41)
x_{plck}	-286***	21.8		-2899***
	(-37.30)	(0.12)		(-11.95)
Z_{grt}	734**	-1430		637***
	(2.58)	(-0.12)		(4.74)
Z_{lgth}	4.95	206	54.1	-122**
	(0.18)	(0.07)	(1.11)	(-3.16)
Z_{hp}	32.1	4751	-890**	347***
	(0.14)	(0.23)	(-3.13)	(4.53)
w,w	-.188***	-1.38***	-.391***	-2.06***
	(-18.10)	(-7.44)	(-9.02)	(-22.69)
w,h_{arth}	-.499***	.0412		-14.8***
	(-8.53)	(1.08)		(-16.56)
w,h_{cod}	.103***	.129***	.764***	1.57***
	(19.41)	(3.89)	(12.24)	(5.51)
w,h_{plck}	.499***	-.0133		.0295***
	(8.53)	(-0.03)		(7.85)
w,x_{cod}	-2.15***	6.68*	-5.21***	
	(-15.91)	(1.96)	(-8.13)	
w,x_{plck}				9.7***
				(11.85)
w,Z_{grt}	-.592***	-8.89*	6.85***	.53
	(-3.84)	(-2.55)	(11.95)	(1.72)

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w,Z_{lgth}	.966***	2.78***	1.2***	2.96***
	(71.32)	(9.42)	(15.65)	(47.83)
w,Z_{hp}	1.86***	.664	-2.59***	2.1***
	(26.01)	(0.57)	(-4.47)	(9.47)
h_{arth},h_{arth}	-7.13*	.0112		-2.96
	(-2.12)	(1.81)		(-0.69)
h_{arth},h_{cod}	.783**	.149		1.91
	(3.14)	(0.88)		(0.58)
h_{arth},h_{plck}	6.19***	.329		.04
	(3.37)	(0.77)		(0.58)
h_{arth},x_{cod}	-215***	65.8*		
	(-3.89)	(2.50)		
h_{arth},x_{plck}				-24.7
				(-1.14)
h_{arth},Z_{grt}	-4.15	.304		6.66
	(-0.93)	(0.10)		(0.59)
h_{arth},Z_{lgth}	-.103	.0277		.181
	(-0.14)	(0.24)		(0.13)
h_{arth},Z_{hp}	.0755	-.0537		-4.1
	(0.04)	(-0.04)		(-1.03)
h_{cod},h_{cod}	-.00331*	-.00658	.0224**	.463
	(-2.27)	(-1.62)	(2.95)	(1.27)
h_{cod},h_{plck}	.0727**	.244		.00164
	(3.10)	(1.65)		(0.11)
h_{cod},x_{cod}	-3.8***	35.5***	-45.8***	
	(-5.06)	(6.32)	(-8.69)	
h_{cod},x_{plck}				19.7***
				(4.71)
h_{cod},Z_{grt}	-.283***	.701	.272	7.22***
	(-3.65)	(0.63)	(0.76)	(6.30)
h_{cod},Z_{lgth}	.0171	-.0603	-.126	-1.15***
	(1.85)	(-0.71)	(-1.73)	(-4.99)
h_{cod},Z_{hp}	.08*	.207	.47	-.706
	(2.36)	(1.01)	(1.08)	(-0.83)
h_{plck},h_{plck}	.0114	-.507		-.000116
	(0.13)	(-0.73)		(-0.85)
h_{plck},x_{cod}	12.9	-41		
	(1.68)	(-0.47)		

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h_{plck},x_{plck}				-.083
				(-1.50)
h_{plck},Z_{grt}	4.97***	-10.8		-.054***
	(4.90)	(-1.00)		(-3.52)
h_{plck},Z_{lgth}	.0173	.982		.0147***
	(0.17)	(0.87)		(4.55)
h_{plck},Z_{hp}	-1.54***	-2.36		-.0171
	(-3.97)	(-0.75)		(-1.64)
x_{cod},x_{cod}	3393***	49561***	2782	
	(8.44)	(5.05)	(1.66)	
x_{cod},Z_{grt}	613***	-1724*	950***	
	(23.38)	(-1.98)	(4.75)	
x_{cod},Z_{lgth}	-63.1***	255***	-147***	
	(-20.30)	(3.52)	(-3.89)	
x_{cod},Z_{hp}	-10.2	-400	653**	
	(-0.81)	(-1.85)	(2.66)	
x_{plck},x_{plck}				179***
				(9.36)
x_{plck},Z_{grt}				5.44
				(1.27)
x_{plck},Z_{lgth}				3.21**
				(3.17)
x_{plck},Z_{hp}				-.6
				(-0.20)
Z_{grt},Z_{grt}	10.8	-386	60.2*	-3.05
	(0.47)	(-0.09)	(2.38)	(-0.98)
Z_{grt},Z_{lgth}	-15.1***	37.5	-8.09*	-6.06*
	(-4.37)	(0.06)	(-2.51)	(-2.22)
Z_{grt},Z_{hp}	6.39	241	5.65	7.44
	(0.22)	(0.13)	(0.33)	(0.82)
Z_{lgth},Z_{lgth}	.733	4.8	1.29**	1.51***
	(1.51)	(0.07)	(2.73)	(4.93)
Z_{lgth},Z_{hp}	8.02	-109	1.87	.0633
	(1.92)	(-0.20)	(0.60)	(0.11)
Z_{hp},Z_{hp}	-37.4***	162	-2.24	-4.65
	(-4.37)	(0.19)	(-0.10)	(-1.69)
V	7312	345	398	3448
R^2	.953	.901	.947	.961

[a] An "*" denotes statistical significance at the 10% level, "**" denotes statistical significance at the 5% level, and "***" denotes statistical significance at the 1% level. The t statistics are in parentheses.

Coefficient names represent the subscripts of the α coefficients in equation (2.3). Names separated by ","denote cross product terms in the cost function Parameters are defined as follows: w represents the daily crew services wage, h represents harvest, x represents the stock, and Z represents fixed vessels characteristics, where *arth* represents arrowtooth flounder, *cod* represents Pacific cod, *plck* represents walleye pollock, *grt* represents gross tonnage, *lgth* represents length, *hp* represents horsepower, and V is the number of observations used to estimate each equation. As the R^2 statistic is not a well defined concept for generalized least squares, the reported R^2 statistic represents the percent of the variance explained by the predictors.

Table 5

Poisson Regression for Annual Number of Trips for Catcher Vessels (CVs)[a]

Coefficient	CV Longline	CV Non-Pelagic Trawl	CV Pot	CV Pelagic Trawl
Z_{grt}	-.0275***	.00157***	.000796	.00271***
	(-8.29)	(4.63)	(1.30)	(12.20)
Z_{lgth}	.0539***	.00674***	-.00321	-.00506***
	(7.02)	(4.67)	(-1.73)	(-5.28)
Z_{hp}	-.00141	-.00994	-.00928	-.046***
	(-0.06)	(-1.74)	(-0.98)	(-14.16)
q_{arth}	-11.2***	1.8*	-6.53***	2.56***
	(-5.05)	(2.49)	(-7.46)	(6.16)
q_{cod}	23.8***	7.73***	15.2***	-7.19***
	(5.78)	(4.32)	(7.52)	(-6.80)
q_{plck}	-2.59***	-.623**	-.671**	.935***
	(-5.75)	(-3.03)	(-2.88)	(8.37)
p_{arth}	-.0448***	-.00894**	-.185***	.00386***
	(-5.17)	(-2.80)	(-14.95)	(5.66)
p_{cod}	.00383***	.00146***	.00391***	-.00189***
	(12.84)	(14.96)	(24.61)	(-30.05)
p_{plck}	-.0293***	.000372	-.0124***	.00591***
	(-18.50)	(1.27)	(-15.95)	(28.78)
w	.00483**	.0283***	.0118***	.00392**
	(3.15)	(11.92)	(5.06)	(3.08)
$h_{lgl,arth}$	.531***			
	(6.18)			
$h_{lgl,cod}$	.0109***			
	(21.68)			
$h_{lgl,plck}$	.721***			
	(7.64)			
$h_{npt,arth}$		.00697***		
		(5.90)		
$h_{npt,cod}$		.00134***		
		(42.91)		
$h_{npt,plck}$		.00417***		
		(13.17)		
$h_{pot,arth}$			-.0664	
			(-1.03)	
$h_{pot,cod}$			.00416***	
			(41.49)	
$h_{pot,plck}$			.00729***	
			(4.49)	

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$h_{ptr,arth}$					.0147***
					(11.70)
$h_{ptr,cod}$					.000301
					(0.72)
$h_{ptr,plck}$					.000149***
					(38.22)
constant	-1.29	-6.64***		-2.4***	.811**
	(-1.51)	(-13.17)		(-4.31)	(2.81)
V	726	1155		1897	1026
Pseudo R^2	0.586	0.446		0.593	0.609

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[a] An "*" denotes statistical significance at the 10% level, "**" denotes statistical significance at the 5% level, and "***" denotes statistical significance at the 1% level. The t statistics are in parentheses. Coefficient names represent elements of the β vector in equation (2.6). Names separated by ","denote cross product terms. Parameters are defined as follows: Z represents fixed vessels characteristics, *q* represents the annual total allowable catch, *p* represents output prices, *w* represents the daily crew services wage, and *h* represents harvest, where *arth* represents arrowtooth flounder, *cod* represents Pacific cod, *plck* represents walleye pollock, *grt* represents gross tonnage, *lgth* represents length, *hp* represents horsepower, *lgl* represents longline gear, *npt* represents non-pelagic trawl gear, *pot* represents pot gear, *ptr* represents pelagic trawl gear, and *V* is the number of observations used to estimate each equation.

Table 6

Poisson Regression for Annual Number of Weeks for Catcher Processors (CPs)[a]

Coefficient	CP Longline	CP Non-Pelagic Trawl	CP Pot	CP Pelagic Trawl
Z_{grt}	-.0341***	-.0314***	.072**	-.0207***
	(-6.29)	(-8.44)	(3.04)	(-8.15)
Z_{lgth}	.000976	.00433***	.0188***	.00541***
	(1.62)	(9.09)	(6.55)	(10.51)
Z_{hp}	-.0212***	-.0186***	-.204***	-.00725***
	(-10.44)	(-11.87)	(-13.98)	(-4.36)
q_{arth}	-2.11***	-29.1***	-9.66***	6.13***
	(-3.30)	(-22.64)	(-3.43)	(5.11)
q_{cod}	11.8***	-25.3***	1.03	-8.14***
	(8.36)	(-15.12)	(0.17)	(-3.61)
q_{plck}	-.926***	-6.34***	-5.16***	-.239
	(-5.34)	(-20.73)	(-6.42)	(-0.81)
p_{arth}	-.00248***	.0113***	-.00124	-.00187***
	(-15.34)	(32.61)	(-1.56)	(-4.95)
p_{cod}	.00139***	-.00261***	.00263***	.000121
	(15.12)	(-21.07)	(7.24)	(0.75)
p_{plck}	-.00194***	-.0075***	-.0101***	-.00115
	(-4.38)	(-12.36)	(-5.18)	(-1.49)
w	.00851***	.0494***	.0518***	.0068**
	(6.05)	(22.17)	(7.58)	(2.73)
$h_{lgl,arth}$	.00249***			
	(11.54)			
$h_{lgl,cod}$	.000513***			
	(64.67)			
$h_{lgl,plck}$	.000217			
	(1.83)			
$h_{npt,arth}$		.000174***		
		(11.34)		
$h_{npt,cod}$		.000298***		
		(20.33)		
$h_{npt,plck}$		.000915***		
		(32.90)		
$h_{pot,arth}$			.326*	
			(2.14)	
$h_{pot,cod}$			.00159***	
			(24.06)	
$h_{pot,plck}$			.122***	
			(3.66)	

Continued on the next page

$h_{ptr,arth}$				-.00711***
				(-9.33)
$h_{ptr,cod}$				.00131***
				(5.84)
$h_{ptr,plck}$				.000086***
				(41.66)
constant	-.486*	10.1***	.0768	.315
	(-2.45)	(30.11)	(0.09)	(0.75)
V	842	661	496	823
Pseudo R^2	0.590	0.645	0.511	0.733

[a] An "*" denotes statistical significance at the 10% level, "**" denotes statistical significance at the 5% level, and "***" denotes statistical significance at the 1% level. The t statistics are in parentheses. Coefficient names represent elements of the β vector in equation (2.6). Names separated by ","denote cross product terms. Parameters are defined as follows: Z represents fixed vessels characteristics, *q* represents the annual total allowable catch, *p* represents output prices, *w* represents the daily crew services wage, and *h* represents harvest, where *arth* represents arrowtooth flounder, *cod* represents Pacific cod, *plck* represents walleye pollock, *grt* represents gross tonnage, *lgth* represents length, *hp* represents horsepower, *lgl* represents longline gear, *npt* represents non-pelagic trawl gear, *pot* represents pot gear, *ptr* represents pelagic trawl gear, and *V* is the number of observations used to estimate each equation.

Table 7

Inverse Demand Model Maximum Likelihood Estimates[a]

Coefficient	Arrowtooth Flounder	Cod	Pollock
p_{arth}	0.7024***	0.3357	0.0908
	(.13)	(.228)	(.067)
p_{cod}	-0.0744	0.3488	0.1048
	(.147)	(.274)	(.079)
p_{plck}	-0.3533	0.5015	0.3772*
	(.388)	(.703)	(.208)
h_{arth}	-0.0192***		
	(.007)		
h_{cod}		-0.0020	
		(.002)	
h_{plck}			-0.00002
			(.0001)
constant	426.27***	600.59**	97.3175
	(97.279)	(295.123)	(85.15)
N	24		
Log Likelihood	-443.21		

[a] An "*" denotes statistical significance at the 10% level, "**" denotes statistical significance at the 5% level, and "***" denotes statistical significance at the 1% level. Standard errors are in parentheses. Parameters are defined as follows: *p* represents output prices and *h* represents harvest, where *arth* represents arrowtooth flounder, *cod* represents Pacific cod, *plck* represents walleye pollock, and N is the number of observations used to estimate the system of equations.

Table 8

Comparison of the multispecies and single species models

Model Outcome	Multispecies Model	Single Species Model
Median arrowtooth stock	893,573	1,410,421
Median cod stock	812,172	1,128,886
Median pollock stock	3,342,853	6,003,977
Median arrowtooth harvest	23,162	263
Median cod harvest	168,780	137,717
Median pollock harvest	1,014,909	1,278,845
Steady State arrowtooth stock	5,464	1,605,987
Steady State cod stock	2,146,524	1,148,500
Steady State pollock stock	9,182,786	5,396,862
Steady State arrowtooth harvest	195	0
Steady State cod harvest	411,691	137,717
Steady State pollock harvest	3,402,099	1,766,370
Median Cost savings from cost complementarities[a]	$345,167,972	$135,657,175
Median Net Present Value	$20,709,805,578	$15,130,291,490

[a] Anti-complementarities are positive

Table 9

Comparison of the base multispecies model, constant arrowtooth harvest rate model, and arrowtooth subsidy model

Model Outcome	Multispecies Model	Constant harvest rate on Arrowtooth	Subsidy on Arrowtooth
Median arrowtooth stock	893,573	1,081,263	1,125,174
Median cod stock	812,172	126,826	506,646
Median pollock stock	3,342,853	3,356,398	4,432,864
Median arrowtooth harvest	23,162	15,000	24,672
Median cod harvest	168,780	56,490	95,987
Median pollock harvest	1,014,909	969,216	1,347,446
Steady State arrowtooth stock	5,464	891,565	11,319
Steady State cod stock	2,146,524	112,235	2,196,158
Steady State pollock stock	9,182,786	3,622,073	6,298,071
Steady State arrowtooth harvest	195	12,468	738
Steady State cod harvest	411,691	44,833	523,727
Steady State pollock harvest	3,402,099	1,901,260	3,747,942
Median Cost savings from cost complementarities[a]	$345,167,972	$75,968,781	$841,196,874
Median total subsidy on arrowtooth			$34,821,608
Median arrowtooth subsidy in $/lb			$0.113
Median Net Present Value	$20,709,805,578	$8,477,792,854	$20,983,364,133

[a] Anti-complementarities are positive

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