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# Spatial and Strategic Aspects of Fisheries Bycatch

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# Spatial and Strategic Aspects of Fisheries Bycatch

## ABSTRACT

Much of the existing scientific and policy literature on fisheries bycatch has focused on the technological aspects of bycatch control. The result for fisheries management has been a rash of command and control regulation centered around gear restrictions and spatial and temporal limits on fishing effort. By contrast, there has been precious little consideration of the role of incentives in fostering or hindering bycatch avoidance and even less thought to the incentive structures found in many real-world fisheries.

This thesis addresses this gap by developing analytical and empirical models for a particular case study with features that are analogous to many other fisheries: the flatfish fisheries of the Eastern Bering Sea. These fisheries are managed under a system of multiple common pool quotas on bycatch and target species which are enforced by quota-triggered closures. We develop a game theoretic model to explain how this system fosters suboptimal bycatch avoidance behavior on the part of fishermen due to their inability to fully capture the benefits of bycatch avoidance. As entry increases, fishermen face escalating discard costs, greatly shortened seasons and a rapid degeneration of rents relative to the optimal solution. We derive the bycatch penalty that aligns private incentives with the rent-maximizing solution and find, surprisingly, that this penalty must *increase* with improvements in the bycatch efficiency of the harvesting technology.

To empirically consider the degree of bycatch avoidance in the fishery we develop a discrete choice model of fishing location choice at a fine level of spatial and temporal resolution. By integrating this model with sophisticated predictions of revenue and bycatch expectations we are unable to uncover the implicit cost of bycatch to fishermen as demonstrated in their avoidance of bycatch over space and time. We find evidence of substantial avoidance in the last few weeks of the season but very little otherwise. This avoidance is dynamic and closely tied to factors such as the scarcity of bycatch quota, anticipated intensity of competition for bycatch and a vessel's horizon of participation. Even at its greatest, the implicit cost accorded to bycatch is well below its value as an unavoidable complement of fishing to the entire fleet. We also find substantial evidence that the common property quota system fosters excessive inertia in the movements of vessels over the fishing grounds.

Finally, we utilize a variety of structural and reduced form modeling approaches to weigh the success of a voluntary program of information sharing and halibut bycatch avoidance. The presence of data both before and after the program's inception and the initial nonparticipation of one cohort of vessels make our problem amenable to a number of variants of the difference-in-differences approach for uncovering the "treatment effect" of the program. Ultimately we find no basis for a positive impact of the voluntary program upon either halibut bycatch outcomes or upon the implicit costs of bycatch to participating fishermen. We confront a number of hypotheses on why cooperation apparently failed and ultimately conclude that poor overarching incentives from the common property quota system exacerbated by the biophysical traits of the bycatch species are likely to blame. This finding highlights the importance of both incentives and biophysical/technological factors in developing effective policies for bycatch reduction.

# Acknowledgements

This dissertation has, in so many ways, been the joint product of the positive contributions of numerous colleagues, dear friends and family. Thanking you sufficiently is a formidable task but here it goes. . .

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The other members of my committee are also deserving of a great deal of thanks. Aaron Smith was always a willing sounding board for my econometric queries, and I really grew to appreciate his learned yet pragmatic approach to empirical research. He also has the considerable distinction of teaching the best class I've had the privilege of taking while at UC Davis. David Layton provided invaluable advice on the discrete choice modeling within this thesis and also brought me confidence at a time when I really needed it. Doug Larson consistently asked the deepest (and most challenging) questions; hopefully I've managed to answer at least a few of them!

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completion of this thesis. Thanks for spurring me onward to its completion! Watching you grow and develop has been the greatest joy of my life over the last few months. I look forward to a lifetime of memories together.

# Table of Contents

# List of Figures

# List of Tables

# Chapter 1

# Introduction and Outline of Research

> *"Bycatch and waste are currently the greatest threats to the commercial fishing industry...A fish that is caught and thrown back dead does not add anything to the economy. It does not put food on the table."* -Rep. Wayne T. Gilchrest (R-MD)[1]

Bycatch, the incidental catch (and frequent discard) of marine species beyond those targeted in commercial fisheries, constitutes one of the most pressing issues in global fisheries management today. A recent FAO report estimates that approximately 7.3 million metric tons of discards – some eight percent of global landings – were generated on an annual basis between 1992 and 2001 (2005).[2] A similar analysis conducted for fisheries within United States territorial waters estimates that over a ton of discards are generated, on an average basis, for every four tons of landings (Harrington, et al., 2005). This ratio is highly variable across regions, gear types and targeted species with a few fisheries, such as the much-maligned Gulf of Mexico shrimp fishery, exhibiting ratios of over four to one. Although there are few reliable estimates of mortality associated with discards the consensus seems to be that it is substantial – particularly for many commercial fisheries in developed nations where relatively non-selective high-volume gear employed by powerful vessels often create conditions that are not conducive to survival after catch (Davis, 2002).

Bycatch is associated with a number of political, economic and management problems. From an economic perspective bycatch often involves the mortality of a commercially valued species. In many cases the bycatch is harvested at a size or handled in a manner that precludes it from achieving its most valued use so that a loss of economic welfare occurs. These economic

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[1] Quoted in the Congressional Record v.141, H10238, 10/18/95.

[2] This estimate may be conservative in that it fails to account for non-fish (e.g. marine mammal, seabird) bycatch and also omits the landing of bycatch for low-valued uses such as fish meal where a more valuable alternative market exists.

losses may fuel contentious political wrangling between competing user groups and fisheries managers as each side attempts to maximize its slice of the allocation "pie". For instance, considerable resentment has arisen between Gulf of Mexico shrimp fishermen and those targeting red snapper as high bycatch removals of snapper by shrimp fishermen have dramatically curtailed the snapper fishery at a time when low population levels have already dramatically reduced the economic viability of the fishery.

Discards also pose significant challenges to fisheries managers. Foremost among these is the simple fact that discards are often surpassingly difficult to quantify and yet doing so is often essential to the assessment of fish stocks and the subsequent determination of total allowable catch (TAC) allocations. In the absence of costly onboard observers, managers must rely on self-reported data from fishermen or the use of flawed statistical methods on landings data to fill this informational void. Bycatch may also exert significant but difficult-to-quantify effects on the marine ecosystem itself by the possible removal of threatened or endangered species, modification of habitat characteristics and trophic patterns due to the volume of dead or distressed bycatch that is dumped overboard (Dayton, et al., 2002) and potential long-term genetic effects due to skewed selectivity of harvest toward certain characteristics (Saillant, et al., 2006).

In addition to the strong economic and ecological rationale for reducing bycatch there is now considerable public pressure on policymakers. The image of millions of tons of marine species being returned dead to the sea at a time when highly publicized studies have advanced the popular perception that the majority of the world's fisheries are in danger of collapse elicits a powerful response from many, and NGOs such Greenpeace, the Ocean Conservancy and Oceana have been quick to exploit this imagery in their lobbying and public relations efforts.[3] This is especially true of the bycatch of charismatic or endangered species. The outcry over dolphin bycatch in the tuna seine fisheries in the late 1970s and 1980s and the subsequent passing of the

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[3] The study of the declines in abundance of large marine predators (e.g. tuna) by Myers and Worm (2003) is a good example. The authors contend that fishing caused a 90% decline in the abundance of these species. However, see the critiques of Polacheck (2006) and Walters (2003).

Marine Mammal Protection Act in the U.S. and the marketing of "dolphin safe" tuna show the power of environmental grassroots organizations, and these groups now employ similar tactics in campaigns against the bycatch of sea turtles in tuna and swordfish longline fisheries and the take of dolphins and small cetaceans in European trawl fisheries.

In response to the increased prominence of bycatch as a serious marine policy issue, the United States Congress passed the Sustainable Fisheries Act Amendments to the Magnuson-Stevens Fishery Conservation and Management Act (MSA) in 1996 to provide a definition of "bycatch" and to require that it be minimized to the extent deemed practicable.[4] Specifically, bycatch was defined as "fish which are harvested in a fishery, but which are not sold or kept for personal use, and includes economic discards and regulatory discards" (16 U.S.C. § 1802(2)).[5] Economic discards are defined as "fish which are the target of a fishery, but which are not retained because of an undesirable size, sex, or quality, or other economic reason" while regulatory discards are "fish harvested in a fishery which fishermen are required by regulation to discard whenever caught, or are required by regulation to retain but not sell". Having defined bycatch, the MSA goes on to declare that fishery management plans "establish a standardized reporting methodology to assess the amount and type of bycatch occurring in the fishery, and include conservation and management measures that, to the extent practicable and in the following priority (A) minimize bycatch; and (B) minimize the mortality of bycatch that cannot be avoided" (16 U.S.C. § 1853(11)). These legal obligations were made all the more binding in 2002 when an environmental NGO demanded that the National Marine Fisheries Service (NMFS) initiate rulemaking to establish a program to "count, cap, and control bycatch in the nation's fisheries" (Oceana, 2002).

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[4] Due to the focus of this research and the need for expositional brevity, much of the policy discussion in this section is framed for United States fisheries, although much of the discussion remains applicable to EEZ fisheries of other nations and (to a lesser extent) the fisheries of the high seas.

[5] Notice that this definition does not account for the bycatch of marine mammals or birds. These are regulated under the authority of the Endangered Species Act, Marine Mammal Protection Act and the Migratory Bird Treaty Act.

Given the mounting pressure to report tangible progress toward their regulatory mandate, NMFS and the Fishery Management Councils developed a National Bycatch Strategy, described extensively by Benaka and Dobrzynski (2004), to guide the agency in obtaining better information on the quantities of discards in the nation's fisheries and controlling their quantity. The quest for a quantification of bycatch has spawned a range of research on the reliability of bycatch estimates from extant data sources while also expanding the quantity and quality of information by encouraging the increased deployment of at-sea observers, the improvement of statistical design in observer deployment and sampling procedures and the slow but growing usage of electronic techniques such as vessel monitoring systems (VMS), digital video cameras and digital observers (National Marine Fisheries Service, 2004). This increase in information paired with a general trend in fisheries management away from the conventional single species framework toward one more embracing of multispecies and ecosystem concepts has also led to the increased consideration of bycatch in stock assessments and quota-setting for many fisheries.

The measures used to control bycatch and discards are varied, frequently predate the 1996 MSA amendments and are typically reflective of the idiosyncratic management philosophies and data limitations of the regional councils. In Alaska, where the pervasive deployment of at-sea observers has enabled the in-season tracking of catch and discards at a relatively accurate level, managers have utilized a complex system of catch quotas on both target and bycatch species to manage the groundfish fisheries. These quotas (with the exceptions of IFQ halibut and sablefish fisheries and the American Fisheries Act cooperatives for pollock and cod) are held in common across particular target species and gear sectors and are enforced by retention restrictions and prohibitions and time and area closures. Certain areas are also closed to fishing regardless of quota status and are frequently devised either to protect vulnerable aggregations of bycatch species (particularly when spawning) or to shelter key areas of habitat. Many fisheries off the coast of Washington and Oregon and those in the Northeast are regulated by trip *landings* limits. This method of management may be motivated by the high costs of accurately observing bycatch or by resistance from the fishing industry itself – landing tickets and other forms of self-reported information are frequently all managers in these regions have to work with. Shrimp fisheries throughout the United States as well as the Hawaii- based longline fisheries have primarily reduced their bycatch through the mandated implementation of gear alterations (e.g. turtle and finfish excluder devices in the Atlantic and Gulf shrimp fisheries (Harrington and Vendetti, 1995) or hook design specifications for the Hawaii swordfish fishery (Gilman, et al., 2006)) or restrictions on the manner in which the gear can be utilized (e.g. bait restrictions and night set requirements for the Hawaiian longline fishery).

Despite this variety of approaches, there is a remarkable paucity of attention paid to the incentive effects of these regulations or to the relative costs and benefits of their implementation to fishermen or the broader public. Common property allocations of bycatch quota, as in the Alaskan groundfish fisheries, may produce a downward-spiraling "race for bycatch"; trip landing quotas combined with penalties or prohibitions on sale frequently encourage regulatory discards (this despite a regulatory mandate to minimize such discards); and zero retention requirements, as specified for halibut bycatch in Alaskan groundfish fisheries, frequently force fishermen to make wasteful choices that they would often forgo in the absence of such regulations. These shortsighted policies bear a striking resemblance to the counterproductive strictures on effort employed to curtail the symptoms of open access in single species fisheries (see Homans and Wilen (1997) and Stollery (1986) for criticisms of these methods). Indeed, much of the discourse in the policy sphere characterizes bycatch as either a technological problem in need of an imposed solution – hence the focus on engineering improvements in fishing gear or seasonal and spatial closures – or as the result of unmitigated greed on the part of fishermen. This latter view is exemplified by the adoption of loaded phrases such as "dirty fisherman" by certain advocacy groups.

Since bycatch lies at the interstices of biological, technological and economic factors it is likely that aspects of all approaches are needed to help ameliorate the problem. However, taking a purely techno-biological approach to the issue may result in "solutions" that are not only dubious from a social welfare standpoint but often generate unintended behavioral consequences that may actually undermine the original policy objectives. Conversely, if regulators first concern themselves with building institutions that "get the incentives right", then the solutions may be closer at hand than ever imagined.

## 1.1 Bycatch and Discards in the Economic Literature

Faced with the prominence of the bycatch issue and the apparent need for economic analysis on the subject, one might be led to believe that there is a longstanding and rich literature on the topic. Such is not the case, however. Aside from a small number of papers, the literature is scarcely over a decade old, and despite a number of worthy contributions created over just a few years, there remains considerable room for work in this area.[6]

Before embarking on a concise summary of the literature, a word on nomenclature is necessary. The literature is roughly bifurcated in the sense that some papers are devoted to the analysis of "bycatch" while others focus more specifically on the topic of "discards". There appears to be some confusion in the literature on exactly what is meant by these labels, so we define them here for the sake of consistency. "Bycatch" is the take of any species or grade of fish or other aquatic organism other than that intended for harvest by the fisherman. It can be imagined as the marginal catch that results from a fisherman's inability to costlessly devise and adopt a perfectly selective harvesting technology. "Discards" are any species that are not landed for sale by the vessel, whether for economic reasons (a practice known as "high-grading") or due to regulatory requirements. These definitions are quite similar to those frequently used in the economic and policy literature, although the implicit expansion of the definition of bycatch to include the incidental catch of inferior grades of a targeted species is not shared by all. Plainly,

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[6] A possible explanation for this slow start may have to do with the gradually diminishing aversion on the part of economists to sacrifice analytical tractability in order to capture the multidimensional aspects of real-world resource management issues (Brown, 2000, Wilen, 2000).

the two concepts are interrelated, but we will typically employ the more inclusive term "bycatch" unless the context is the disposition of the catch with respect to landings.

Given the rapid development of the bycatch literature in economics journals over the last decade, it should come as no surprise that the progression of ideas has followed anything but a linear pattern. For this reason, we deviate from a chronological presentation, instead choosing to group papers by their applied focus or shared methodological approach.

Much of the basic economic thinking concerning bycatch is expressed within Boyce (1996). In this paper the author employs a simple but flexible single-season model with two fish populations (the bycatch and target species) and homogeneous fishermen to elucidate a variety of useful scenarios. The model encompasses both the case in which the bycatch species in one fishery has commercial value and is the source of a directed fishery of its own and that in which there is no commercial fishery for the bycatch but it nevertheless retains a positive non-use value. Fishermen for the non-bycatch species maximize their profits by choosing their rate of harvest for the season where the costs of separating, counting and processing bycatch are included in their payoffs. The rate of harvest is linked technologically to bycatch via a function that implies that fishermen can only lower their ratio of bycatch to target catch by slowing the rate of harvest of the target. This simple characterization is meant to express the tradeoff that is typically present when target and bycatch species exhibit positive spatial correlation due to shared habitat preferences or trophic interconnections.

Having developed the model, the author ventures to answer three questions: 1) How should bycatch be divided between competing interests?, 2) How does open access affect bycatch rates?, and 3) Can policy instruments such as individual transferable quotas (ITQs) or landings taxes achieve the first-best levels of bycatch and effort? With regard to the first question, Boyce determines that the bycatch quota should be allocated across groups so that its marginal value as bycatch or target catch is equalized. Furthermore, fishermen for the target species should set their rate of harvest so that the marginal profitability of a unit of harvest is equalized with the sum of the scarcity rents for both species which typically involves a slower rate of harvest than would be optimal for a single species fishery. Finally, each fishery should remain in operation for as long as possible, as this allows the fishermen to spread their quota across the entire season, thus avoiding the increasing marginal costs associated with faster rates of harvest.

An assessment of the open access conditions is marred by apparent mathematical errors which are propagated throughout the analysis.[7] One predictable result seems sure, however; open access leads to excessive entry and a larger amount of bycatch (although not necessarily a higher bycatch rate) than is optimal.

Fortunately, the errors in the analysis of open access do not affect the conclusions concerning the rationalization of bycatch with ITQs. Boyce demonstrates that a competitive quota market can maximize social welfare but only if there are competitive markets for the quota of both species. Specifically, the bycatch quota must be tradable between the two fisheries to ensure this result. Also, ITQs cannot achieve the social optimum if there are external benefits from preserving the bycatch stock (as in the case of bycatch of sea lions or dolphins which have little commercial value but ostensibly high existence values). In this context, an additional Pigouvian tax must be levied to ensure efficiency. Finally, and somewhat provocatively, Boyce demonstrates that the rationalization of an open access fishery by ITQs, while guaranteed to lower aggregate bycatch through the removal of excess capacity, may or may not result in lower bycatch *rates* among the remaining participants. "Fewer fishermen, behaving badly" is a possible outcome of rationalization under Boyce's model.

Hoagland and Jin (1997) differs from the static, single-season model of Boyce by providing a characterization of the optimal multispecies fishery that is fully dynamic and considers trophic interactions between the two species. This is a valuable contribution in that 1)

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[7] Equations 27 and 29, the equations describing the individual profit maximizing choices of harvest level, are the primary sources of the errors. The derivations are not included but seem to confound the fleet-wide profit maximization problem with that of individual vessels (although errors remain even under this interpretation). A conversation with the author confirmed the validity of our suspicions.

even in the absence of harvest quotas or intra-seasonal stock effects, the bycatch of a species may impose a dynamic stock externality on another stakeholder group and 2) biological interactions between species may have a significant impact on the evolution and magnitude of this externality. They characterize the optimal harvest program for a special case where the bycatch species has no commercial market but is valued by a group that engages in its passive use. They further simplify the solution by positing a fixed-proportions Schaefer harvest technology – assuming away any possibility of bycatch avoidance given a particular mix of target and bycatch stocks. They are then able to derive the Pontryagin maximum conditions for effort (and thus harvest and bycatch) and show that the optimum time path and steady-state levels of fishing effort are highly dependent on the nature of the interactions between the two species. What is missing from their discussion, however, is any assessment of how this optimal outcome can be enforced via economic or regulatory instruments.

Whereas both Boyce and Hoagland and Jin are concerned with the optimal management of bycatch under conditions of certainty, Androkovich and Stollery (1994) focus on dynamic management under conditions of regulatory ignorance. Specifically they utilize a discrete-time two species model where fishermen pursuing either species are unable to avoid the bycatch of the other, thus creating a bilateral externality across fisheries. Like Hoagland and Jin, they assume fixed proportions (Schaefer) harvest functions but allow the catchability parameters to act as random variables from the viewpoint of the regulators – but not from the point of fishermen to whom they are known beforehand. Biomass evolves in a deterministic fashion; however, the fact that catch-per-unit-effort (CPUE) is a random variable to the regulator leads to an evolution of the stock variables that is stochastic.

By introducing specific simple functional forms for the benefit functions, operating costs and biomass equations for each fishery and by calibrating their model to 1969 data for the Nova Scotian cod and haddock fishery, the authors are able to solve their stochastic dynamic programming model using approximate numerical methods. They then consider the relative merits of three policy prescriptions: 1) a uniform tax for each species that is applied without respect to the target fishery, 2) a dual tax where each tax is levied only on fishermen targeting a particular species, and 3) a catch quota on the target catch of each species. The objective in all cases is to maximize the net present value of total net benefits from both fisheries. For their particular specification they find that either tax prescription easily dominates the quota instrument. Interestingly, they also find that the decoupled tax (option 2) performs only slightly worse on an average basis than the coupled tax. Also, the quota system is found to perform *worse* than the unregulated (open access) scenario under high levels of stochasticity (although this relationship no longer holds when the variability is reduced). This poor performance is plausible on the basis that quotas, unlike taxes, intrude upon the adjustment of effort to realizations in the stochastic variables in the CPUE relationship when the stochastic variables are known beforehand by fishermen in each period. The conclusion seems to lend overwhelming support for the use of landing fees under conditions of regulatory uncertainty.[8]

The preceding papers have largely focused on the properties of the optimal management of bycatch in comparison to polar property rights scenarios (i.e. open access vs. ITQs or optimal taxation). While useful, this research says little about the economic merits of much *actual* bycatch regulation. To fill this vacuum, Ward (1994) and Pascoe and Revill (2004) examine the implementation of bycatch reduction devices, Bisack and Sutinen (2006) compare the merits of ITQs and time/area closures and Larson et al. (1996) examine the optimal allocation of common property catch quotas to bycatch and target species across competing user groups.

Ward (1994) was motivated by a proposal of a mandated gear modification in the Gulf of Mexico and Atlantic shrimp fisheries to exclude finfish from shrimp trawls. In this paper he

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[8] This result anticipates a debate over "prices vs. quantities" under various forms of uncertainty in the fisheries management literature that began with Weitzman (2002) and then continued with Jensen and Vestergaard (2003) and Hannesson and Kennedy (2005). Caution should be exercised, however, in applying Androkovich and Stollery's results as the numerical approximation techniques used to solve the problem, while standard for the time, may be too crude to provide reliable rankings of the policy alternatives.

develops a bioeconomic model to look at the long run effects of such restrictions. The model is similar to that employed by Hoagland and Jin but the bycatch and target stocks are constrained to be independent in their dynamics. Also, Ward allows the second (bycatch) species to be the target of a directed fishery of its own, but the gear in this fishery is perfectly selective with respect to the first species so that fishermen targeting this species impose a unilateral stock externality on those pursuing the bycatch species. The author also assumes perfect price elasticity of demand for both fisheries (thus implying the existence of close substitutes or that the fisheries are a small part of a global market), that the bycatch species has no value to fishermen targeting the first species, and, finally, that long-run entry drives rents to zero. With these assumptions in place, Ward examines the implications of a very optimistic technology – one that reduces bycatch by sixty percent with no attendant decline in target catch. The bycatch device has no long run effect on the equilibrium of the fishery for species 1; nevertheless, the reduction in bycatch mortality leads to increased recruitment in the targeted bycatch fishery, thus driving up rents and leading to increased entry. The high elasticity of demand for the bycatch species prevents prices from falling and acting as a brake on entry; the end result is complete rent dissipation with higher levels of effort and harvest than before the gear change but no increase in the biomass of the bycatch species. The cautionary message for regulators is that technological solutions to the bycatch problem, when applied in disregard of open access incentives, may have the unintended consequences of merely increasing capacity in the fishery for the bycatch species without effecting any substantial progress towards conservation goals.[9]

Whereas Ward's analysis is primarily based on analytical features of a bioeconomic model under admittedly ad hoc assumptions, Pascoe and Revill (2004) carefully calibrate a bioeconomic model of North Sea brown shrimp trawl fisheries to examine the impacts of EU mandated modifications to shrimp trawls for the avoidance of whitefish bycatch. Unlike Ward,

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[9] If bycatch species demand is less elastic than Ward assumes, then some increase in bycatch biomass may occur in the long run; however, no additional rents will be generated in the process.

they estimate the long run elasticity of demand and find it to be approximately unitary. They also allow for diminishing returns to fishing effort in their specification. Finally, they modify the objective function of their nonlinear programming problem to reflect the limited access characteristics of the participating country's management regimes. They then examine a range of potential catchability losses for the target species (shrimp) from the use of the whitefish-avoidance gear and find that total gross margins for the shrimp fisheries would show a small *increase* from the use of the technology – although the benefits and costs are not evenly distributed with some nations coming out as clear winners and losers. This happens despite the reductions in CPUE caused by the new gear.[10] Given that the technologies would generate upwards of €6,685 m of revenues to whitefish fishermen, the policy seems to easily pass a cost-benefit test.[11]

Bisack and Sutinen (2006) consider the imposition of another common command-and-control method of bycatch control – time/area closures – with an alternative policy of an ITQ market for the bycatch species. Their particular case study is the bycatch of harbor porpoise in the New England gillnet fishery. To compare these policies, they utilize data on individual fishing trips, stock abundance and vessel costs to develop and calibrate a model in which fishermen choose their effort allocation by season and port so as to maximize their variable rents. They then used this model to compare the rents arising under closures of fishing grounds adjacent to particular ports with the rents from an ITQ system with an equivalent allocation of bycatch quota. They find that ITQs are 2%-15% more profitable than closures depending upon the particular scenario considered. This occurs despite lower landings of commercial species under

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[10] These results are complex and are driven by a number of factors in the model such as country-specific limitations on effort, prices that are responsive to total landings, diminishing returns to effort and the fact that some nations already had substantial adoption rates of the technology before it was mandated.

[11] The analysis is marred by the fact that the entry, price and cost effects which are so carefully derived for the shrimp fishery are not calculated in the case of the whitefish fishery. Also, the loss (gain) of consumer surplus due to higher (lower) equilibrium shrimp (whitefish) prices is not included in the analysis. Finally, simply generating a positive net benefit does not necessarily justify the gear restriction, particularly in the face of potentially welfare-dominating policy options.

the ITQ system, reflecting a reallocation of quota and effort to more profitable season/port combinations. Not unexpectedly, industry profits decrease under either instrument as the degree of protection for harbor porpoise increases, but the distribution of damages across ports and seasons is markedly more homogeneous under ITQs than with spatial closures – possibly increasing the appeal of ITQs to fishing communities. Finally, the authors note that ITQs are well designed to precisely manage the quantity of bycatch, whereas time/area closures may generate unexpected outcomes depending upon the ability of affected fishermen to mitigate their losses by diverting effort to neighboring grounds.

Larson et al. (1996) utilize weekly data from the Bering Sea/Aleutian Islands (BSAI) catcher-processor fleet to shed light on an important and contentious policy issue: how should the allowable catch for a species be allocated across competing use groups to maximize social welfare?[12] Target and bycatch quotas in the BSAI are allocated to several different fleets harvesting a variety of species with a range of gears. In this system the catch or bycatch of a species by one group can impose significant costs on another as the total quota is largely predetermined before the allocation process begins and so one group's loss is another's gain. The authors calibrate a fairly sophisticated "nonparametric" linear programming model to allocate effort across competing fisheries and then utilize this solution in a second step in which the regulator allocates the quota to maximize short run rents over all fisheries subject to the constraints embodied by the TACs for each species. Finally, they allow the most efficient operations represented in the data to be replicated at will (i.e. inefficient operations are free to emulate their more efficient peers) in order to produce a "long run" model of the fishery as well. By comparing the marginal quota valuations from these two models, they obtain a probable envelope for the true values. By holding all quotas in the fishery at their 1992 levels while varying the bycatch quota for halibut they obtain short and long-run demand curves. By

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[12] The definition of optimal employed here is similar to that employed by Boyce in that stock effects are not considered and the goals underlying the TAC for each species are taken as given.

comparing the marginal quota valuations from these curves against an estimate of the marginal opportunity cost of halibut quota in the targeted halibut longline fishery (developed by Marasco and Terry (1982)) they are able to draw some interesting conclusions.

First, the marginal value of halibut quota in the groundfish trawl fishery appears high relative to its opportunity cost – at least in the short and intermediate term – suggesting that more halibut quota should be taken from the longline fishery and allocated to the groundfish fleet. However, if fishing technology were aligned along more efficient lines (both in terms of the choice of targeted species and the efficiency with which it is fished) then the groundfish fisheries could operate with a considerably lower quota. In addition, the authors find that the allocation of halibut bycatch to user groups within the groundfish fleet, if accomplished efficiently, would change dramatically from that actually observed in 1992.[13] They conclude that given the complexities of allocating quotas in an optimal fashion, particularly in the face of shifting effort across fisheries due to changing market and biological conditions, that a less information-intensive method of allocating TAC is needed (such as ITQs or some manner of bycatch fee).

In addition to the aforementioned papers which are overwhelmingly concerned with bycatch, there is also a parallel literature that places its primary emphasis on the fishermen's decision on whether to land some portion of his catch and how various regulatory strictures affect the incentive to discard catch. Much of this literature focuses on the informational deficit regulators are faced with when trying to assess total removals from an ecosystem when high monitoring costs, considerable natural stochasticity, binding hold constraints and regulatory strictures all conspire against them and then demonstrate how fishermen can be induced to land (or at least truthfully report) their bycatch in accordance with some economic or regulatory goal.

Arnason (1994) laid the groundwork of this literature by developing an elegant dynamic model over multiple "grades" of fish (this single species story can be easily extended to the case

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[13] For instance, gains in bycatch efficiency within the Pacific cod fleet would, in the long run, allow for a considerable expansion of the midwater pollock fishery which, although highly profitable, had higher-than-average halibut bycatch.

where the grades represent different species) where, subject to a chosen level of vessel effort and the aggregate biomass, fishermen are assumed to harvest the various grades according to a fixed-proportions technology and any discarded grades are assumed to die before contributing to future biomass.[14] The key result is intuitively straightforward. A grade of fish should be discarded when the marginal cost of landing the catch (including the costs of handling, processing and storage) exceeds the sum of the marginal opportunity costs of discarding (the unit price of the grade/species in question) and the marginal direct costs. Indeed, the optimal (fishery rent-maximizing) discard decision may be to discard a significant proportion of catch depending upon market prices and the nature of landing costs.[15] Furthermore, Arnason finds that the open access and optimal discard rules actually coincide – a result that is driven by the assumption that discards exhibit complete mortality and thus no stock externality ensues from the discard decision. (Fishermen would likely *under* discard relative to the optimum if some portion of discards survived.) Finally, the author extends his model to investigate the question of how the implementation of a single ITQ market on landings of the various grades of fish affects discards. The intuitive finding is that ITQs generate an excessive incentive for discarding catch due to the fact that a positive quota price on landings raises the marginal cost of landing any particular grade. This shortcoming of ITQ management could theoretically be overcome by introducing separate markets for each grade/species, but this may be problematic in some cases due to the inherent vagueness and potential temporal variability of the definition of a "grade" and the potential for thin markets.

Anderson (1994), much like the contemporaneous paper by Arnason, analyzes the incentives to highgrade in ITQ fisheries. However, unlike Arnason's multi-grade dynamic model

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[14] This is likely a reasonable assumption for many deepwater fisheries where rapid pressure changes, extensive gear contact, sudden changes in temperature and light conditions and anoxia due to crowding of caught fish all increase the odds of mortality (Davis, 2002).

[15] This seems to condemn, at least on efficiency grounds, the "no-discard" and "full retention" policies embraced, with a range of caveats and qualifications, by a number of countries (Kelleher, 2005). Norway, in particular, has placed a rather hard ban on discards within its waters.

with no (explicit) technological constraints, the author employs a trip-level static model with two grades of fish (high and low value) and an explicit hold constraint. The first order conditions in the unregulated fishery case uncover the rule that governs discards. A fishermen will find it optimal to discard a unit of the lower grade of fish when the price differential between the two grades exceeds the sum of the costs of the extra effort needed to replace the discard with the higher grade and the extra costs of discards – not simply when there is a wedge between the landings prices of grades of fish as had been assumed previously. He also finds that discarding will be privately optimal for a range of hold sizes with complete highgrading occurring for relatively small holds and partial highgrading occurring for a range of holds of intermediate capacity.[16]

The author then goes on to argue that the demand curve for hold capacity that arises from the individual fishermen's optimization problem has a parallel interpretation as a demand curve for ITQs in a problem where there is no hold constraint. The result, which is essentially identical to that of Arnason when there are no additional costs to landing beyond the cost of quota, is that highgrading will take place whenever the price of a unit of ITQ is greater than the opportunity cost of discard. Any additional impetus to highgrade that is provided by the ITQ system is suboptimal from the viewpoint of social welfare. He then goes on to discuss how a combination of taxes and subsidies on landings of high and low grades could be used under ITQs to induce a zero highgrading outcome while maintaining a balanced budget. A similar outcome may also be possible by imposing landing restrictions such that fishermen are charged for their catch of the low valued grade even if they do not choose to land it. The first-best theoretical properties of such instruments are shown to erode somewhat when the regulator is charged with controlling a fleet with heterogeneous costs and catch proportions, but these measures may nevertheless have some utility in facilitating a desirable second-best outcome.

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[16] Although Anderson makes the link between hold capacity and the optimality of discards explicit, the same result can be intuited from Arnason (1994) if one allows the cost of landing to be a decreasing function of hold capacity.

Both Arnason and Anderson make considerable simplifying assumptions in their analysis. Arnason ignores the nature of fishing as a discrete number of trips and thus neglects the effects of hold constraints on discards whereas Anderson limits his analysis to a two species system, ignores the choice of the number of trips, assumes zero landing costs and ultimately disregards hold constraints when looking at the effects of ITQs. Vestergaard (1996) addresses these shortcomings with a static model in which fishermen choose the number and length of trips in a season as well as the discards of each of $J$ species. The harvest technology remains of the fixed proportions variety and fishermen face hold constraints for each trip as well as positive landing costs for each species.

The expression for the optimal discard rule is, as expected, more complex than in the preceding literature. Specifically, discarding of grade $j$ is optimal if the ensuing marginal benefits of another day's fishing are greater than the marginal costs, including the cost of discard of the day's catch of $j$ plus average daily trip profits for the season, which constitute the opportunity cost of another day at sea due to the limited duration of the season.[17] This rule differs from that of Anderson because the objective is to maximize *seasonal* profits as opposed to *trip* profits. As a result, trips are predicted to last longer in Anderson's model – and thus typically generate more discards – than predicted here.

The author goes on to predict the effects of key model parameters on the incentive to discard and concludes that an increase in the steam time between trips will increase the tendency to discard due to the resulting decrease in average trip profits. Similar effects are noted for increases in trip fixed costs. Furthermore, he finds that the incentives to discard a particular species or grade are driven more by its own price than that of the other grades.

Vestergaard then turns to a comparison of the discard effects of three different regulatory systems: total allowable catch, individual non-transferable quotas (INTQs) and ITQs. He finds that TAC management should have no immediate impact on discard behavior (although entry

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[17] All of these quantities are of course evaluated at zero discards and the optimal trip length.

may lead to lower CPUE in the long run and thus reduced incentives to discard). The analysis of INTQs is made difficult by the complex interplay between the choice of trip length and discards, but the author finds that binding individual quotas can induce discards even when the hold constraint is not binding and that INTQs increase the incentive to discard relative to the unregulated case, even if discarding was not profitable before regulation. Vestergaard finds that ITQs increase the incentive to discard relative to the TAC or no regulation case insofar as the price of quota is positive – a stronger result than obtained by either Anderson or Arnason who predict that increased discards will only occur if the quota price exceeds the opportunity cost of discards. However, relative to INTQs, tradable quotas decrease the incentive to discard. The discard implications of a change in management approach depend, predictably, upon the status quo.

Turner (1997) abstracts away from the realistic but confounding issues of hold capacity, costly discards and the choice of the number of trips and instead utilizes a simple graphical two species/grade model to focus attention on the issue of ITQ induced discards. However, by making these simplifications he is able to introduce a degree of realism into the characterization of the multispecies production technology that is been lacking elsewhere in the analytical literature. Specifically, he loosens the assumptions of a fixed proportions technology for a given level of fishing effort to allow fishermen to alter their production mix. This ability is constrained, however, by the imperfect selectivity of gear and the spatial coexistence of target and bycatch species. He then compares the discard implications of an aggregated ITQ system (a single quota on the combined catch of both grades), a disaggregated ITQ system and a value based quota system (in which fishermen trade rights to land a particular value of total catch). Utilizing simple arguments, Turner proves, with costless discarding, that the only way to avoid discards by profit maximizing fishermen under either aggregated or disaggregated ITQs is to set the TACs of the grades such that they occur at a technologically efficient point in production space. Finding such a point places a high informational burden upon the regulator, especially in environments with rapid technological progress or fluctuating fish stocks. On the other hand, a tradeable quota on the value of landings will (under the assumptions of a "regular production technology") induce a level of harvest such that neither species is ever discarded. This advantage is tempered somewhat by the fact that a value based quota system provides regulators considerably less control over removals in that both total and grade-specific harvest will vary with changes in market conditions. Nevertheless, the fact that the value quota closes the vexing gap between total removals and landings created by quantity regulations may more than compensate for this unfortunate feature.

The previous papers, while offering important insights, fail to address one of the major issues associated with discards – that of monitoring and compliance. In the absence of extensive, and often prohibitively costly, onboard monitoring of catch and a significant credible threat that illegal discarding will be caught and punished, technological, economic and regulatory forces will likely induce fishermen to understate their discards. Therefore, discards may be characterized as a moral hazard problem since the fishermen possess private information, their true catch and its composition, that is frequently unknown to the regulator. Jensen and Vestergaard (2002) and Herrera (2005) consider various aspects of this problem.

Jensen and Vestergaard consider a single species model where each fisherman receives an allocation of the TAC for the season but individual catches are unknown to the regulator due to the fact that landings are not tracked. There is therefore an incentive for fishermen to make "illegal landings" of their catch beyond the allotted quota.[18] To attempt to remedy this problem, the authors adapt a mechanism from the non-point pollution literature (Segerson, 1988) in which regulators are assumed to have a target end-of-season fish stock in mind and are able to measure this stock after the season has ended.[19] Fishermen are then levied a tax (or paid a subsidy) that is proportional to the gap between goal biomass and the level actually achieved. Fishermen are

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[18] Although not strictly concerned with discards, the model nevertheless applies in the case where individual vessel catch (as opposed to landings) is unobserved to regulators.

[19] In this sense, regulators do observe *ex post* the total catch for the season, although the distribution of that catch across fishermen is never revealed.

assumed to maximize their own portion of total resource rents (less the stock tax) subject to their beliefs about the total removals on the part of other fishermen and how those removals will impact the end-of-season stock level. By assuming the fishermen reach a Cournot-Nash equilibrium and then comparing the resulting first-order condition to that under the social optimum model, the optimal stock tax/subsidy can be determined. The authors then calibrate their model to a small Danish cod fishery and show that the taxes needed to ensure optimal landings on the part of fishermen were actually surprisingly small (less than 10% of the market price over the same period). This mechanism does possess considerable limitations, however. First, the use of taxes in fisheries has been extremely unpopular whenever it has been suggested. Nonetheless, the authors do note that the collected rents could be redistributed in an incentive compatible way back to fishermen. Secondly, the stock tax requires that regulators possess strong information on both biomass and fishing costs. Thirdly, the mechanism will only work if the number of fishermen is sufficiently small, and their own take of the stock sufficiently large, to cause fishermen to perceive that their individual harvest behavior significantly influences the end-of-year biomass. Nevertheless, the authors conclude that the stock tax has promise as a tool to eliminate moral hazard in illegal landings and discards for small fisheries with reliable stock assessment and minimal levels of natural variability as an alternative to more draconian command and control policies.

Herrera develops a model that is similar to that of Androkovich and Stollery in that he uses a dynamic two-species/two-fishery model with stochastic "shifters" on the catchability terms in the CPUE relationship.[20] Fishermen choose whether to participate in the fishery, their number of trips and their level of effort on each trip. Regulation occurs in three ways: 1) by a limit on the number of boats in each fishery, 2) by a constraint on the number of trips taken by all vessels in

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[20] There are some subtle simplifications, however. For instance, bycatch occurs in only one fishery. Also, stochasticity is only present in the catchability of the bycatch species. Incidental catch of the second species in the first fishery is allowed to be marketed but the market price they receive is lower than that received by those in the targeted fishery for species two. Finally, the stock dynamics follow logistic laws of motion as opposed to linear ones.

each fishery, and 3) by a constraint on the retention of the bycatch species.[21] Unlike Androkovich and Stollery, however, the author does not assume perfect oversight and so harvest may exceed landings.

With the model in place, the author considers four instruments for the regulation of bycatch: no constraint, a per-unit tax/subsidy on bycatch, a trip limit on retained bycatch and a value-based quota for all retained catch and bycatch. The analysis of the incentive effects of each of these instruments for the choice of the number of trips, the level of effort and the decision of how much of each species to discard is tedious and not recounted here. Ultimately, however, after numerical simulations of the four policy instruments based on reasonable parameter values, the author establishes the superiority of the bycatch tax (followed by the value quota) to trip limits. He also finds that the relative merit of the price-based (tax) approach grows with the degree of regulatory uncertainty concerning the CPUE for the bycatch species. This effect is due to the fact that exact knowledge of the harvest technology is not necessary to eliminate discarding using the price instrument while such knowledge is required with the quantity instrument.[22]

The previous studies, whether couched in abstract terms or calibrated to actual fisheries, have typically relied upon a particularly restrictive assumption on the technology of fishing – that targeted catch and bycatch are harvested in fixed proportions for a given level of variable input.[23] Such an assumption, while formally convenient, ignores substantial evidence that fishermen *are* able to alter their catch composition somewhat by their choice of fishing location, depth, time of fishing or other subtle aspects of their behavior. Fortunately, there is a well established literature

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[21] These methods of regulation are meant to reflect those in use in the northwest Atlantic.

[22] The paper is marred somewhat by the fact that there is no cost (either due to limited hold space or landing costs) to the fishermen from landing bycatch apart from the costs imposed by the regulations. As a result, full retention is consistently regarded as a desirable outcome despite the earlier literature which has repeatedly shown that such a goal may be welfare deficient.

[23] Boyce avoids this assumption by specifying an increasing relationship between target harvest and the rate of bycatch. Turner allows for substitution between bycatch and target species for a given value of variable input but makes no attempt to empirically implement his model.

in which economists have adopted empirical techniques from duality theory to multispecies fisheries that allow for a far more flexible and rich specification of fishing technology.[24]

Squires and Kirkley (1991) pioneered the application of these methods to multispecies fisheries by using trip level data from a Northern California trawl fishery with six different species groups. They consider the effects of introducing individual trip quotas for one of these species, sablefish. By estimating the input-compensated supply functions for each species group and then exploiting the duality between primal and dual constraints under conditions of certainty, they are able to consider the effects of trip quotas by looking at the signs and magnitudes of the estimated price elasticities of supply. The presence of an insignificant own-price elasticity for sablefish leads them to conclude that implementing trip quotas will fail to reduce the quantity of sablefish caught in the short run – rather, it will merely induce discards of excess catch. This effect remains even when effort is allowed to adjust in response to the implicit tariff on sablefish. The authors also discover substantial scope economies due to cost complementarities between sablefish and other species, indicating that the marginal costs of harvesting a given species decline as increasing amounts of sablefish are added to the mix. This echoes the conventional wisdom that it is cheaper to fish indiscriminately than to target a specific stock. In other words, the imposition of a binding sablefish catch quota would apparently increase the marginal cost of harvest for almost all other species.

Squires and Kirkley (1996) extend their earlier results by considering the introduction of ITQs in the same fishery. They again exploit the link between primal and dual constraints and horizontally sum the derived inverse trip quota demands over the trips in their sample to yield the "market" demands for quotas of each species. Solving these equations at given prices and effort levels yields market clearing prices in each of the permit markets. They use these estimated equations to test the impacts of separate ITQ markets for thornyheads and sablefish and found

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[24] We do not attempt to list every example from this literature here as they tend to utilize similar techniques and often arrive at comparable results.

that both markets generated positive rents when implemented individually. They then consider the case of a dual permit system, but here they run into the problem of regulatory inconsistency. Consistency requires that the quota allocation be along the industry production possibilities frontier for a given level of inputs. Otherwise, excess supply of one or the other quota may occur, leading to a price of zero in that market and underfishing of the resource. Alternatively, the initial allocation may fall below the production frontier, resulting in excess production capacity and discards or illegal landings in the short-run and possibly followed by disinvestment over a longer horizon. When the authors implemented the double permit system with historical levels of TACs for each species, they found that the sablefish permits were in excess supply, so they lowered the quota until it became binding. In the end they found that total rents under this dual permit system were considerably lower than the sum of the rents under the individual permits – largely due to Le Chatelier effects, which may be considerable for joint products.

The importance, in a multispecies setting, of getting the quotas "right" is emphasized in Larson et al. (1998) . In this paper, the authors attempt to determine the "optimal" bycatch quota rules – those that equalize the marginal value of quota as either bycatch or targeted catch – for the Bering Sea/Aleutian Islands (BSAI) midwater pollock fishery in the event of the implementation of a multispecies ITQ on both pollock and bycatch species. To do this they develop a constrained aggregate quasi-rent function. This equation represents variable rents under a quota system and is constrained in that production is evaluated at the level of the aggregate quotas and the marginal costs of increasing production of any particular species are augmented by the addition of an implicit price reflecting the marginal value of an additional unit of production. From this equation the authors are able to derive estimable expressions for the quasi-rent shares of each species. Lacking sufficient historical variation in quotas and quasi-rent shares to estimate their model the authors instead utilize pseudo-data from a linear programming model similar to that utilized in Larson et al. (1996) which maximizes variable rents, subject to quotas, by choosing weekly effort intensities for each vessel while treating each vessel's actual catch composition in that week as parametric.

The estimated quasi-rent equations are revealing in a number of ways. First, fishermen are generally willing to pay for extra quota of all species caught in the pollock fishery, even if regulations prohibit the sale of the species. This outcome is due to scope economies arising as a result of complementarities of bycatch species in the harvest of pollock. Second, the marginal willingness to pay for a unit of quota typically depends on the levels of quota for all species, such that a loosening of the quotas for bycatch species will actually raise the value of the target species quota. Thirdly, when the quota rent equations are set equal to the opportunity cost of the species in its most highly prized outside fishery, it becomes obvious that a variety of bycatch species should have been reallocated toward the pollock fishery if the regulatory goal was to maximize system-wide fishery rents.[25]

## 1.2 An Assessment of the Economic Literature

Given the relatively brief period of time in which economists have studied the bycatch problem, a great deal can be gleaned from their efforts. Indeed, the greatest contribution to date may simply lie in elevating the discourse from one focusing on bycatch as unnecessary "waste" to one which focuses on both the current and future external costs that bycatch imposes on competing user groups and society as a whole (Boyce, 1996, Hoagland and Jin, 1997), acknowledges the complex interplay between technological and economic forces in determining fishermen's ability and willingness to alter their catch composition (Larson, et al., 1998, Squires and Kirkley, 1996, Squires and Kirkley, 1991) and carefully weighs the immediate and induced costs and benefits from proposed "solutions" to the bycatch problem – often finding them lacking (Bisack and Sutinen, 2006, Pascoe and Revill, 2004, Ward, 1994). The theoretical literature on

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[25] Of course goals other than rent maximization often drive fishery management. See Witherell and Pautzke (1997) for a review of the development of the BSAI system of bycatch allocation and control.

discards has also made useful contributions by demonstrating how economic, technological and regulatory parameters all act to influence discard behavior on the part of profit-maximizing fishermen (Anderson, 1994, Arnason, 1994, Turner, 1997, Vestergaard, 1996). It has also gone a long way towards showing that, insofar as harvest technology is given, some level of discards is likely to be welfare enhancing, both from the point of view of fishermen and society at large (Arnason, 1994).

Despite these successes, the recommendations of economists for regulating bycatch and discards, at least as presented in the peer-reviewed literature, are likely to confuse even the most erudite non-economist policymaker. Indeed, the assertion, attributed to Winston Churchill, that "if you put two economists in a room you get two opinions" seems especially apropos here.[26] Nonetheless, on closer inspection, this apparent muddle can surrender some insight when considered in light of the specific assumptions made by each author and their stated, or implied, social objective function. For instance, the relatively optimistic conclusions of Boyce (derived under assumptions of perfect observability of catch and a simple dual production technology) that ITQs can correct many of the external costs associated with bycatch seem to evaporate when considered in light of less flexible harvest technologies, the possibility of unobserved discards and stochasticity in the bycatch rate. Nevertheless, many of these later studies, in an attempt to embrace greater model realism and complexity, often overlook the basic premise of Boyce's work – that fishermen can alter the composition of their catch – assuming a simple fixed proportions technology instead.[27] This assumption leaves open the question of the relative merits of various regulatory instruments when a realistic model of technology substitution, stochasticity and asymmetric information are combined. Of course, such a model would likely be highly intractable and require the combination of numerical simulation techniques and careful calibration and sensitivity analysis to grant any appreciable insights. Given this unattractive

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[26] The quote goes on to say "unless one of them is Lord Keynes, in which case you get three opinions".

[27] Notable exceptions are the empirical, duality-based models (Larson, et al., 1998, Squires and Kirkley, 1996, Squires and Kirkley, 1991) and the analytical model of Turner (1997).

prospect and the relative youth of the literature, economists should not be held to task for failing to reach a unified consensus on the regulation of bycatch and discards. Indeed, given the multidimensional aspects of the problem due to technological limitations, costly and imperfect observation of catch, stochasticity and the multitude of margins on which fishermen can potentially alter their behavior, it is highly dubious that any single instrument will show itself to be uniformly superior for all scenarios.[28] Ultimately, the regulator's choice of instrument(s) will often involve the weighting of possibly incongruous goals (of which economic efficiency may be only a minor contributor) under conditions of formidable uncertainty and intense political pressure. In this complex decision context, the aforementioned models may nevertheless serve a valuable role as "templates" with which to discipline one's thinking.

This being said, there are a number of issues left unaddressed in the literature that are suggestive of future work. First, in the realm of analytical modeling, the reliance on "fixed proportions" technological specifications has served to perpetuate the perception that, given a particular gear configuration, the composition of bycatch is predetermined when there is ample evidence in many fisheries that this composition is controllable to a significant degree by a fisherman's choice of fishing location as well as by various aspects of gear utilization (Adlerstein and Trumble, 1998, Gauvin, et al., 1995, Gilman, et al., 2006).

Second, notwithstanding the analyses of Boyce and Turner, there has been surprisingly scant analysis of how the incentive structures created by regulation may lead fishermen to alter their production mix in the short run or affect the development and adoption of bycatch-averting gears in the long run. Instead, most analysts have been happy to treat these aspects as exogenous to the problem, choosing instead to focus on the incentive effects of regulation on discards. Given that discard mortality could likely be mitigated in many fisheries by more selective harvest practices, this choice of focus is somewhat unfortunate.

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[28] The number and length of fishing trips, catch composition, discard decisions, choice of fishing location and port of origin and (in the long run) the reconfiguration of vessels and gears are just a few of these dimensions of choice.

Third, to our knowledge, there has been no consideration of the possibility of strategic behavior between fishermen when it comes to bycatch or discard decisions, this despite the fact that many fisheries are regulated via instruments (i.e. TACs, spatially or temporally defined quotas, days at sea limitations) which place some portion of the right to bycatch or its associated targeted catch in the common domain. For some fisheries, for instance the stereotypical open access situation, this omission is likely justifiable due to the large number of fishermen pursuing the resource. However, for fisheries where a small number of fishermen compete for a right to a share of a limited resource, strategic behavior may run rampant, possibly leading to a "race for bycatch" and considerable dissipation of rents. There are a number of recent developments in fisheries management that may encourage such gaming behavior. First, the introduction of limited access rights into an increasing number of the world's fisheries has dramatically limited the number of vessels with the ability to harvest particular stocks. Second, fishery regulation has often become increasingly tailored at fine temporal and spatial scales. It is likely in many cases, particularly for coastal fisheries, that these regulations create de facto use rights for relatively few fishermen – heightening the possibility of a localized "small numbers" situation amenable to gaming behavior. Finally, vessel buybacks and other methods aimed at reducing capacity have tended to increase the average efficiency of the remaining fleet in many fisheries. As a result, the actions of any one competitor are more likely than before to be worthy of consideration in determining one's own harvest strategy.

Fourth, despite the rapid influx of spatial ideas in resource economics over the past decade, there has been little consideration in either analytical or empirical models of bycatch as a spatial phenomenon.[29] This neglect is curious given the abundant evidence that space is often

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[29] Sampson (1994) appears to be the lonely exception. He develops a highly stylized two-species model in which one's decision of where to fish is determined by the degree of spatial overlap of the species as well as their distance profile from port. He finds that the degree of spatial overlap can have a major bearing on the impacts from landings quotas for each species. Highly overlapping species densities may result in considerably higher discards to achieve the landings quotas than would have occurred in a system with a

critically important in determining the relative proportions of catch and bycatch stocks and their availability to the fishing gear (Adlerstein and Trumble, 1998, Gauvin, et al., 1995, Gilman, et al., 2006, Mikol, 1997). Modeling and empirical analysis of spatial behavior by harvesters as it relates to bycatch and discards may help illuminate the micro-level decisions that form the basis of bycatch avoidance and may be suggestive of alternative regulatory and non-regulatory approaches to ameliorating the problem.

Fifth, and connected to the previous point, is the unfortunate tendency in the econometric literature on multispecies fisheries toward the exclusive utilization of techniques borrowed from the production literature (Larson, et al., 1998, Squires and Kirkley, 1996, Squires and Kirkley, 1991). This trend may be driven by data availability issues – many such models are estimable using commonly available information on landings, prices and costs – but also appears to be motivated by the tremendous amount of information that can be extracted from this data by the application of modern duality theory (Kirkley and Strand, 1988). Certainly, many useful contributions have arisen as a result, but there are a number of concerns that broadly apply to such studies that seem to necessitate alternative, complementary, approaches.

First, many if not most production analyses of fisheries are based upon landings rather than catch data. The implication is that the results are not strictly applicable to the fishing technology itself but are rather the complex amalgamation of both harvest and discard decisions. Unfortunately, this limitation is not typically acknowledged and statements such as "fishermen have very little ability to substitute between X and Y" are often made with such data when it could be that fishermen's discard decisions have masked this ability. Secondly, the use of relatively stable market data over short time periods may lead to estimation results that are only

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greater degree of spatial stock separation. Unfortunately, this paper has received little subsequent attention from economists – perhaps due to the journal in which it is published.

valid for small changes in prices.[30] Regrettably, these models are frequently enlisted to analyze the effects of policy changes (for instance, the introduction of ITQs) that often imply non-marginal changes in the implicit prices of various species to fishermen. Thirdly, these models ignore the effects on the observed production frontier of the overarching superstructure of property rights. Simply observing that fishermen fail to substitute between species under one scenario (say, open access) does not imply that such substitution would not be forthcoming under an alternative scenario in which fishermen found it in their best interest to do so (for instance, a system of bycatch penalties or multispecies ITQs). Finally, and to a similar point, the current application of these methods fail to account for cases in which individual production possibilities or profit-maximizing decisions may depend critically upon the behavior, either real or anticipated, of one's competitors. In short, the machinery of production economics, which has proven admirably suited for the analysis of industrial or agricultural output, may be less amenable to the complex and idiosyncratic features of real-world fisheries.

## 1.3 Outline of Chapters

This dissertation addresses these criticisms by developing analytic and empirical approaches to studying bycatch that are spatially aware, cognizant of the incentive effects of regulation and the possibility of strategic behavior among fishermen, flexible in the consideration of harvest technology and grounded on the most basic choice behavior of fishermen. The chapters are developed around a unifying case study – the Bering Sea head and gut groundfish trawl fishery.

Chapter 2 describes the history of the Bering Sea multispecies groundfish fishery, its complex system of regulation and the nature of its bycatch problems. It therefore provides the

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[30] This problem may be exacerbated by the ubiquitous use of flexible functional forms such as the translog or generalized Leontief which improve in-sample fit but may yield unrealistic predictions outside the limited range of the data.

biological, institutional and regulatory context for the analytical and empirical chapters that follow.

Chapter 3 presents a game-theoretic model of bycatch behavior under multiple common pool output quotas. The analytical framework mimics the system of TACs which are utilized in many BSAI fisheries. The model illuminates the perverse incentives created by this method of regulation but also demonstrates how the competitive behavior of fishermen can be brought into harmony with the TAC-constrained optimal solution.

Chapter 4 sets the table for the empirical analysis to follow by cataloging the data sources which are drawn upon in the subsequent analysis. This research requires a synthesis of numerous sources of information, and this chapter describes the origin, strengths and limitations of each of these.

Chapter 5 exposits a discrete choice model of fishing location choice in the spring-summer-fall trawl fishery targeting yellowfin sole and various other groundfish. The model is employed to uncover the implicit value accorded to halibut bycatch by fishermen and to show how this value has changed across and within seasons due to a variety of regulatory and strategic factors. The model also uncovers a number of other interesting factors that govern the spatial choices of fishermen – many of which have not been acknowledged elsewhere in the literature.

Chapter 6 analyzes the impact of a voluntary bycatch avoidance program (Sea State) that was introduced by a group of fishermen in 1995. Under this program, participating fishermen received summary views of bycatch rates across the fleet and were then able to use this information to avoid bycatch "hot spots" and to encourage their competitors to do the same. We utilize two different empirical approaches to study the success of this program for the yellowfin sole fishery. In the first, we utilize simple summary statistics to compare the performance of vessels in avoiding bycatch both before and after the institution of the Sea State program and across participating and non-participating fishermen.

The second approach augments the model structure developed in Chapter 5 with a modified difference-in-differences estimator to go beyond simple outcomes to uncover whether the program had any significant effect on *incentives* to avoid bycatch for those that participated. Both empirical approaches suggest that Sea State had no discernible influence on incentives to avoid bycatch. Some reasons for these findings are discussed and we discuss why Sea State seems to have shown evidence of success in other fisheries but not in our particular case.

Chapter 7 summarizes the findings from the previous chapters and concludes the dissertation with some thoughts on the future of incentive-based policies for bycatch management.

# Chapter 2

# The Eastern Bering Sea Head and Gut Fishery: History, Geography and Management

The commercial targeting of groundfish species in the Eastern Bering Sea (EBS) has its origins in the late 1950s and early 1960s when foreign fleets (primarily hailing from Japan and the USSR) began harvesting large quantities of groundfish for the at-sea production of fish meal (Wilderbuer, et al., 1992). Some two-thirds of this early catch was composed of flatfish species (Trumble, 1998).[31] This foreign fishery persisted relatively unchecked into the late 1970s when the passage of the Magnuson Fishery Conservation and Management Act (MFCMA) in 1976 extended US jurisdiction over its coastal waters to 200 miles. The result of this legislation was a long period of joint ventures between the foreign fleets and domestic companies that ultimately ended in 1991, by which time the entire groundfish fleet had become domestically owned and operated.

The groundfish fleet that emerged from this domestication process consists of three classes of vessels: catcher vessels, small vessels which deliver their catch in unprocessed form; motherships, which do not engage in fishing but receive catch from other (mostly catcher) vessels; and catcher processors, which are relatively large vessels that process and freeze their catch onboard and then deliver their products to brokers or wholesalers for direct sale or further processing. Since the overwhelming majority of flatfish in the EBS are caught by catcher processor vessels – the proportion of total trawl-caught flatfish taken by catcher processors

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[31] "Groundfish" in Alaska are any fish species that, in its adult state, spends the majority of its time on or near the seafloor. Flatfish (as opposed to roundfish) are a class of groundfish that are distinctive for their flat profile and the fact that both eyes lie on one side of their head. All species with "halibut", "turbot", "sole" or "flounder" in their common names are considered flatfish in Alaskan waters.

between 1994 and 2000 averaged 92% and virtually all flatfish catch is taken by trawl (Hiatt and Terry, 1999) – we limit our description and subsequent analysis to this portion of the fleet.

## 2.1 The Domestic Catcher Processor Trawl Fleet

Despite the previous classification, the catcher processor trawl fleet is itself quite heterogeneous in terms of the degree of capitalization of vessels, the species targeted and the regulatory strictures that are incumbent upon vessels. Roughly speaking, however, the groundfish catcher processor fleet can be divided into two groups. The first, targeting primarily walleye pollock and Pacific cod, are large (roughly 260-370 feet in length) vessels that maintain extensive processing facilities in their holds for the production of products such as fillets, surimi or fish meal.[32]

The second class, known as the head and gut fleet, use bottom trawl gear to pursue a wide variety of species in the Bering Sea/Aleutian Islands as well as the Gulf of Alaska. These vessels typically range in size from 110 to 230 feet and possess relatively low horsepower of between 1,200 to 3,600.[33] This fleet has ranged in size somewhat over the years with some reduction in participation in the years following domestication (Gauvin, 2006); however, there are roughly 25 or so vessels active for any particular season. The range of species pursued by these vessels is considerable and varies depending upon seasonal, market and regulatory conditions, but the primary targets are flatfish (e.g. yellowfin, rock and flathead sole), Atka mackerel, Pacific cod and rockfish. Within the Bering Sea, flatfish (in particular, rock and yellowfin sole) are overwhelmingly the most important target species, although cod and, to a lesser extent, rockfish are also pursued at various stages within the season.

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[32] Surimi is a processed paste made from minced fish that is employed to produce products such as artificial shrimp or crab meat.

[33] This characterization, while true of much of the fleet, is not exhaustive. One vessel in the fleet has a length of 295 feet (comparable to a pollock trawler) and another is highly powered at 6000 horsepower.

Given the relatively small size of these vessels, they typically lack the capacity for extensive processing machinery and personnel. They therefore conduct only fairly rudimentary processing of their catch. The primary product designation is "head and gut" (H&G) which is, predictably, the beheaded and eviscerated catch. These are then sorted into trays and flash-frozen into blocks which are then exported to Asian and European markets where they are typically subjected to further processing (such as filleting) before reaching their ultimate retail markets. In addition to head and gut product, there are also markets for kirimi (portion-cut H&G product with the tail removed), whole fish and roe-in H&G products (H&G female fish packed with the roe intact). Kirimi and whole fish are popular product designations for yellowfin sole while roe-in H&G is an important (and valuable) seasonal product designation for the rock sole fishery.

While, this section has provided a rough description of the target species and products of the H&G fleet, the next section provides a much more detailed view of the fishing activities of the vessels as seen over both space and time.

## 2.2 The Head and Gut Fleet – A Closer Look

The targeting behavior of H&G fishermen in the North Pacific and their attendant movements in space follows a complex seasonal pattern that is determined by a number of factors, both natural and regulatory. Understanding this pattern necessitates an understanding of the geography of the Eastern Bering Sea and the underlying climatic, oceanographic and biological conditions that govern the spatial distributions of targeted species.[34]

### 2.2.1 The Eastern Bering Sea Environment

The most prominent feature of the Eastern Bering Sea is the enormous extent of the continental shelf (see Figure 2.1). At 1,200 km wide and with a minimum width of over 500 km,

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[34] Given the focus of this dissertation on fishing activities within the Bering Sea, we largely ignore the Aleutian Islands and Gulf of Alaska in this discussion although the H&G fleet does fish in these areas as well.

it is the widest continental shelf found outside the Arctic Ocean (Wilderbuer, et al., 1992). This shelf is composed primarily of vast stretches of sand and mud bottom that, aside from providing an ideal habitat for many benthic organisms, also make it relatively easy to trawl with minimal risk of snagging or gear loss (McConnaughey and Smith, 2000).

The continental shelf in this region, although gently sloped, is actually composed of three distinct regions with their own unique oceanographic features. These features are critical in driving the distribution of commercial fish species. The outer shelf domain, extending from the 100m isobath to the shelf break between 170-200m, experiences strong currents that carry many of the nutrients and phytoplankton that form the basis of the marine food web into pelagic waters or into the open oceans of the Aleutian Basin. Accordingly, there is relatively little biomass of demersal (i.e. bottom dwelling) groundfish in this region (Wilderbuer, et al., 1992). In contrast, the middle shelf, which spans the zone from 50 to 100m, experiences very slow flushing of its waters. As a result, much of the primary productivity in these waters settles to the bottom and supports an extensive benthic food web, including substantial biomass of commercially harvested flatfish species (Wilderbuer, et al., 1992). The final area, known as the coastal zone, includes the nearshore waters less than 50m in depth and experiences strong wind and tidal mixing, making it much more variable in temperature than the other zones. These waters are also typically less saline than the deeper regions due to abundant inflows from rivers. This zone is frequented by many groundfish species during their annual mating migrations and also serves as a sheltered habitat for many juvenile groundfish species.

In addition to the broad continental shelf, there is also a relatively less productive, but nevertheless important, continental slope. This steeply sloped region serves to separate the shelf from the open ocean of the Aleutian Basin. Deepwater flatfish such as Greenland turbot thrive in these waters, and rockfish species such as Pacific ocean perch frequently occur in aggregations along canyon edges at the leading edge of the slope (Brodeur, 2001).

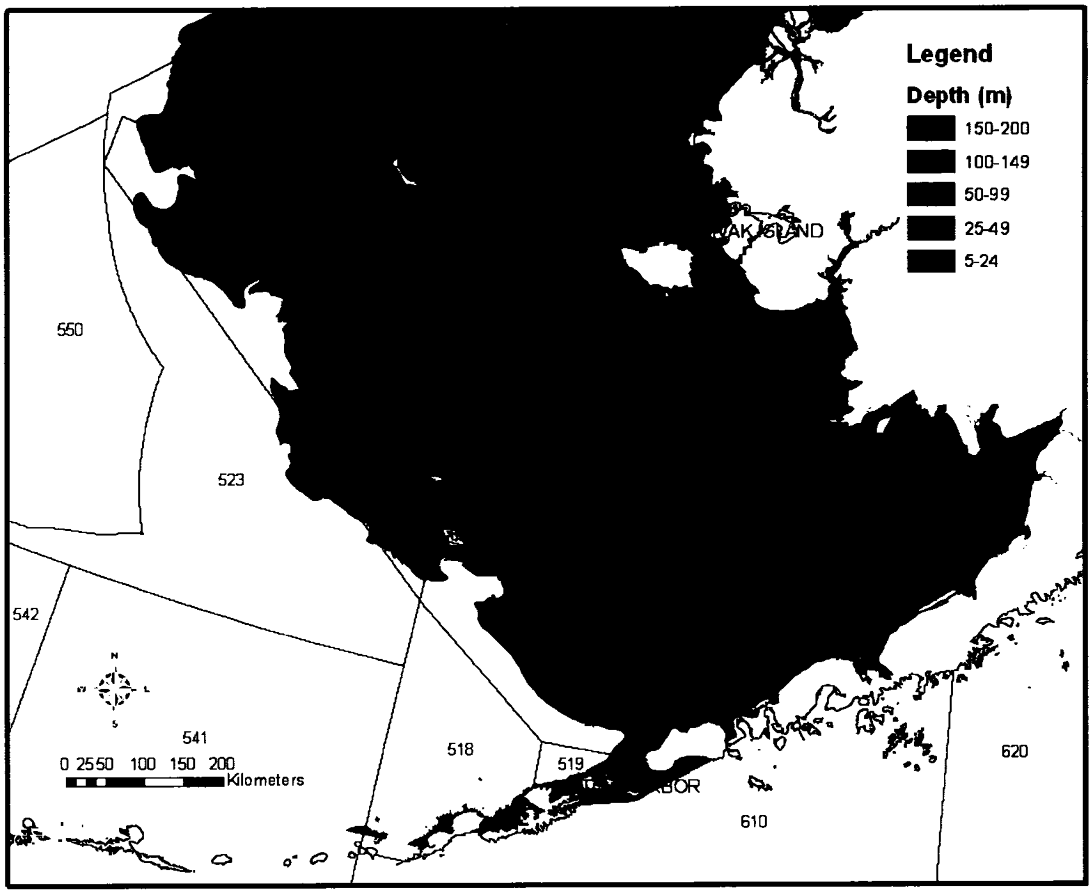

Figure 2.1: The Bathymetry of the Bering Sea Shelf (with NPFMC regulatory zones)

The Eastern Bering Sea is a highly variable environment, particularly with respect to climatic conditions, and one of the primary shapers of the marine environment is the annual advance and retreat of sea ice. Every winter, ice begins forming along south-facing coasts; this icing progresses southward at a rate of around 12 percent per month until 60 to 65 percent coverage is attained by late March (NMFS, 2004).[35] It then melts over the spring until it has completely cleared by some point in July. This icing is important for fostering spring algal blooms which increase the productivity of the ecosystem; also the seasonal movements of many species are controlled either directly or indirectly by the extent of seasonal icing and its retreat (NMFS, 2004).

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[35] The extent of coverage varies substantially from year to year. Some years show very little icing over the southeast portion of the EBS while others are quite extensive.

As an example of the importance of bathymetric and seasonal conditions in driving the locations of groundfish species, consider the case of yellowfin sole. Adult yellowfin sole spend the winters around the shelf break (approximately 200m). Two sub-populations have been identified: one that overwinters off Unimak Island near the edge of the Alaska Peninsula and another located to the west of the Pribilof Islands (Nichol, 1997). As the ice begins to recede in the spring, these populations move with the ice frontier across the shelf to nearshore (<50m) spawning areas in Bristol Bay and off Nunivak Island, respectively (Nichol, 1997, Wilderbuer, et al., 1992). Spawning spans from May through August, after which the two sub-populations gradually retrace their way to the bountiful waters of the central shelf over the fall months to feed.

The nature of the temporal and spatial variability of concentrations of various species in the Eastern Bering Sea differs to a marked degree upon the species. Some species, such as Pacific cod, range over a wide range of depths and habitat types with relatively little predictability while others, such as Pacific ocean perch, are associated with a narrow range of depths and substrates. Some species, such as rock or yellowfin sole, undergo substantial and recurring seasonal migrations while still others (again, Pacific ocean perch is a good example) exhibit only minor seasonal movements.

Figure 2.2 shows a kernel density estimate of the distributions of particular species target designations over bottom depth. These target designations are uniquely assigned to each fishing haul according to a standard employed by NMFS and are typically based on whatever species constitutes the majority of a haul by weight.[36] This graph therefore provides a fair indication of the depth ranges at which various species are targeted by the H&G fleet.[37] These densities are broadly consistent with the mean habitat preferences of these species for the months in which

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[36] This standard is not exactly true for certain flatfish such as rock sole, yellowfin sole and flathead sole. To assign a target among these three, it must first be the case that the total weight of flatfish exceeds the weight of any other target category. Given this, if 70% or more of the total flatfish catch is yellowfin sole, then the target is yellowfin sole; otherwise, the target is whatever flatfish species is most prevalent.

[37] The distribution of Greenland turbot-targeted hauls is clearly truncated at 400m. We have done this for the sake of visibility of the other species' distributions; however, very little fishing occurs below a depth of 400m.

they are fished. The densities also seem to reflect substantial diversity of species designations at depths above 150m – this being indicative of the high spatial overlap of many targeted species. A substantial drop in this diversity occurs at depths below 150m, with species such as Pacific ocean perch and turbot forming the primary targets in these depths.

Despite the utility of this graph, there are at least two limitations of Figure 2.2 as a summary of fishing behavior. First, by looking only at depth, it provides little indication of how fishing effort is distributed in two dimensional space. Second, the possible multimodal nature of some of the densities suggests that fishermen may pursue species in different locations across the season. We consider the distribution of fishing effort over space and time in the next section.

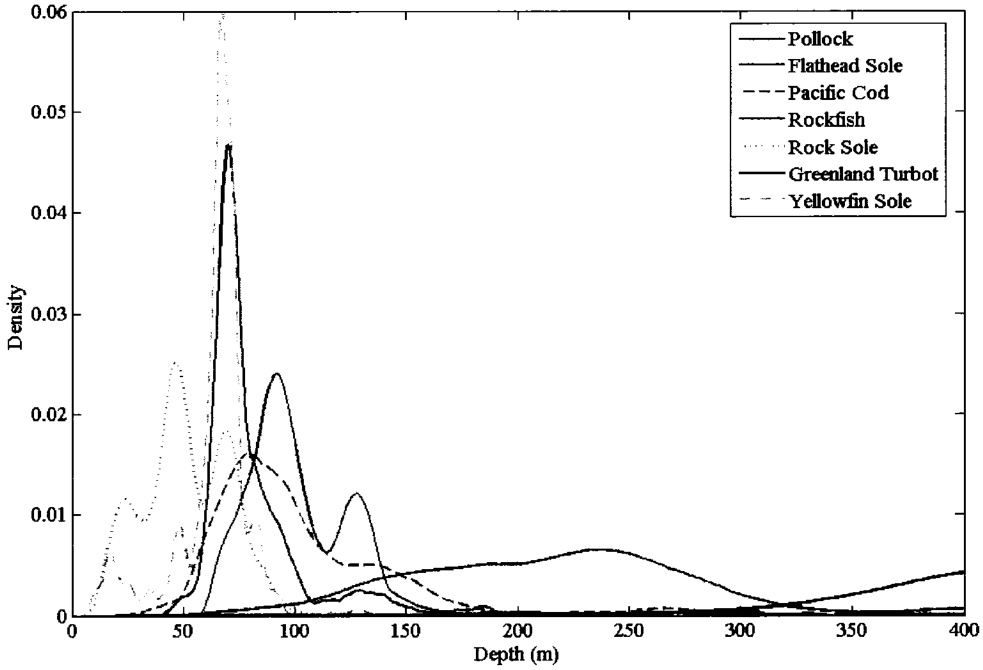

Figure 2.2: Kernel Density of Species Targeting Indicators by Depth

### 1.1.1 A Spatiotemporal View of Fishing Effort

Figure 2.3 shows the monthly average real weight equivalent of production in the Bering

Sea/Aleutian Islands by species for 28 H&G vessels over the period 1994 to 2000.[38] A real weight equivalent is the extrapolated retained catch necessary to produce the reported amounts of each product type by each vessel, taking into account the product recovery rates by species. A glance at these production patterns reveals that, although certain species predominate, the H&G fleet derives products from a variety of species throughout the season. This pattern is partially reflective of diverse targeting practices by fishermen in response to the ebb and flow of economic incentives and regulatory strictures; however, it is also broadly indicative of the diverse composition of catch encountered by the use of non-selective bottom trawl gear on a productive and biologically diverse benthic habitat.

Much of the catch shown in Figure 2.3 derives from fisheries in the Bering Sea; there is one notable exception, however. Atka mackerel is pursued almost exclusively in the Aleutian Islands where it is found in dense aggregations around highly-specific nursing habitats. Most H&G fishing in the Aleutian Islands is directed at Atka mackerel, although there is also fishing for Pacific cod and certain species of rockfish there as well.

A further look at Figure 2.3 shows that production (and by extension, effort) fluctuates a great deal from month to month. Peak production typically occurs in January and February (groundfish fishing in the BSAI does not begin until January 20th, so the seemingly low production in this month is misleading), spurred on by the Atka mackerel season in the Aleutian Islands, the Pacific cod fishery in the Bering Sea and Aleutian Islands and the valuable Bering Sea rock sole roe fishery. Production subsides somewhat in the spring as regulatory restrictions and natural factors (such as the end of the rock sole spawning period) bring these fisheries to a close and as some fishermen leave the BSAI temporarily to pursue alternative fisheries in areas

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[38] This sample was constructed as an exhaustive list of the major participants in the H&G fleet. This selection process was complicated somewhat by the occasional targeting of the same species by the pollock fleet. However, information on vessel characteristics, product types and targeting behavior allowed us to distinguish between the two fleets. In the end, we corroborated our list with industry representatives (Gauvin, 2006).

such as the Gulf of Alaska.[39] During the spring and early summer months, production is varied although atka mackerel and yellowfin sole have the largest shares of the real weight equivalent overall. Fishing for Pacific ocean perch becomes more important in the wake of the temporary subsidence of the yellowfin sole fishery (usually due to regulatory closure). Starting in August, however, the targeting of yellowfin sole begins again in earnest and production spikes again in the late summer. Production and effort continue through the fall but they diminish on average due to frequent regulatory closures and the exit of some vessels from the fishery as the season draws near its end.

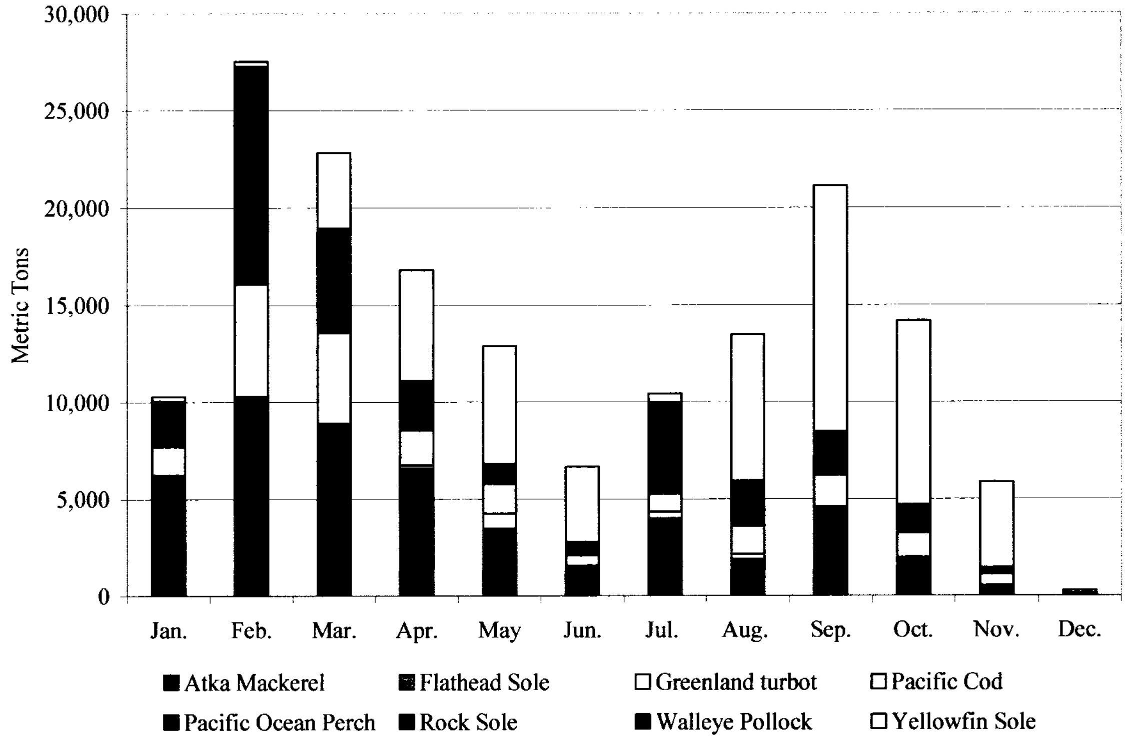

Figure 2.3: Average Monthly Real Weight Equivalent Production by Species: 1994-2000

The spatial distribution of effort associated with this temporal pattern of production in Figure 2.3 is shown in Figure 2.4-Figure 2.6. These three maps depict fishing as occurring in three distinct seasons, the winter (January to March), the spring and early summer (April to July)

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[39] We discuss the evolution of fisheries management and the impact of regulations on the H&G fleet in the next section.

and the late summer and fall (August to December). These figures provide kernel-smoothed estimates of the density of fishing effort per square kilometer for each sub-season over this seven year period.[40]

Examining Figure 2.4 it is apparent that effort in the fishery centers on the southern Bering Sea as well as several small "hot spots" in the Aleutian Islands. This first concentration is explained by the brief but intense fishery for roe-bearing rock sole. These fish congregate in the relative shallows north of Unimak Island and the Alaska Peninsula to spawn. The activity in the Aleutian Islands is primarily directed at small but spatially concentrated populations of Atka mackerel although cod is also sought at this time in both the Bering Sea and Aleutians. The less intense central concentration of effort in the neighborhood of the Pribilofs is associated with the targeting of yellowfin sole and other flatfish, mostly in the last few weeks of the winter sub-season.

During the spring months, fishing effort is distributed over a much wider area; however fishing is much more oriented toward the north and north central Bering Sea than in the previous months (in part because the receding sea ice makes this possible). As mentioned before, fishing in this period is often targeted at yellowfin sole, and the effects of the two spatially distinct groups of spawning yellowfin can be easily seen in Figure 2.5 with the effort devoted to one sub-population being mostly contained with management area 514 while that devoted to the second group is squarely located in the central Bering Sea. There is also a small concentration of effort in the southern Bering Sea associated with the targeting of Pacific cod while the clustering of effort in relatively deep water along the continental shelf edge in northern waters is frequently associated with the targeting of rockfish such as Pacific ocean perch.

Figure 2.6 shows the remnants of some of the early summer patterns of targeting; however, the primary tendency in the late summer onward is the dominance of yellowfin sole as

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[40] These graphs were created using the ArcToolbox package by ESRI software. The density estimates are produced using a quadratic kernel with a relatively small radius of 15km in order to preserve detail in areas with relatively sparse visitation.

the primary target.[41] As a result, effort becomes concentrated on the areas where the recently spawned fish retreat to feed – the highly productive waters of the central shelf. There is also a limited fishery for Atka mackerel at this time, thus explaining the activity in the Aleutian Islands.

The role of natural spatiotemporal factors in driving the distribution of targeted species and the associated patterns of fishing effort should not be underestimated; however, there are also numerous factors associated with the management of the Bering sea fisheries that also play a key role in fishermen's targeting decisions and movement across space and, by extension, their bycatch rate. We discuss these factors in the following section.

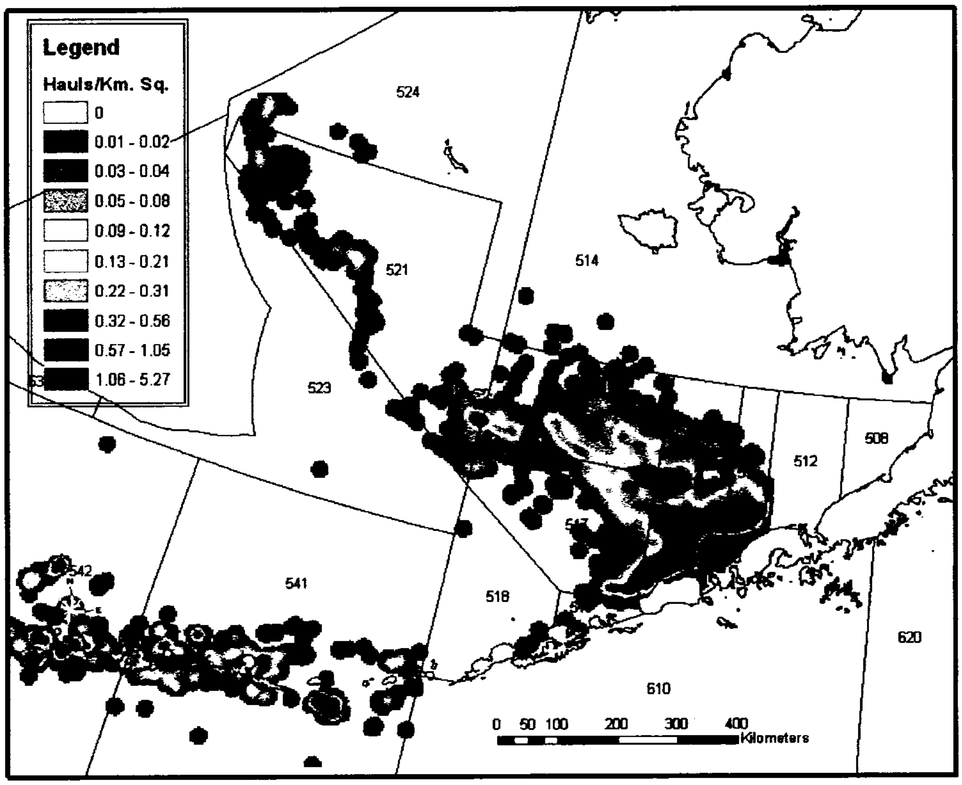

Figure 2.4: Kernel Density of January-March Fishing Intensity for 1994-2000 for the H&G Fleet

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[41] As explained in the next section, this dominance is strongly driven by regulatory restrictions that often limit the quantities of other species that may be retained at this late stage of the season.

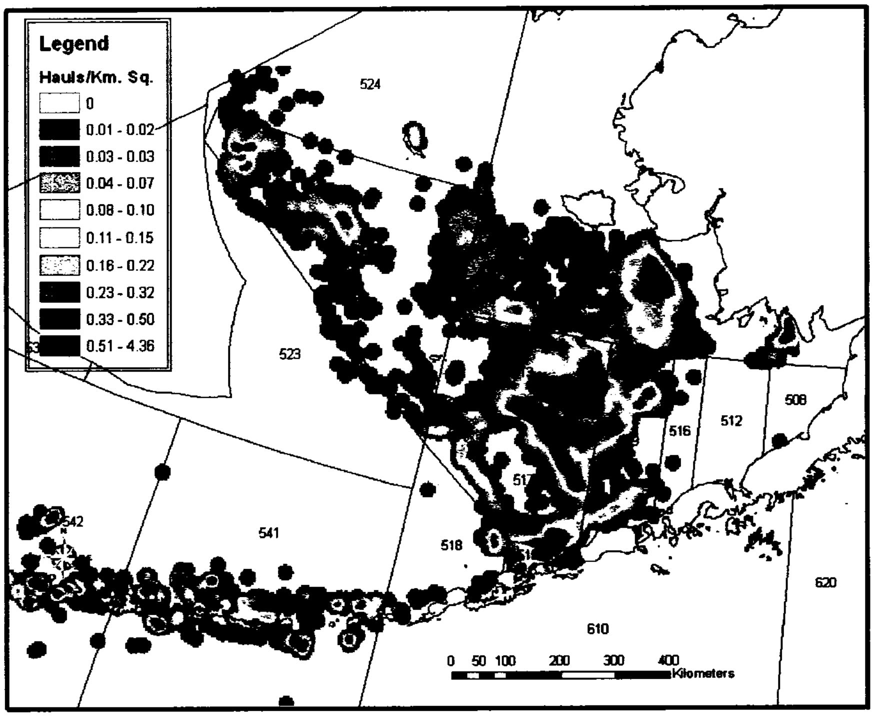

Figure 2.5: Kernel Density of April-July Fishing Intensity for 1994-2000 for the H&G Fleet

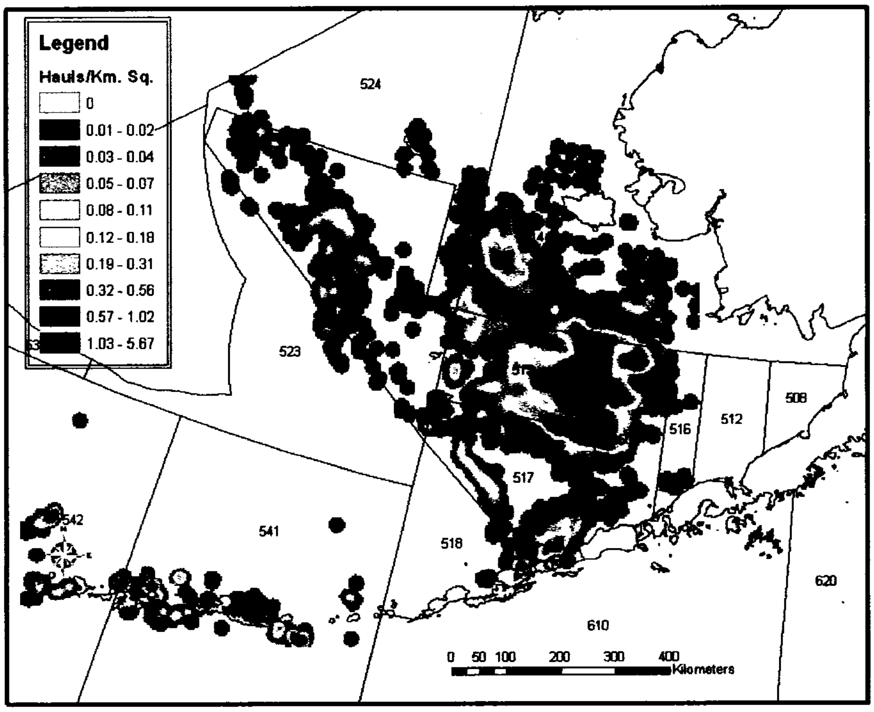

Figure 2.6: Kernel Density of August-December Fishing Effort for 1994-2000 for the H&G Fleet

## 2.3 Management of the Head and Gut Fishery

The management of the groundfish fisheries in the federal waters off the coast of Alaska under the auspices of the North Pacific Fishery Management Council (NPFMC) is exceedingly complex, and an exhaustive description of the institutions of the regulations and institutions of enforcement in these fisheries is beyond the scope of this work.[42] Instead, we focus on those institutions that were most salient to the head and gut fleet in the Bering Sea during our empirical period of study, 1994 to 2000. These are, with minor exceptions, quite similar to the system of management faced by the fleet at the current time. For convenience, we divide these regulations into four categories: 1) limitations on participation, 2) limitations on spatial distribution of effort, 3) limitations on target species catch, and 4) limitations on catch and retention of prohibited species.

### 2.3.1 Limits on Participation

The establishment of the 200 mile exclusive economic zone (EEZ) and the eventual domestication of the groundfish fleet did not solve the problems of open access and overcapitalization in Alaska fisheries; rather, the legislation merely transformed a globally accessible commons to a *de facto* open access resource for all U.S.-owned vessels. The result for the groundfish fleet was a rapid expansion of domestic capacity such that by 1988 there was already sufficient vessel capital to harvest the resource and yet the fleet continued to expand rapidly (Megrey and Wespestad, 1990). Alarmed by this explosion of effort, the NPFMC implemented a moratorium on the entry of additional vessels into the groundfish and crab fisheries in the federal waters off Alaska in 1995. The purpose of the moratorium was to "buy time" for the Council until a more permanent solution was found.

In 1996, the Council proposed a license limitation program (LLP) in place of the old moratorium. Under this plan, licenses were created for particular regions (e.g. Bering Sea,

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[42] For an examination of the history of the regulatory institutions in the North Pacific see Holland and Ginter (2001), Trumble (1998) and Witherell and Pautzke (1997).

Aleutian Islands or Gulf of Alaska) and particular classes and sizes of vessels. A vessel required a license to operate and such a license was only granted to vessels that had made at least one groundfish landing during the period between January 1988 and June 27, 1992 (Ginter and Muse, 2002). In addition to a permit, vessels were also required to hold endorsements that allowed them to fish for specific species or in particular areas; the qualifying requirements for these endorsements were, again, based upon historical participation. Transfers of permits between vessels were allowed, although these transfers are limited somewhat by the facts that endorsements are not severable from the attached permit and increases in vessel length are either strictly curtailed or limited depending upon the original size class of the vessel. After much debate and modification of the details of the program, the LLP was finally implemented with the start of the fishing season in 2000.

Both the moratorium and the LLP that followed it have been criticized as providing no substantive limit on fishing effort (Ginter and Muse, 2002, Holland, 2000). The programs allowed far more vessels to participate in the groundfish fishery than were necessary to efficiently harvest the resource stock and allowed considerable latitude for those vessels with licenses to transition across fisheries and increase their harvesting capacity along a number of unregulated dimensions.

Despite these criticisms, the effect of the moratorium and the ensuing LLP for the head and gut fleet appears to be one of stabilization. With the exception of the re-introduction of a refurbished factory trawler by U.S. Seafoods in 1999, effort in this subset of the groundfish fishery has remained fairly steady when measured by the number of vessels. Indeed, the exit of a handful of a small number of unprofitable vessels in the mid 1990s combined with the forced retirement under the American Fisheries Act of several vessels primarily harvesting pollock and cod (but also, on occasion, flatfish) has, if anything, *reduced* the number of vessels at any given point of time targeting flatfish and other non-pollock groundfish. The recent history of the head and gut fleet has been characterized by a very stable and moderately sized (25-30 vessels) cadre of participants – many of which have participated in the fishery since the early days of the domestic fishery.

### 2.3.2 Limits on the Spatial Distribution of Effort

The NPFMC has an extensive track record of utilizing spatially delineated management instruments to control fishing effort in the Bering Sea and other management areas. In many cases these spatial controls take the form of blanket prohibitions on fishing (or fishing with bottom trawl gear), either for the entire season or for a particular window of the season. Still others, which we discuss in Section 2.3.4, are triggered by the achievement (or anticipated achievement) of quotas for either bycatch or target species and do not typically involve a prohibition on fishing per se, but nonetheless place significant constraints on the retention of economically valuable species in an attempt to curtail targeted effort in these areas.

Figure 2.7 depicts those closures of relevance to the Bering Sea head and gut fleet in the 1990s that constitute blanket prohibitions of fishing within their boundaries.[43] This period was one of rapid change in many aspects of fishery management, and the implementation of spatial closures was no exception. Of all the closures depicted here, only Zone 1 and Zone 2 (which were established for the protection of crab and halibut stocks) were in place at the beginning of the decade. The mid-1990s saw a spate of new reserves with the establishment of the Chum Salmon Savings Area (CSSA) in 1994, the Red King Crab Savings Area (RKCSA) and the Pribilof Islands Habitat Conservation Area in 1995 and Nearshore Bristol Bay Closure Area in 1996. Some of these closures, such as the RKCSA and CSSA, were expressly designed to counter bycatch of non-targeted species whereas the others, while at least partially motivated by bycatch issues, were primarily designed to protect juvenile habitat (the Nearshore Bristol Bay Closure Area) or to shelter endangered or depressed stocks of crab, seals, seabirds and their prey

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[43] This map does leave out some small closures around islands for the protection of Steller sea lions and walrus. These closures have grown in number over the years; however, most of these closures are located in the Aleutian Islands management area.

items from the direct and indirect effects of commercial fishing. The enforcement of these restrictions on location, although not carried out by onboard observers (see Chapter 3), is, nevertheless, facilitated by their data gathering activities. The actual enforcement of spatial closures falls upon NMFS and the U.S. Coast Guard, and there are considerable financial and criminal penalties for willful infringement.

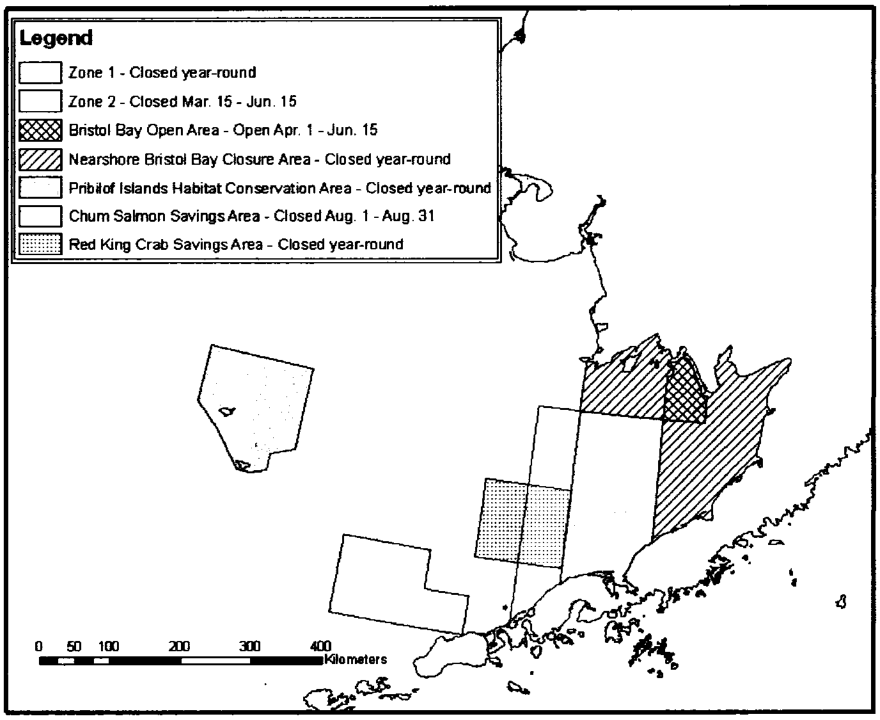

Figure 2.7: Spatial Closures for the Head and Gut Fleet in the Bering Sea

### 2.3.3 Limits on Targeted Catch

Given the broad spatial area, multiple species and competing user groups that characterize the Bering Sea fisheries, it is not surprising that the polices and procedures utilized to govern and allocate catch are often staggeringly complex. Behind these policies, however, is a bedrock of scientific fishery management that is widely considered among the best in the world

The total removals of individual groundfish species within the Bering Sea are governed by the setting of total allowable catch (TAC) limits. These limits are set on the *catch* of marine species, regardless of whether the species is targeted catch or bycatch or whether it is landed or discarded back into the sea. These TACs are weakly less than allowable biological catch (ABC) levels which are determined from annually updated estimates of population status from trawl surveys conducted over the Bering Sea shelf and slope regions and the Aleutian Islands. These ABCs are selected based on a conservative guideline that treats the maximum sustained yield (MSY) stock – a common "safe" target stock in fisheries management – as a lower bound to be avoided. Further precaution is built into the system by guidelines that lower the ABC for stocks with limited stock assessment information or those for which biomass is below the average historical level (Witherell, et al., 2000).

In practice, TACs are often set substantially below the ABC levels. At times this merely reflects precautionary management on the part of the Council; however, the total removals from the Bering Sea and Aleutian Islands are also subject to an "ecosystem cap" in the range of 1.4 to 2 million metric tons (Witherell, 1997). This cap is often below the combined ABCs for all species, requiring that some species' TACs fall (often substantially) below their ABCs. The Council has a fair bit of latitude in setting TACs, and socioeconomic – and, perhaps, political – conditions often come into play. Specifically, the NPFMC is allowed to consider factors such as the "promotion of efficiency, optimum marketable size of fish, impacts on prohibited species and dependent domestic fisheries, desire to enhance depleted stocks, seasonal access to the groundfish fishery by U.S. vessels, commercial importance to local communities, subsistence needs, and the need to promote utilization of certain species" (Witherell, 1997). Our cursory review of the annual rationale for TACs published in the Federal Register suggests that the projected ability of particular sectors of the fleet to harvest the ABC for a species, given seasonal and regulatory constraints, plays a key role in whether the TAC for a species is "shortchanged" or not.

After reaching a consensus the Council publishes preliminary TACs in the Federal Register in September and then receives public comment in October and November before finalizing the TACs in December for the upcoming season. As of 2000, these TACs were set for some 17 species and species groups in the Bering Sea/Aleutian Islands. TACs are typically specified for the entire groundfish fleet, although some targeted species, particularly pollock, are allocated to particular sectors that have the exclusive right to these portions of the TAC.[44]

The progress of the groundfish fleet against these TACs is monitored throughout the season by the Alaska Regional Office of NMFS who synthesize data from onboard observers and weekly production reports to provide in-season projections of catch. If regulators anticipate that a TAC will be filled in the near future, they usually close the fishery to "directed fishing". This designation allows the species to be retained in greatly reduced proportions by establishing maximum retainable bycatch amounts (MRBs) which are calculated based upon proportions of target species for which a curtailment on retention is not in place. Such measures are intended to remove the incentive to continue targeting the species in question while not unduly burdening the continued pursuit of other species.[45] If, after a directed fishing closure, regulators determine that a TAC will be exceeded, they can then prohibit the retention of the species entirely. In rare cases, where serious overfishing may result, the regulator may actually terminate other fisheries or require gear modifications to dramatically curtail the incidental take of the species (Witherell, 1997).

### 2.3.4 Limits on Catch of Prohibited Species

In addition to limits on the catch of targeted species, groundfish fishermen also face constraints on the catch and retention of certain bycatch species known as "prohibited species". The species in this category include Pacific halibut, king and *C. bairdi* tanner crab, salmon and herring, although only the halibut and crab species are of any significance to the non-pollock groundfish fisheries. These species are valuable targets to fishermen outside the groundfish fleet

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[44] The head and gut fleet does not fall into any these sectors and do not receive allocations of their target species that are uniquely their own although they are the dominant users of TAC for several species, especially flatfish.

[45] The effectiveness of this mechanism in actually curbing targeting behavior is questionable. Fishermen may actually pursue "closed" species to the maximum extent allowable under MRBs – particularly when a strong market for this "bycatch" exists. Anecdotal evidence suggests that this "topping off" behavior may occur for Pacific cod in the head and gut fisheries (Hezel, 2006). Ackley and Heifetz (2001) find empirical evidence for similar targeting of sablefish "bycatch" in the Gulf of Alaska rockfish fisheries.

and their primary management responsibility rests on institutions outside of the NPFMC. For instance, the management of crab, salmon and herring fisheries rests with the State of Alaska while Pacific halibut is administered by an international partnership between the U.S. and Canada through the International Pacific Halibut Commission (IPHC). In many cases the targeted fisheries for these species are pursued by numerous small vessels with strong ties to the state economy with many vessels hailing from small local ports and delivering to local processors. This contrasts dramatically with much of the catcher processor groundfish fleet which is highly capitalized by comparison and most vessels are owned and operated by personnel from the lower-48 states with many vessels based out of Seattle. Many of the fisheries for prohibited species also have extensive histories of local fishing before the development of the offshore fleet in the late twentieth century. Finally, some of these fisheries are of great importance to the continued subsistence of many indigenous communities.

Given these factors, it should come as no surprise that the bycatch of these species by the groundfish fleet has often been a sore issue; however, it is, to some extent, unavoidable given the similar spatial affinities of groundfish and prohibited species and the limitations on the selectivity of groundfish gear. With the scientific fishery management standards in place with ADFG and the IPHC, the allowable take of crab and halibut by their target fleets are adjusted for anticipated mortality of these species as bycatch in the groundfish fleets. For instance, in the commercial halibut fishery allowable catch is not only affected by the direct loss of harvestable species – a relatively small loss due to the skewed selectivity of much groundfish gear for juvenile halibut (Spencer, et al., 2002) – but is also affected in future seasons due to yield losses from the past removals of undersized fish as well as the associated loss of reproductive potential (Sullivan, et al., 1994). These effects can be significant; in 1995, bycatch mortality for halibut was equivalent to 22% of its total allowable catch.

In an effort to encourage the groundfish fleet to reduce its bycatch and avoid the active targeting of these species, fishermen are prohibited from retaining prohibited species (hence their name). In addition, there are system-wide limitations on the total amounts of bycatch that can be caught during each season. These limitations are calibrated to the assessed abundance of crab species while the limit for trawl-caught halibut is enshrined in regulations as a fixed amount, regardless of its estimated biomass.[46] These aggregate allocations of bycatch are then parsed out among various target fisheries based on their anticipated usage of the quota. These target fisheries are demarcated by species or species group. For instance, yellowfin sole and Pacific cod receive their own prohibited species allocations while rock sole is combined with flathead sole and "other flatfish" (a catch-all category that includes, among others, Alaska plaice). These targeting standards are based upon the quantity of *retained* catch of particular groundfish species and are assigned to a vessel on a weekly basis (see footnote 36 for details on targeting designations).

Monitoring and enforcement of prohibited species catch (PSC) quotas is handled in a manner that is quite similar to the monitoring of quotas for targeted species. Regulators monitor the progress of bycatch against the individual quota allocations and when they anticipate that a particular PSC allocation will be met, they prohibit directed fishing for the associated target species. For instance, a regulator might prohibit directed fishing for yellowfin sole (so that retention would be limited by the MRB quantity) if they foresaw that the assignment of halibut bycatch quota to the yellowfin sole targeted fishery would be met or exceeded in the near future.[47] In the case of halibut bycatch, these restrictions apply over the entire fishing ground whereas in the case of red king crab and *C. bairdi* tanner crab, both the PSC quotas and their associated fishery closures only apply to particular subsets of the grounds (see Figure 2.8).

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[46] In the 1990s this limit was 3,775 mt of estimated halibut *mortality* although the quantity later fell slightly to 3,675 mt. Halibut quota is based on the estimated *mortality* of the bycatch since a portion of the discarded bycatch is assumed to survive to recruit back into the fishery. Mortality rates are determined by gear and target fishery for each year, however, so that there is a one-to-one correspondence between catch and mortality rates for the purposes of regulation. These mortality rates (which are published with the quota specifications on an annual basis) have changed somewhat over the years with some gear/targets showing improved rates while others have worsened. The assumed halibut mortality for rock and yellowfin sole has hovered around 80 percent.

[47] The details of the onboard observer program and the information systems utilized by the Alaska Regional Office to monitor quotas are discussed in Chapter 4.

It is important to note that PSC quotas are *not* assigned to individual vessels or skippers. Instead, they are held in common by a portion of the fleet; this mimics the allocation of TACs for targeted species, although the breakdown of PSC quota by target fishery and gear type often reduces the scope of common ownership considerably. This shared ownership and the inherent complementarity of target and bycatch species in harvest are critically important in understanding the incentives and production possibilities facing fishermen in the head and gut fleet.

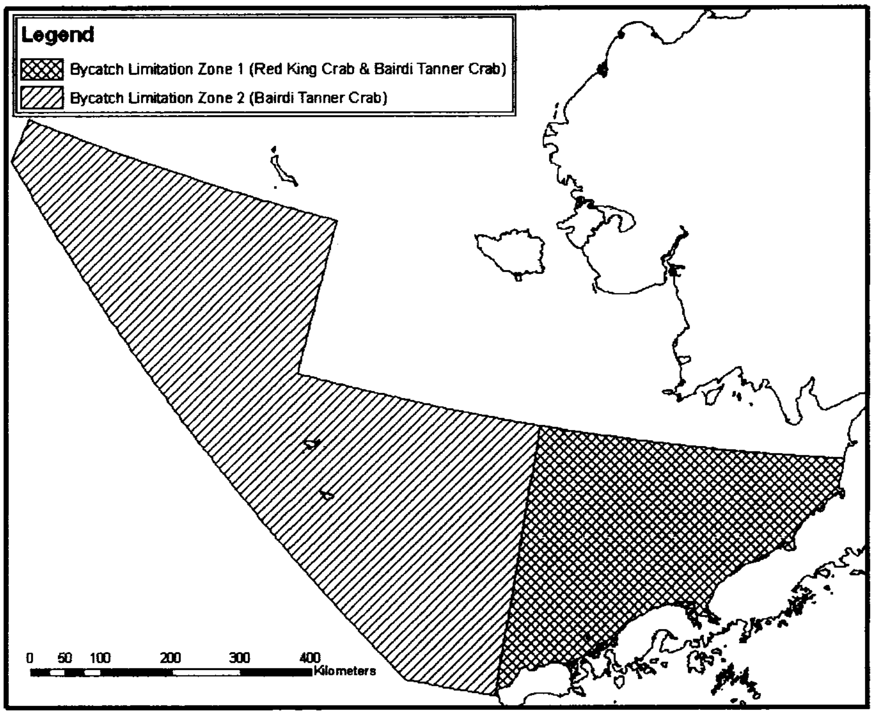

Figure 2.8: Bycatch Limitation Zones for PSC Crab Species

## 2.4 The Common Quota System – A Retrospective View

The management system for groundfish in the North Pacific is widely applauded as an example of the triumph of scientific fisheries management and as an exemplar of the "ecosystem approach" to fisheries management (Witherell, et al., 2000). Indeed, from an ecological perspective there is substantial evidence to support these claims; a 2000 review found that no single groundfish species was considered overfished by accepted standards (Witherell, et al., 2000) – this when many of the world's fisheries are struggling to rebuild struggling marine populations. The quantity and quality of scientific research, conservative catch and bycatch quotas and a strong system of monitoring and enforcement are all to credit for this legacy of successful biological management.

However, from an economic perspective, there are a number of elements of the management system for groundfish and bycatch, in particular the use of common pool quotas for target and PSC species, that give us reason for pause.[48] As noted by Homans and Wilen (1997), the success of a system of fishery management cannot be judged merely upon its ability to maintain "healthy" stock levels. The propensity of the management system to foster the generation of economic rents and minimize the costs of management is also important.

By placing both catch and bycatch in the public domain where "first in time, first in right" is the de facto rule of ownership, we argue that regulators have created a perverse environment in which fishermen engage in a mutually-destructive "race for bycatch" that each fisherman would prefer to avoid but nevertheless find individually profitable given the overarching incentive structure. The successive chapters analyze this structure from both theoretical and empirical perspectives. However, before embarking on these analyses, a simple examination of the track record of fisheries management in the head and gut groundfish fishery is warranted. To accomplish this, we focus on an important targeted species for this particular fleet, yellowfin sole.

### 2.4.1 The Yellowfin Sole Fishery

Figure 2.9 shows the annual TAC for yellowfin sole in the Bering Sea alongside the actual total catch for the years 1993-2004. It is immediately clear that the catch of yellowfin sole has fallen well short of its quota in all but the most recent years. This shortfall is telling given the

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[48] Our focus in this chapter, and indeed the entire dissertation, is on the incentive problems associated with the common quota system for bycatch and targeted species. We take as given the regulatory goals underlying the setting of catch and bycatch TACs and their allocation across targets and gears in order to maintain this focus. There are considerable reasons, nonetheless, to question the allocation process. In particular the parsing of halibut TAC between the targeted halibut and groundfish fleets seems to favor halibut fishermen at the considerable expense of allocative efficiency. See Spencer, et al. (2002) and Larson, et al. (1996).

conservative TACs relative to the estimated abundance of yellowfin sole in this time period, the relatively strong export markets for flatfish products and the presence of more than ample capacity to harvest the TAC in the time allotted.

The primary reason for this shortfall is shown in Figure 2.10. The bycatch of Pacific halibut by the groundfish trawl fleet has shown a recurrent pattern of meeting or exceeding its PSC quota allocation well before the yellowfin sole TAC is closed to binding. As a result fishermen find themselves precluded from targeted fishing for yellowfin sole over the entire grounds for weeks at a time due to restrictions on directed fishing. These restrictions, when placed in the context of other contemporaneous strictures, often cause fishermen to either radically alter their targeting practices toward other, less profitable, species or else to exit the fishery entirely. The losses that arise from these closures are substantial. Tens of thousands of metric tons of sustainable yield are frequently left un-harvested on an annual basis with foregone revenues often exceeding 20 million dollars.[49]

The manner in which these closures unfold is actually a bit more complex than hitherto suggested. Rather than provide a blanket allocation of halibut quota at the beginning of the season, regulators actually parse the quota into sub-seasonal allocations. Closures are then enforced based on these sub-allocations where any under or over-utilization in a period is carried forward to the next.[50] This process began in 1994 when the halibut TAC for yellowfin sole was divided into two allocations – one to last through July and another forAugust through December. Later, in 1996, the first sub-season was elongated slightly into the first third of August and then divided into three unequal seasons supported by their own PSC allocations, thus leading to a

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[49] This estimate is based on multiplying the gap between yellowfin sole TAC and catch by the real weight equivalent price of one of its most common products (kirimi). The real weight equivalent (RWE) price accounts for the product-specific loss of catch weight due to processing. Calculated lost revenues range between a modest $58,000 in 2002 (where all but 100 mt of TAC were harvested) to over $74,000,000 in 1993 where an un-fished 81,000 mt of TAC and a strong kirimi price of over $920/mt (RWE) are jointly responsible.

[50] However, any under or overfishing relative to the total PSC quota does *not* carry forward to the subsequent season. There is, accordingly, little incentive to leave unfished bycatch quota at the end of a season.

grand total of four separate sub-seasons. The evolution of the seasonal division of available quota and the relative sizes of the sub-allocations (which vary little in a proportional sense from year to year) is depicted for two typical years by the red dotted lines in Figure 2.11 and Figure 2.12.

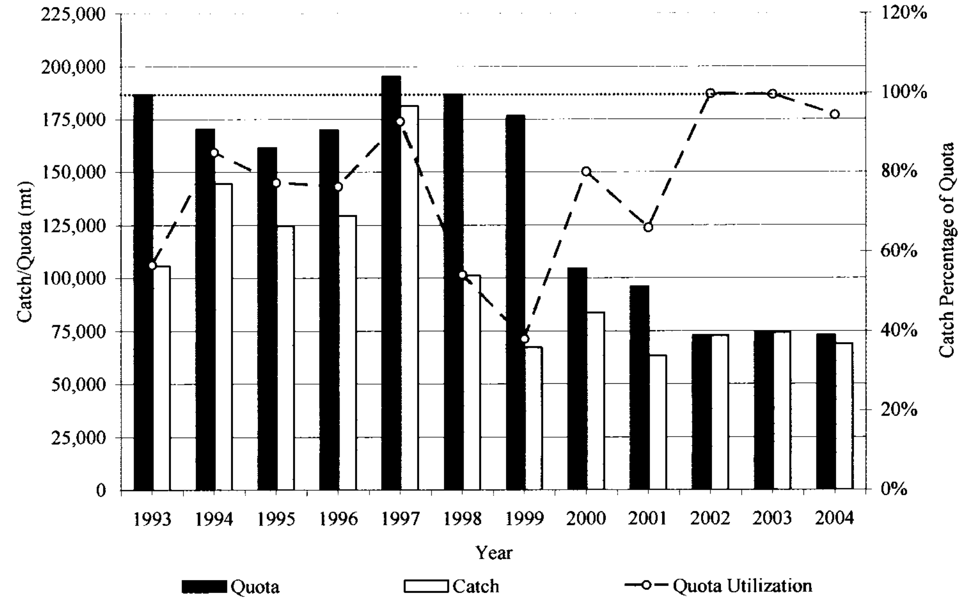

Figure 2.9: Annual Catch, Quota and % Quota Utilization of Yellowfin Sole in the BSAI

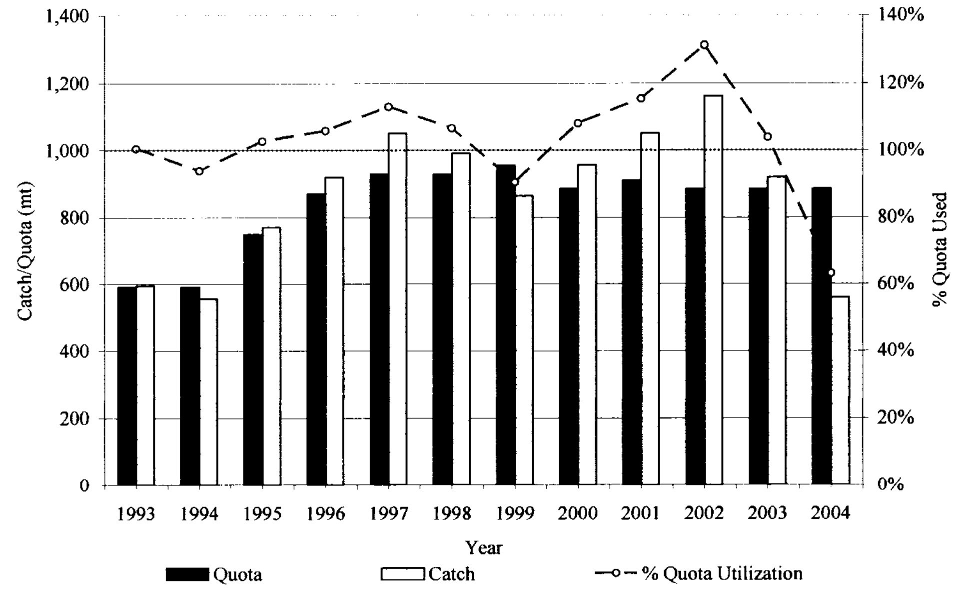

Figure 2.10: Annual Catch, Quota and % Utilization of Halibut PSC Quota for the Yellowfin Sole Target Category

These divisions of the season are largely intended to guarantee the availability of necessary PSC quota throughout the season. Nevertheless, as suggested by Figure 2.11 and Figure 2.12, the legacy of the common quota system has been weeks, if not months, of closures due to halibut bycatch.[51] Inadequate allocations of halibut bycatch TAC relative to its abundance is likely partially to blame for these outcomes – it has been alleged by both fishermen and scientists that halibut biomass rose in the BSAI throughout the 1990s and the current decade although there are few reliable estimates of halibut biomass for this region of the North Pacific. The rigid nature of the regulations for setting the halibut groundfish TAC does not allow for an adaptive ratcheting of the PSC quota, with the likely outcome that certain fisheries have become increasingly constrained by complementarities in their production of target catch and bycatch. Nonetheless, it is likely that there is something far more pernicious at work in the yellowfin sole fishery. Namely, the pooling of bycatch quota combined with a biophysical setting that makes the avoidance of this bycatch costly (both in direct terms and in terms of foregone targeted catch) has created a setting where fishermen compete against one another for a slice of the bycatch "pie". The result is one in which the bycatch rate is well above that which the fleet as a whole would prefer for the maximization of their joint profits. This "race for bycatch" has been noted and decried by both industry representatives (Gauvin, et al., 1995, Gauvin and Rose, 2000) and scientists involved in fishery management (Marasco and Terry, 1982, Trumble, 1998, Witherell and Pautzke, 1997). Furthermore, similar incentives and outcomes have been noted in other fisheries in the North Pacific, such as those for Pacific cod, rock sole and rockfish.

The common quota system has far reaching deleterious consequences for other aspects of fishery management as well. For instance, the deadweight losses of monitoring and fishery enforcement may be substantially augmented as a result of this institutional structure. This may be partially attributed to an increased incidence of fraudulent or deceptive fishing practices but is

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[51] There have also been occasional closures due to bycatch of *C. bairdi* tanner crab in Zone 1. However, these closures only restrict retention of yellowfin sole within Zone 1 itself and are thus relatively minor compared to halibut closures which affect the entire Bering Sea.

also due to the difficulties of keeping pace with the rapid pace of catch and bycatch fostered by the derby system. Figure 2.11 and Figure 2.12 provide evidence of this inability in the substantial overshoot of catch relative to quota in several instances. Regulators hope to implement closures before dramatic overages occur, but the accumulation of bycatch simply outpaces their ability to update their estimates of cumulative catch.

Another symptom of the common pool quota system is the dramatic decrease in yellowfin sole TAC in the years after 2000. This decrease, although concurrent with a small decrease in the assessed biomass, is simply not justifiable based on this decrease alone – the ratio of TAC to ABC (an indicator of the percent of "full utilization" allowed by regulators) fell from 98% in 1999 to 64% in 2000 and remained low in the years thereafter. Over this same interval, several other species at "healthy" levels (such as pollock and cod) were allocated TACs exactly equal to ABC. The difference between these species and yellowfin sole is that their fisheries had not shown a historical inability to harvest their entire TAC due to PSC limitations. Given the 2 million mt cap on removals from the BSAI, it is therefore of little surprise that the Council saw fit to reallocate this valuable unused asset to fleets that would actually profit by it. In a "use it or lose it" system of allocation, fleets that race for bycatch may find themselves increasingly marginalized.

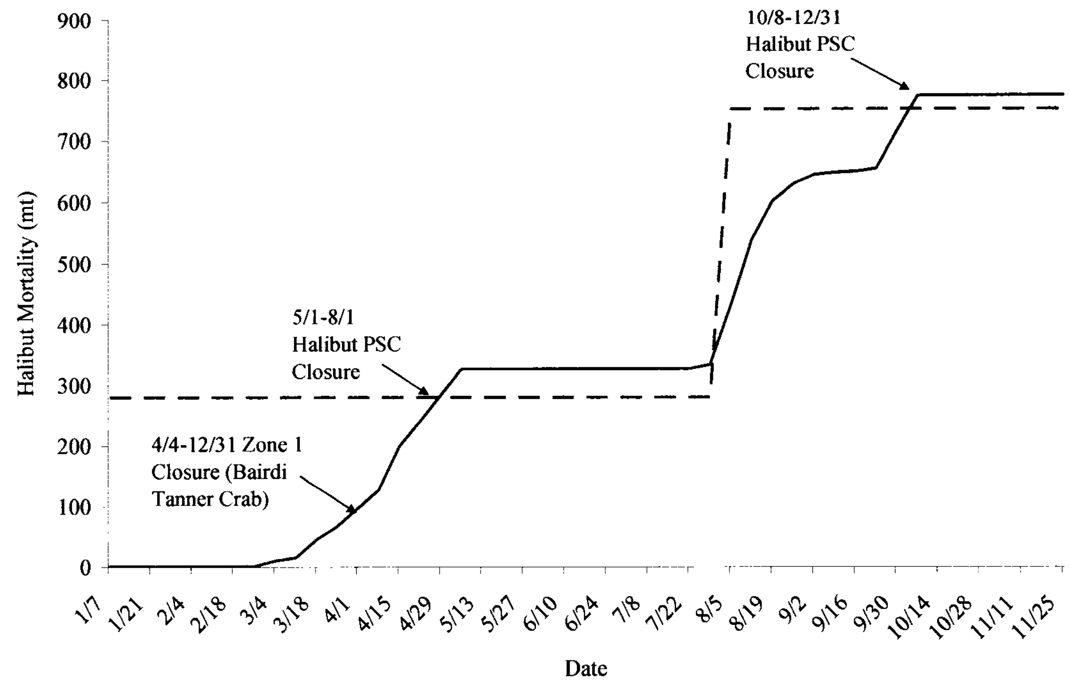

Figure 2.11: Weekly Accumulation of Yellowfin Sole Halibut PSC Catch (blue line) vs. Available Quota (red line) for 1995

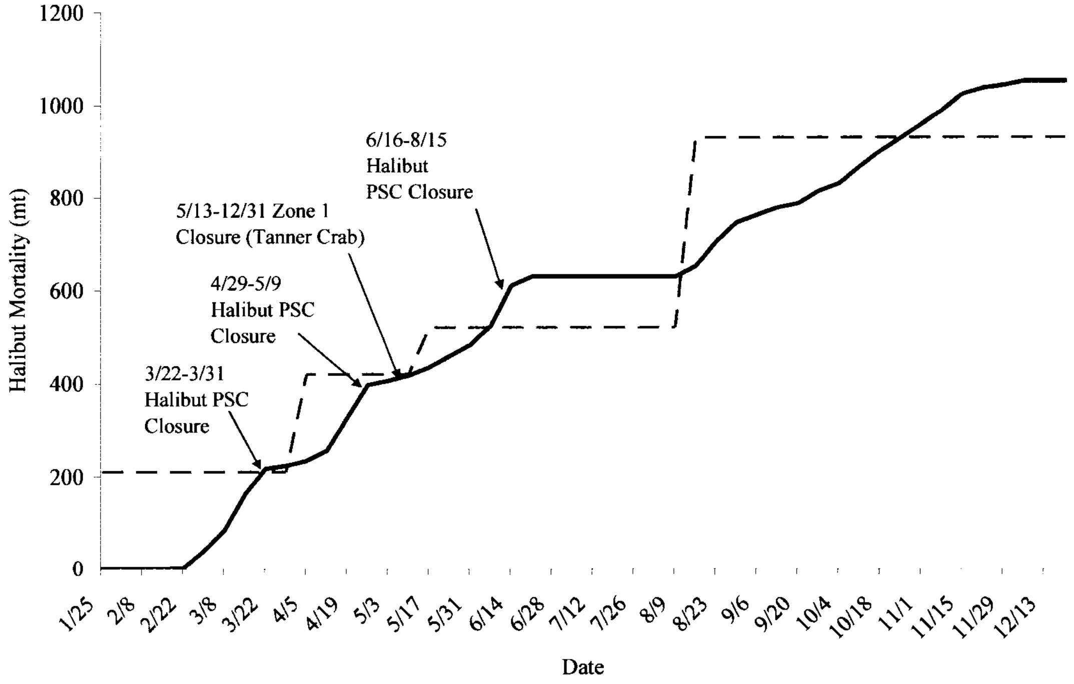

Figure 2.12: Weekly Accumulation of Yellowfin Sole Halibut PSC Catch (blue line) vs. Available Quota (red line) for 1997

### 2.4.2 The Response of Regulators – The Vessel Incentive Program

It would be a mistake to infer that regulators in the North Pacific have failed to see the problems inherent in the common quota system. Indeed, from the early years of the domestic fishery the NPFMC sought to provide groundfish fishermen with incentives to curb their bycatch. In 1990 the Council entertained a number of options, the foremost of which was the so-called "penalty box". This plan required that any vessel whose bycatch rates of crab or halibut were greater than two times the concurrent fleet average be suspended for between five days to six weeks. These suspensions were to be served immediately within the season in question. Ultimately, however, this plan failed to win approval from the Secretary of Commerce as it was found to be inconsistent with a variety of regulatory guidelines. In particular, there were a number of concerns with the use of unverified observer data for purposes of inseason enforcement (Renko, 1998).

Given the rejection of the penalty box program, the NPFMC implemented an alternative measure known as the Vessel Incentive Program (VIP) in 1991. Under this policy, acceptable bycatch rates are declared at the beginning of the season for particular target species and times of the year. Observer data is then used to calculate the monthly bycatch rate for each vessel in the relevant fisheries. Those vessels with bycatch rates in excess of the published standards are considered candidates for enforcement action.

The enforcement mechanism is via civil penalty, and it is this feature of the program that appears to be its Achilles' heel. It takes NMFS approximately three to four months following a supposed violation to collect and verify the onboard observer data (including the sampling methods employed by the observer); only then can NMFS even notify the vessel of its violation and the potential for legal action. Following this notice, NMFS must then decide whether to form a case against the vessel.

Given the burden of proof of the civil procedure, observer sampling methods and data must be subjected to a battery of tests; unfortunately, a number of these validity criteria can be influenced by the crew during the observer sampling process. Given the inherent variation in even the best of sampling protocols and the considerable demands placed on observers at sea (see Chapter 4), it should come as no surprise that many cases have not proceeded due to perceived inadequacies in the data relative to the burden of proof. This situation has been exacerbated by the high costs of civil procedures relative to internal enforcement measures and limited personnel and resources within NMFS for prosecuting such cases.

As of 1998, only two VIP penalties had survived the appeals process with penalties in the range of $100,000 (Renko, 1998, Trumble, 1998). The apparently small probability of punishment combined with fines that, while substantial, are not likely to offset the perceived gains from infractions seems to bode poorly for the success of the VIP. The program is widely considered a failure, both among fishermen and the Council itself, and its repeal is being considered by the NPFMC at the time of our writing due to its costliness and lack of any demonstrable proof of improvement in fishermen's incentives for bycatch avoidance. Accordingly, we have chosen to disregard this program in the ensuing analysis.

### 2.4.3 The Response of Fishermen – Sea State

Tired of premature closures due to PSC species, the head and gut fleet banded together in 1995 to hire a private company, Sea State, Inc. of Seattle, to establish an information system to rapidly assimilate and relay information from the onboard observer program to fishermen on the grounds. Under this program, information on PSC bycatch, including the location of the catch, the estimated quantity of bycatch and fishing effort (tow duration), is submitted on a daily basis via satellite to Sea State where it is pooled with information from all other participating vessels to provide summary maps of bycatch rates over space along with commentary by Sea State's owner, Karl Haflinger, on trends in bycatch hotspots and possible actions for skippers to undertake to reduce their bycatch.[52] These data services are relayed on a daily basis, or even faster, to participants via email.

The use of Sea State by fishermen in the head and gut fleet began in 1995 with the winter rock sole fishery for the avoidance of red king crab bycatch. By receiving pooled information on hotspots, fishermen are able to utilize the information to move to other grounds with much lower takes of crab and to exert pressure on their colleagues to do the same. The results for this fishery have been dramatic. Fishermen credit the program with a sevenfold decrease in the take of red king crab in its first year (Gauvin, et al., 1995), and these reductions have persisted in subsequent years, albeit not at quite the levels achieved in the infancy of the program (see Figure 2.13). The result of these gains, as depicted in Figure 2.14, has been a dramatic reduction in the take of red king crab – thus avoiding the massive bycatch overages of previous years. The results for season length have been dramatic as well with the roe season expanding by days or even weeks. Given that daily gross revenues for a single vessel in the rock sole fishery are about $50,000 per day and that Sea State charges an average annual fee of $2,000 for its services (Gilman, et al., 2006), the program appears to have dramatically improved outcomes for the rock sole fleet.

The implementation of Sea State for the avoidance of halibut bycatch in the yellowfin sole and other late-season groundfish fisheries seems to have been less successful – at least when viewed from trends in average bycatch rates. There are a number of subtleties involved in addressing the success of the program in this context, however, and we withhold judgment until we address these at length in Chapter 6. The success of the cooperative information sharing arrangement in the context of the rock sole fishery is telling, nonetheless. It suggests that the "tragedy of the commons" predicted by economic models may not be inevitable when a small and

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[52] The array of services provided by Sea State has expanded somewhat over time. In recent years, for instance, participants have received lists on a periodic basis of the bycatch rates of all other participating vessels. This has allowed skippers to identify "clean" and "dirty" fishermen and single them out for either informal sanction or reward.

stable group of participants are able to band together and police themselves for the achievement of a mutually beneficial end (Ostrom, 1990).

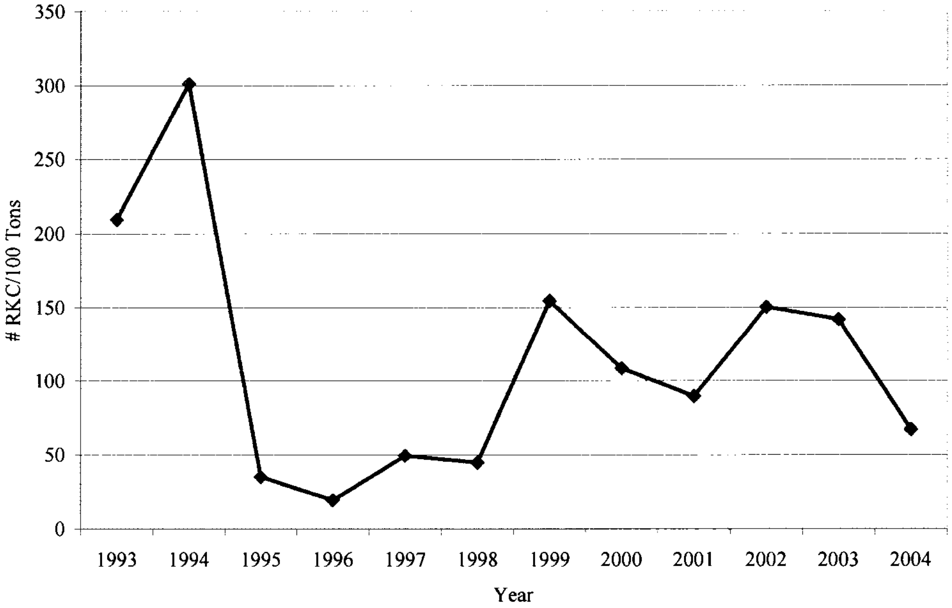

Figure 2.13: Bycatch Rate of Red King Crab for Rock Sole Fishery

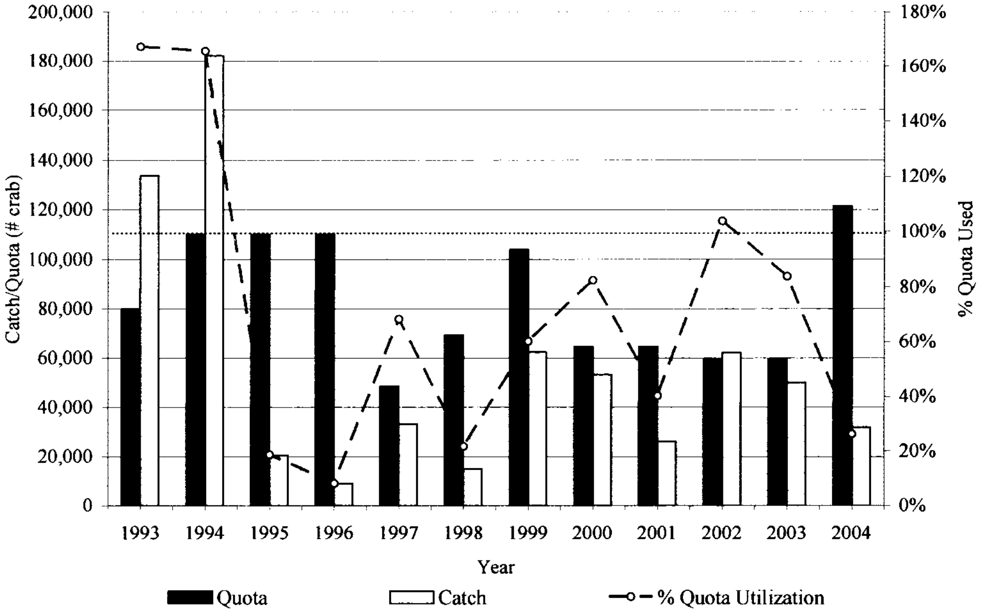

Figure 2.14: Annual Catch, Quota and % Utilization of Red King Crab PSC Quota for the Rock Sole & Other Flatfish Target Category

## 2.5 Conclusion

This chapter has set the stage for the analytical chapters to follow by describing the spatiotemporal patterns of fishing effort in the Bering Sea head and gut fleet and how these patterns are shaped by the seasonal distribution of targeted species and by regulatory restrictions on where fishing can occur and on what species can be retained for processing and landing. We have also described the system of multiple common pool catch quotas on both targeted and prohibited species and have provided historical evidence that this system of management produces distortionary effects on incentives for bycatch avoidance. In the following chapter we develop a simplified analytical model to precisely characterize the incentives and outcomes forthcoming under this system of management and to elucidate possible solutions to the common property dilemma.

# Chapter 3

# A Model of Joint Harvesting of Target and Bycatch Species With Common-Pool Output Quotas

As noted in Chapter 1, much of the established economic literature on bycatch has focused on somewhat polar examples (e.g. first best optimum or IFQs vs. open access) of fishery management institutions rather than the complicated "middle ground" that usually characterizes real-world fisheries. Many fisheries, such as the North Pacific head and gut fleet described in the previous chapter, the swordfish longline fleets of the Hawaiian Islands and the New Zealand squid fisheries operate under limited access systems wherein a restricted group of users competes with imperfectly selective gear under multiple fleet-wide quotas on both catch and bycatch species. This combination of limited participation, imperfectly selective gears, and common property quotas opens up the interesting possibility of strategic behavior in the harvest decisions of fishermen.[53] In such cases, fishermen know that regulators will either close or drastically curtail the target fishery when one of the quotas becomes binding. This fact gives fishermen the incentive to consider, if only partially, the impact of their harvest behavior –conditional on the anticipated behavior of their competitors – on the equilibrium season length. This strategic behavior, when wedded to the complexities inherent in joint production, may yield a rich array of behaviors. Illuminating the connection between regulatory institutions, fishermen's incentives and bycatch outcomes in this context is a worthwhile undertaking, not only for understanding the

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[53] Strategic behavior in the arena of bycatch and discards is not a foreign topic in the literature. Herrera (2005) and Jensen and Vestergaard (2002) consider the problem of strategic interactions between catch-discarding fishermen and a regulator; however, their work concerns the moral hazard problem that arises due to imperfect observability of catch to regulators whereas ours focuses on the intra-seasonal game played between fishermen and between fishermen and regulators even when complete and perfect information is available on all sides. In some fisheries (such as many in the EU) this moral hazard problem is likely significant due to a lack of extensive onboard monitoring and enforcement while in still others (as in that of our case study) it may be of lesser importance.

status quo, but also to aid in the development of more effective policies for solving the bycatch policy problem.

To this end, we develop a simple static game in which fishermen jointly harvest a target and a bycatch species in a setting where the avoidance of the bycatch species entails increased costs in terms of foregone target species harvest. Regulators observe fishermen's behavior and close the fishery when either the predetermined target or bycatch quotas bind for the industry. In the first section we lay out the model structure and solve the quota-constrained social planner's problem. In the second section we present the symmetric, pure-strategy Nash equilibrium to the game theoretic model and show how it relates to the optimal solution. The third section explores the significance of our findings by considering the effects of changes to the policy variables and by exploring the nature of the remedies needed to bring the non-cooperative behavior of fishermen into accord with the objectives of the social planner. Section 4 concludes the analysis.

## 3.1 The Model and the Quota-Constrained Optimum

Assume for a particular season there are *N* vessels operating in the fishery. The vessels and their captains are homogeneous in all respects and they face no significant stock or congestion externalities and intra-seasonal discounting of rents is minimal so that a static modeling framework can be reasonably employed. We also presume that unavoidable fixed costs coupled with the costs of reconfiguring capital ensure that fishermen remain in the fishery and do not alter their gear in the course of a season so that only variable revenues and costs are salient to decision making. At the beginning of the season, captain *i* makes a choice of the quantity of target species to harvest ($h_X$) on a daily basis, limited by restrictions of gear, fishing time, and the intrinsic productivity of the grounds so that $0 \le h_X \le \overline{h}$.

There is a corresponding level of bycatch ($h_B(h_X)$) associated with this choice of harvest. This function has the following properties:

*Assumption 3.1.* $h_B(0) = 0, \qquad h_B^{'} > 0, \qquad h_B^{''} > 0$.

This assumption describes bycatch as the unavoidable complement of the harvest of the targeted species. Furthermore, this incidental catch increases at an increasing rate with the rate of harvest. These technological assumptions imply that the avoidance of bycatch necessitates that a greater degree of care be exercised in the pursuit of the target species, thus slowing its rate of harvest. For instance, in a heterogeneous marine environment, overlapping habitat and feeding preferences may cause population densities of bycatch and target species to exhibit a high overall degree of spatial correlation. Seeking out local exceptions to this global tendency may entail substantial investments of time, and even when such low bycatch areas are found, they may possess lower densities of the targeted species.[54]

This technical description has an analogous relationship to the prototypical model of the polluting firm (a relationship first noticed by Boyce (1996)). Captains may only avoid pollution (bycatch) at the expense of harvest, and the marginal cost of "abatement" (the value of the foregone catch) is increasing as fishermen strive to fish in a "cleaner" fashion.

To simplify the derivations of the mathematical solutions to the problem, we propose the following simple form for the bycatch function:

$$h_B(h_X) = bh_X^{\alpha}, \qquad b > 0, \qquad \alpha > 1. \tag{3.1}$$

Fishermen supply their harvest for which they obtain a fixed price $p$, which is the market ex-vessel price net of the costs of any on-ship processing. They also face a direct unit cost for the sorting and discard of bycatch; we represent these costs by $c$. Seasonal variable rents are thus:

$$\pi(h_X) = ph_X - ch_B(h_X). \tag{3.2}$$

---

[54] This spatial motivation for bycatch avoidance has a respectable empirical basis. Adlerstein and Trumble (1998a, b) find substantial evidence of spatial and temporal patterns which might be exploited to avoid halibut bycatch in the Bering Sea groundfish fisheries. The voluntary establishment of spatial bycatch control systems (e.g. Gauvin et al. (1995)) lends further support to the supposition that fishermen can affect their bycatch rate for a given gear configuration through the careful choice of fishing location.

Note that this function is concave, although not necessarily increasing, for all feasible values of $h_X$. Notice the absence of any direct costs for the harvest of the target species. This reflects our assumption that once a captain has committed to full participation in the fishery – as indeed he must given his assumed lack of short-run flexibility – there is no obvious relationship mapping the expenditure of variable inputs (such as fuel) to fishing output. Notice as well the lack of any revenue from the catch of the bycatch species. This assumption is maintained for the sake of clarity of the analytical results and also to reflect the nature of many fisheries in which the landing of certain bycatch species is either economically prohibitive or (as in our case study) expressly forbidden.

The regulator is charged with the task of enforcing quotas on both the target and bycatch species which are denoted by $Q_X$ and $Q_B$ respectively. They accomplish this by manipulating the season length, $T$. They perfectly observe the daily harvest and bycatch of all fishermen and close the entire fishery when either one of the quotas is met or the maximum season ($\bar{T}$) is achieved. This decision rule (in effect the reaction function of the regulator) can be written as follows:

$$T(h_X^1,\dots,h_X^N,Q_X,Q_B,\bar{T})=\min\left\{ {Q_X}\Big/{\sum_j h_X^j},\ {Q_B}\Big/{\sum_j h_B(h_X^j)},\ \bar{T}\right\}. \tag{3.3}$$

Before presenting the solution to the social planner's problem, we find it convenient to make the following simple assumption:

*Assumption 3.2:* $N \geq \max\left\{ {Q_X}\Big/{\bar{T}h_{\max}},\ {Q_B}\Big/{\bar{T}h_B(h_{\max})}\right\}$ *where* $h_{\max}=\min\{\bar{h},h_{\pi\max}\}$

*and* $h_{\pi\max}=\arg\max \pi(h_X)$.

This assumption assures that there is sufficient participation in the fishery so that both quotas can be exhausted when all vessels harvest at their maximum rate – so that the use of quota regulation is in some sense "justified" by the size of the fleet. This maximum rate may be less than the physical upper bound on harvest if the daily profit function peaks at a value ($h_{\pi\max}$) that is less than $\bar{h}$. In this instance, it is never sensible, either in the social planner or noncooperative case, for a vessel to harvest on the decreasing arm of the daily profit function since doing so will only result in a lose-lose situation of lower daily profits and a shortened season. Assumption 3.2 is of some use in the following derivations as it allows us to eliminate *a priori* uninteresting cases in which both quotas are slack.

This formality aside, we can now express the objective function of the quota-constrained social planner:

$$\max_{h_X} \ \min\left\{\frac{Q_x}{Nh_X}, \frac{Q_B}{Nh_B(h_X)}, \bar{T}\right\} * N\pi(h_X) \quad s.t. \quad 0 \le h_X \le \bar{h}. \tag{3.4}$$

The planner maximizes seasonal rents subject to the constraints of the quota allocations and the maximum season length. Note that Assumption 3.2 precludes any case in which $\bar{T}$ binds alone.

Given the concavity of daily profits, it is clearly optimal to harvest at a minimal rate such that one of the quotas just binds at the maximum season length. From the vantage of the entire fishery, the marginal benefits from cutting back on harvest – the increases in profits from a longer fishing season – always exceed the costs incurred from smaller daily harvests. This logic is expressed mathematically in the following theorem:

*Theorem 3.1: The quota constrained optimal program ($h_X^*, T^*$) is as follows:*

$$h_X^* = \frac{Q_X}{N\bar{T}}, \quad T^* = \bar{T} \quad if \quad N \ge \frac{1}{\bar{T}}\left[\frac{bQ_X^\alpha}{Q_B}\right]^{\frac{1}{\alpha-1}}$$

$$h_X^* = \left(\frac{Q_B}{bN\bar{T}}\right)^{\frac{1}{\alpha}}, \quad T^* = \bar{T} \quad if \quad N \le \frac{1}{\bar{T}}\left[\frac{bQ_X^\alpha}{Q_B}\right]^{\frac{1}{\alpha-1}}.$$

Notice that the determination of the binding quota is dependent upon the number of active vessels in the fishery. Large numbers of fishermen only need to harvest at a low intensity for a quota to bind by $\bar{T}$. Low rates of harvest also correspond to regions of low bycatch rates and so $Q_X$ binds. Obviously, the larger the relative magnitude of $Q_X$ to $Q_B$ the larger the range of fishery sizes for which $Q_B$ binds and vice versa. Finally, it should be noted that these conditions necessitate a steady *decline* in the optimal rate of harvest, and also the bycatch rate, as $N$ increases. *High bycatch rates are solely a phenomenon of lightly capitalized fisheries when the fishery is managed optimally.*

## 3.2 The Nash Equilibrium Solution

Of course, under the incentive structures existing in most commercial fisheries, the social planner's harvest profile is of little relevance since fishermen compete without secure access privileges for the allowable harvest quota. Total industry-wide quota allocations in many scientifically managed fisheries are fairly transparent and are announced prior to the opening of the season. As a result, we should expect that fishermen would incorporate the quota rule into their decision processes. Formally speaking, the objective for fisherman $i$ is:

$$\max_{h_X^i} \quad T(h_X^i, h_X^{-i}, Q_X, Q_B, \overline{T}) \cdot \pi(h_X^i) \qquad s.t. \qquad 0 \le h_X^i \le \overline{h} \tag{3.5}$$

where $h_X^{-i}$ is a $(N\text{-}1)x1$ vector of the harvest choices of other fishermen. The game is played in two stages. In the first stage – presumably happening just prior to the opening of the season – fishermen simultaneously choose their daily harvest rate for the season while taking into account the anticipated actions of their competitors and the decision rule of the regulator. In the second stage, the regulator closes the fishery as mandated by this rule.[55] The equilibria we henceforth describe as Nash equilibria are thus actually subgame-perfect equilibria, although in a trivial sense as the "reaction function" of the regulator is predetermined by his legal role in the system rather than arising from the consideration of his own preferences.

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[55] Notice that regulators exactly enforce quota rules and are thus immune to any pressure from the industry to protract the season. In fisheries with well-established scientific management practices where regulatory hierarchies separate the tasks of quota setting and enforcement (as in the federal fisheries off Alaska) this may be the case. Deviations of total catch from quota nonetheless occur but are typically the result of imperfect systems of catch accounting and regulatory control rather than the results of political corruption. Wilen and Homans (1998) develop a model in which both biological and political criteria affect management.

For the sake of simplicity, we consider only symmetric, pure strategy Nash equilibrium solutions. Therefore, in equilibrium all fishermen select a single daily harvest rate that is in their best interest *given the exact same behavior on the part of their competitors.* Furthermore, the fishermen's shared conjecture of the binding season length and quota are supported in equilibrium by the induced behavior of the regulator. If a fisherman foresees that a particular quota will bind in equilibrium, then the agent's reaction function is defined by the first order condition:

$$T(h_X^i, h_X^{-i}) \cdot \pi'(h_X^i) = -\frac{\partial T(h_X^i, h_X^{-i})}{\partial h_X^i} \cdot \pi(h_X^i). \tag{3.6}$$

The choice of harvest rate is thus determined by a tug-of-war between the marginal benefits of increased daily profits – the left hand side of (3.6) – and the *personal* marginal costs due to a reduction in fishing opportunities from an increase in the harvesting rate. Fishermen do not, however, consider the external costs of their choice on the remainder of the fleet.

Despite the appealing simplicity of the preceding result, there are various features of the individual decision problem that prevent it from serving as an adequate characterization of an agent's reaction function. Firstly, constraints on the maximum season length and harvest rate may lead to cases in which (3.6) cannot be satisfied. Secondly, the regulatory decision function, although continuous in $h_X$ is not differentiable at the breakpoints between quotas. This implies that agents, when faced with the choice of selecting a harvest rate that alters the binding quota regime, must conduct a non-marginal comparison of whether such a shift is in their best interest.

Figure 3.1 reveals the substance of these observations in graphical form for the choice of parameter values given in Table 3.2 and with $N$=2 (motivation for these particular parameter values will be supplied in the next section). The first panel shows a particular vessel's profits as a function of its own harvest and that of its competitor. A close examination of this graph reveals that rather than being smooth, it is actually perforated by multiple ridges. The exact nature of these ridges is clearly revealed in the second panel which shows the level sets of the individual profit function. The third panel in the figure demonstrates that these kinks in the level sets are essentially borders between regimes in the quota system that hold for particular values of own and competitor harvest. By finding the highest point on the profit surface (i.e. the highest level set) for each level of competitor harvest, we can effectively define the reaction function of the fisherman – as demonstrated in both the second and third panels of Figure 3.1. A glance at this reaction function shows a number of distinct "phases" through which a reaction function typically passes; understanding each of these phases is useful for comprehending the decision process of fishermen and the nature of the Nash equilibrium.

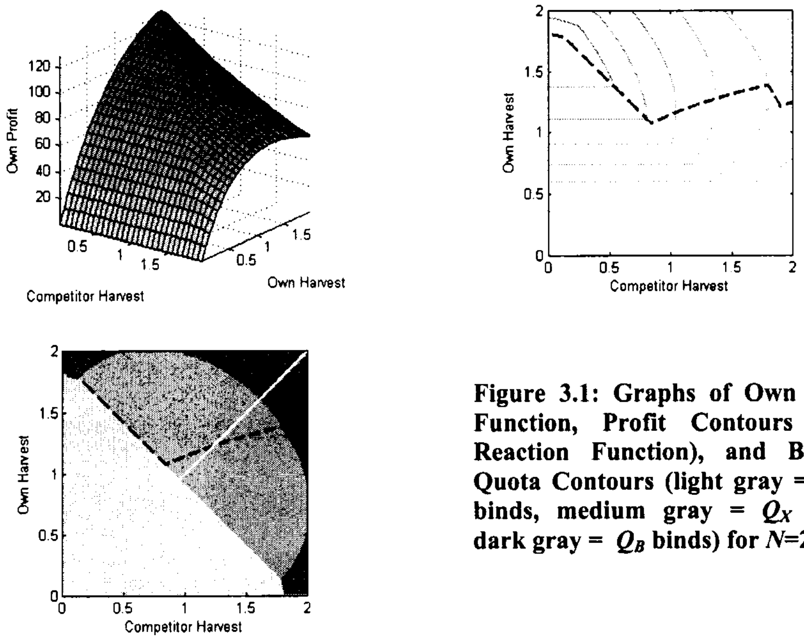

**Figure 3.1: Graphs of Own Profit Function, Profit Contours (with Reaction Function), and Binding Quota Contours (light gray = Tbar binds, medium gray = $Q_X$ binds, dark gray = $Q_B$ binds) for $N$=2.**

Note first, that for small rates of competitor harvest, it is possible for our fisherman to cause $Q_B$ to bind alone. However, the agent optimally chooses instead to harvest along the knife-edge of the $Q_B$ / $\overline{T}$ boundary – reacting to increasing conjectured harvest on the part of his competitor by decreasing his own catch. Recall from the social planner case, that the system-wide marginal benefits of increasing harvest are always exceeded by the marginal costs of doing so. When the competitor harvests very little, then our fisherman essentially constitutes the entire fishery and so he internalizes a sufficiently large quantity of the marginal costs of his harvest so that his behavior mimics that prescribed by the social planner. Similar logic applies at the boundary between $\overline{T}$ and $Q_X$. In either case, the constraint on the maximum season length has a positive shadow value – our fisherman is willing to incur a cost proportional to the wedge between the marginal costs and benefits of increased harvest to raise $\overline{T}$. This excess of marginal costs over benefits can be clearly seen in the second panel by noting how, for low levels of competitor harvest, the profit contours are bowed backwards from the cusps along the $Q_X$ / $\overline{T}$ boundary.

Of course this dominant behavior cannot stand in the face of increased competition. The growing rate of harvest of the competitor increasingly dilutes the proportion of the full marginal costs of harvest that are born by the individual so that eventually marginal benefits of increased harvest exceed marginal costs at $\overline{T}$. Then it is no longer individually rational to meet increased competitor harvesting by decreasing one's own fishing. Marginal personal benefits and costs are instead equalized at a season length below the maximum and increases in harvest intensity on the part of one's competitors are responded to in kind. This can be seen in the first increasing stretch of the reaction function in Figure 3.1.

For sufficiently large values of competitor harvest, an individual agent faces a similar scenario to that experienced on the boundary with $\overline{T}$, only now the decision is one of whether to take action (by lowering one's own harvest rate) to preserve a situation in which $Q_X$ binds. Not surprisingly, the decision depends on the relative magnitude of marginal benefits to marginal costs evaluated at $Q_B$ binding. If the marginal costs of harvest exceed the marginal benefits, then the target species quota has a positive shadow value and the agent finds it best to draw back on his own harvest and cling to the razor's edge where both $Q_X$ and $Q_B$ hold simultaneously. This explains the second downward phase of the reaction function along in Figure 3.1. Of course, the "dilution" of marginal costs with increases in competitor harvest continues to apply, and so the captain eventually chooses to raise his effort so that $Q_B$ binds and marginal benefits and costs are once again equalized.

Figure 3.2 presents the same information for the case in which $N = 12$.[56] The first panel clearly shows how even small rates of harvest from the eleven competitors quickly decrease one's own profits while the steep, almost vertical frontiers between quota contours in the third panel show the decreased sensitivity of the realized quota to individual manipulation. The reaction function shows all the same qualitative characteristics as the $N = 2$ case (including a brief and scarcely visible phase along the $Q_B / \bar{T}$ frontier for minute quantities of competitor harvest) with one notable additional feature. Notice how the increase in the function in the $Q_X$ region is eventually limited by the maximum feasible harvest rate. Due to the quantity of competitors and their relatively high rate of harvest, personal marginal costs are driven to a level where they are exceeded by marginal benefits at even the highest harvest intensity. This explains the flat stretch of the reaction function in Figure 3.2.

The symmetric Nash equilibria for both of these scenarios are indicated by the intersection of the reaction function and the 45° line in the third panels of Figures 3.1 and 3.2. When $N = 2$ the equilibrium occurs with both players harvesting at a level such that $Q_X$ binds at a season length less than $\bar{T}$. When $N = 12$ the equilibrium occurs with all players harvesting at maximum capacity with a (much) shorter season than previously. These cases demonstrate two of six qualitatively different equilibrium classes; the various symmetric Nash equilibrium harvest rates along with their necessary and sufficient conditions are presented in Table 3.1 for the most general case in which it is technologically feasible for either $Q_X$ or $Q_B$ to bind.[57] Equilibrium

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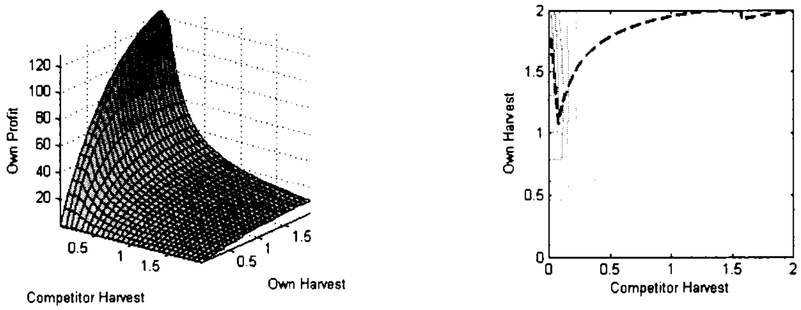
[56] In order to reduce the dimension of this graph to three dimensions, we force the ($N$-1) competitors to act as if they coordinate so as to harvest at an identical rate. Although, not strictly correct in terms of the game-theoretic motivation, no substantial harm arises from this simplification due to our focus on symmetric equilibria.

[57] Formally, this entails that the maximum possible bycatch rate exceeds the ratio of bycatch to target quota, $Q_B / Q_X \leq h_B(h_{\max}) / h_{\max}$.

conditions for the alternative case in which only $Q_X$ can bind as well as proofs for all conditions are presented in Appendix A.



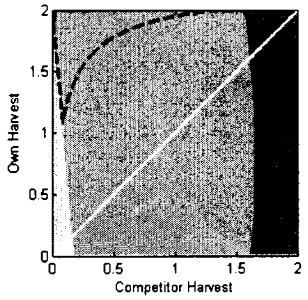


**Figure 3.2: Graphs of Own Profit Function, Profit Contours (with Reaction Function), and Binding Quota Contours (light gray = Tbar binds, medium gray = $Q_X$ binds, dark gray = $Q_B$ binds) for $N$=12.**

While not immediately transparent, these mathematical conditions yield some interesting generalities on closer inspection. Note that for fixed values of the parameters, the determination of the pertinent equilibrium is solely a matter of the number of participating vessels. Indeed, these conditions exhaust the range of fishery sizes fulfilling Assumption 3.2 and never overlap in $N$ such that these conditions yield one and only one Nash equilibrium solution for a given set of parameters.

The equilibria given in the first and fourth rows of Table 3.1 are interior in that marginal *personal* benefits and costs are balanced. They correspond to equilibria occurring in the increasing stretches of the reaction function. Indeed, the equilibrium described in the first row of the table corresponds with that shown in Figure 3.1. Not surprisingly, the equilibrium harvest rate is increasing in the number of participants. Note also that $Q_X$ binds for a smaller range of fishery sizes than does $Q_B$.

Table 3.1: Equilibrium Conditions for Game when Either Quota is Capable of Binding[58]

| Quota | Conditions | $\hat{h}_X$ | $\hat{T}$ |
|---|---|---|---|
| $Q_X$ | $f(p,c,b,\alpha,Q_X,\bar{T}) \le N \le \frac{1-\left({}^{cQ_B}\!/_{pQ_X}\right)}{1-\alpha\left({}^{cQ_B}\!/_{pQ_X}\right)}$ | $\left(\frac{p}{cb}\cdot\frac{(1-{}^{1}\!/_{N})}{(\alpha-{}^{1}\!/_{N})}\right)^{\frac{1}{\alpha-1}}$ | $\frac{Q_X}{N\hat{h}_X}$ |
| $Q_X$ | $\frac{1}{\bar{T}}\left(\frac{bQ_X^{\alpha}}{Q_B}\right)^{\frac{1}{\alpha-1}} \le N \le \min\left\{f(p,c,b,\alpha,Q_X,\bar{T}),\frac{1-\left({}^{cQ_B}\!/_{pQ_X}\right)}{1-\alpha\left({}^{cQ_B}\!/_{pQ_X}\right)}\right\}$ | $\frac{Q_X}{N\bar{T}}$ | $\bar{T}$ |
| $Q_X/Q_B$ | $\max\left\{\frac{1}{\bar{T}}\left(\frac{bQ_X^{\alpha}}{Q_B}\right)^{\frac{1}{\alpha-1}},\frac{1-\left({}^{cQ_B}\!/_{pQ_X}\right)}{1-\alpha\left({}^{cQ_B}\!/_{pQ_X}\right)}\right\} \le N \le \frac{\alpha\left(1-\left({}^{cQ_B}\!/_{pQ_X}\right)\right)}{1-\alpha\left({}^{cQ_B}\!/_{pQ_X}\right)}$ | $\left(\frac{Q_B}{bQ_X}\right)^{\frac{1}{\alpha-1}}$ | $\frac{Q_B}{Nb\hat{h}_X^{\alpha}}$ |
| $Q_B$ | $\max\left\{g(p,c,b,\alpha,Q_B,\bar{T}),\frac{\alpha\left(1-\left({}^{cQ_B}\!/_{pQ_X}\right)\right)}{1-\alpha\left({}^{cQ_B}\!/_{pQ_X}\right)}\right\} \le N \le \frac{\alpha(p-cbh_{\max}^{\alpha-1})}{p-\alpha cbh_{\max}^{\alpha-1}}$ | $\left(\frac{p}{cb}\cdot\frac{(1-{}^{\alpha}\!/_{N})}{(\alpha-{}^{\alpha}\!/_{N})}\right)^{\frac{1}{\alpha-1}}$ | $\frac{Q_B}{Nb\hat{h}_X^{\alpha}}$ |
| $Q_B$ | $N \le \min\left\{\frac{1}{\bar{T}}\left(\frac{bQ_X^{\alpha}}{Q_B}\right)^{\frac{1}{\alpha-1}},\frac{\alpha\left(1-\left({}^{cQ_B}\!/_{pQ_X}\right)\right)}{1-\alpha\left({}^{cQ_B}\!/_{pQ_X}\right)}\right\}$ *or*<br>$\frac{\alpha\left(1-\left({}^{cQ_B}\!/_{pQ_X}\right)\right)}{1-\alpha\left({}^{cQ_B}\!/_{pQ_X}\right)} \le N \le g(p,c,b,\alpha,Q_B,\bar{T})$ | $\left(\frac{Q_B}{bN\bar{T}}\right)^{\frac{1}{\alpha}}$ | $\bar{T}$ |
| $Q_B$ | $N \ge \frac{\alpha(p-cbh_{\max}^{\alpha-1})}{p-\alpha cbh_{\max}^{\alpha-1}}$ | $h_{\max}$ | $\frac{Q_B}{Nb\hat{h}_X^{\alpha}}$ |

The conditions in the second and fifth rows describe corner solutions in which the season length constraint has a positive shadow value. The case in which $Q_X$ binds clearly maps to lower values of $N$ than its interior analog. Intuitively, this equilibria occurs when an alternative "equilibrium" at the interior harvest rate would lead to a slack quota at season's end; as a result,

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[58] The implicit functions $f(\cdot)$ and $g(\cdot)$ are defined, respectively, as the values of $N$ such that the interior equilibrium season lengths evaluated at the internal solution values of $\hat{h}_X$ for $Q_X$ and $Q_B$ (as found on the 1st and 4th rows of Table 1) will equal $\bar{T}$.

individuals have an incentive to nudge their effort upward until the target quota is exhausted just as $T = \overline{T}$. The fifth row shows two cases in which $Q_B$ binds at $T = \overline{T}$. The first condition implies values of $N$ that are not only too small for an interior $Q_B$ solution but are also too small for $Q_X$ to bind in any equilibrium (interior or not). The second set of conditions describes a situation in which $N$ is too large for a $Q_X$ equilibria (in other words, the "peak" of the objective function occurs at a value of $h_X$ that is beyond the range of harvest rates for which $Q_X$ binds) and yet too small for an interior equilibrium in $Q_B$ to bind in $T \leq \overline{T}$. In either of these cases, a symmetric Nash equilibrium occurs where the harvest rate just exhausts $Q_B$ at $\overline{T}$. Note how for both the $Q_X$ and $Q_B$ corner solutions, the equilibrium harvest rate is decreasing in fishery participation as prescribed by the social planner's solution. Indeed the symmetric Nash equilibrium harvest rates for these two cases correspond exactly with those of the social planner's solution – albeit for fisheries of limited size.

The solution depicted in the third row occurs for an intermediate range of $N$ and reflects a situation in which $N$ is too large for $Q_X$ to bind and yet too small for $Q_B$ to hold in either an interior sense or with $\overline{T}$ binding. In this case the quota on the target species possesses a positive shadow value and so the equilibrium harvest rate is invariant over a range of fishery sizes. This equilibrium occurs in the downward sloping phase of the reaction function along the $Q_X/Q_B$ frontier shown in Figures 3.1 and 3.2.

The sixth row solution reflects a situation in which the fishery is sufficiently large so that marginal benefits cannot be reconciled with marginal costs for the bounded range of possible harvest rates. In this case (which corresponds to the graphical situation depicted in Figure 3.2) fishermen are compelled to harvest at the maximum possible rate throughout the season. We may therefore expect that for fisheries over some critical participation threshold (the value of which is given in row 6 of Table 3.1) an increase in the number of competitors will carry no significant behavioral effects, at least in the short run, although the length of season and average rents will continue to decline with entry.[59]

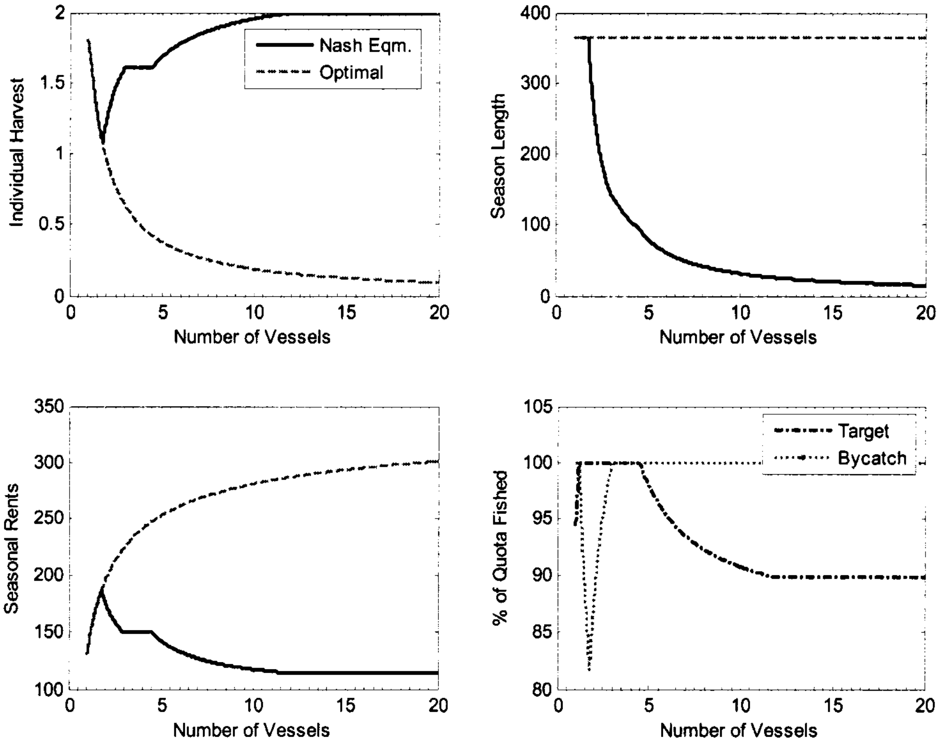

Figure 3.3: Nash Equilibrium and Optimal Harvest, Season Length, and Rents and Percentage of Quotas Fished Under the Nash Equilibrium Solution for Various Fishery Sizes.

Figure 3.3 provides a graphical depiction of the spectrum of symmetric Nash equilibrium harvest rates, season lengths and total rents for a range of fishery sizes and compares their values against those associated with the social planner's solution. It also displays the percentage of each quota harvested in equilibrium for every case. The parameter values used for this simulation are presented in Table 3.2 and were chosen so that sorting and discard costs are relatively high while ensuring that daily profits are strictly increasing over the range of allowable harvest rates.

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[59] A word of caution is warranted. If the curvature of the daily profit function is such that $h_{\max} = h_{\pi\max}$ then the right hand side of the participation condition in Table 3.1 goes to infinity showing that the $Q_B$ interior solution has no upper bound. Intuitively, given even an infinitesimal personal marginal cost of increased harvest (as is the case with large numbers of competitors), it always pays to stop short of maximizing daily profits.

Qualitative observations on real-world fisheries suggest that the costs of sorting and discard of bycatch species are typically quite low relative to the extra revenues obtained from the associated target harvest and so our parameterization is deliberately skewed from this reality in order to give fishermen the strongest possible incentives to avoid bycatch. Figure 3.4 shows the bycatch rates obtained at different harvest levels for the given values of quota allocations and technological parameters. This parameterization is suggestive of a fairly "clean" technology and generous allocation of bycatch quota; only by harvesting at greater than 80% of one's daily capacity can the bycatch rate exceed the ratio of bycatch to target quota. Again, these parameterization decisions are motivated by a desire to test the common quota system under conditions which are most conducive to its success.

Despite the relatively high cost of discard, efficient technology and fairly generous specification of quota, we nevertheless discover that the bycatch quota binds rather quickly. Indeed, a fishery of five participants is sufficient to cause bycatch to bind exclusively while twelve participants drive the harvest rate to its upper bound.[60] When very small numbers of fishermen participate in the fishery, the equilibrium harvest rates correspond to those given by the quota-constrained social optimum and so they decrease with increased participation. (This only happens for values of $N$ less than 1.8 in this case, but there is no reason to believe that two or more fishermen may not harvest optimally under a different parameter specification.) Very soon, however, the lack of full internalization of the marginal costs of harvest begins to manifest itself, leading to a phase in which $Q_X$ binds in an interior fashion before entering a brief transitional plateau (between $N = 3$ and 4.5) in which both quotas bind and harvest rates are inelastic with respect to changes in fishery participation.

The effects of this lack of cost internalization are evident in the equilibrium season length and total variable rents. As $N$ increases, season durations fall very quickly below the optimal

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[60] In an effort to emphasize the transition between the different solution phases shown in Table 3.1, we represent $N$ as a continuously varying quantity although Nash equilibrium solutions for non-integer values of $N$ lack a clear interpretation in this model.

level, simultaneously opening a chasm between the rents obtainable if the social planner's recommendations were implemented and the level achieved when fishermen act non-cooperatively.

The common allocation of quota creates an interesting variant of the "tragedy of the commons". The essence of this tragedy is not, as has been casually suggested, that bycatch quota binds well before all of the target quota can be fished. At most, this is a symptom (albeit a strongly suggestive one) of the underlying disease, and, as shown in Figure 3.2, its absence does not indicate that all is well. The essence of the tragedy lies in the mutually destructive *incentives* generated by the common quota structure that cause fishermen to increasingly ignore the effects of their behavior on the equilibrium season length. The result leads inexorably (with the rare exception of extremely small fisheries) to wasted quota of either bycatch or target species and sub-optimal rents due to shortened seasons and excessive costs of sorting and discard.

The fact that bycatch quotas are more often reached before target quotas than vice versa may, as fishermen and biologists often claim, have something to do with the imperfect nature of their gear and the inadequate share of bycatch quota allowed by regulators. However, the results of this analysis demonstrate that the perverse incentives generated by the regulatory system can easily overwhelm the advantages of clean fishing gears and liberal allocations of bycatch quota.

Table 3.2: Base Parameter Values for Policy Simulations

| | | | |
|---|---|---|---|
| $B$ | 0.45 | $\alpha$ | 1.5 |
| $Q_X$ | 700 | $Q_B$ | 400 |
| $P$ | 0.5 | $c$ | 0.5 |
| $\bar{T}$ | 365 | $\bar{h}$ | 2.0 |

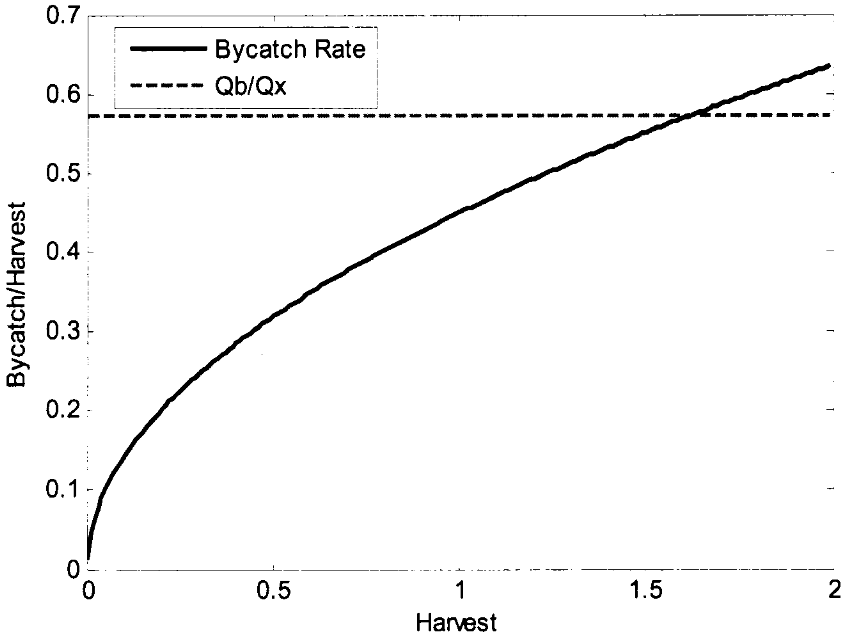

Figure 3.4: Bycatch Rate for Various Harvest Rates at Base Parameter Values

## 3.3 Model Sensitivity and Policy Considerations

To explore the implications of perturbations in the parameters of the model, we now utilize the initial values in Table 3.2 as our point of reference and conduct sensitivity analysis.[61] We consider the effects of changes in prices and bycatch disposal costs, quota allocations, and technological parameters.

### 3.3.1 Changes in $p$

Figure 3.5 shows the equilibrium harvest rates for a spectrum of fishery sizes using the reference price level and values above and below it. It is immediately obvious that increases in the price of the targeted species typically increase the harvest rate and thus the rate of bycatch; note the dramatic escalation of harvest to its maximum level at less than four vessels when $p$=0.6. Recall from Theorem 3.1 that the social planner's harvest rate exhibits no dependence on the

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[61] A MATLAB program that utilizes the analytical conditions in Table 3.2 to produce the graphical output in this paper is available upon request.

level of economic parameters such as prices or discard costs – it only depends on technological and policy parameters. In contrast, under a regulated equilibrium with common quotas, positive price shocks for the targeted species amplify the perverse incentives of fishermen and further widen the gap between optimal and Nash equilibrium rents.

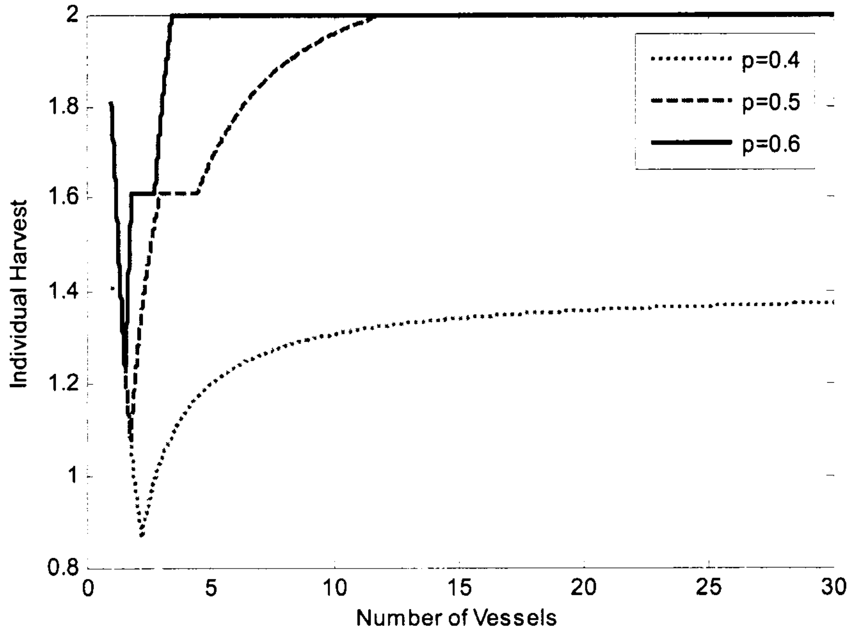

Figure 3.5: Nash Equilibrium Harvest Rates for Various Target Species Prices

When prices fall to a sufficiently low level (such as $p$=0.4 in Figure 3.4) an unusual phenomenon occurs. The low price relative to the marginal costs of bycatch causes the peak of the daily profit function to occur within the feasible range for $h_X$. As a result, the equilibrium harvest rate approaches (but never exactly reaches) $h_{\pi \max}$ as the size of the fishery grows. This implies that even "large" fisheries may exhibit some behavioral response in harvest and bycatch rates as $N$ varies when prices are sufficiently low.

What are the implications of these findings? First, when fisheries are of small or moderate size we can expect that fluctuations in the price of targeted species have a marked effect upon harvest and bycatch behavior. Secondly, when fisheries have a large number of participants and prices are relatively high compared to discard costs, we can expect that significant increases or moderate decreases in prices will have little or no behavioral impact. (This effect can be seen for $N>12$ when $p$ fluctuates between 0.5 and 0.6.) However, negative price shocks that drive price below a critical threshold will always have a behavioral impact, regardless of the level of active capacity in the fishery.

### 3.3.2 Changes in technological parameters

A decrease in $b$ reduces the bycatch rate experienced for any level of targeted harvest. This parametric change seems to closely approximate the nature of many alterations to gears that are made to reduce bycatch. For instance, the use of technologies that rely upon size or behavioral differences between species to reduce bycatch (e.g. Bublitz (1996), Stone and Bublitz (1996) and Gauvin and Rose (2000)) typically result in the escapement of both targeted and bycatch species. However, as long as the rate of escape for bycatch exceeds that of the target, without regard to how or where the gear is used, then a decrease in $b$ captures this effect in a qualitative sense. By controlling which gears are acceptable for use in the fishery, regulators may attempt to reduce equilibrium bycatch, lengthen fishing seasons and, hopefully, increase rents.

Figure 3.6 shows the results of various mandated technology changes that are depicted by shifts in $b$. Note that "cleaner" technologies actually induce higher harvest rates of the target species. This occurs because a decrease in $b$ lowers the effective marginal cost of a unit of harvest. The increased incentive to harvest generally outweighs the increase in harvesting efficiency so that increases in the cleanness of technology typically lead to *decreases* in the equilibrium season length. There are limitations on the range of circumstances over which this result occurs, however. When the decrease in $b$ is implemented from an already low level and $b$ drops to a point where bycatch can no longer bind (as in the change from $b$=.45 to $b$=.35) then the resulting increase in harvest may be sufficiently small (due to the bound on the maximum harvest rates) to cause equilibrium seasons to increase versus the status quo for larger fishery sizes. This can be seen in the fourth panel of Figure 3.6.

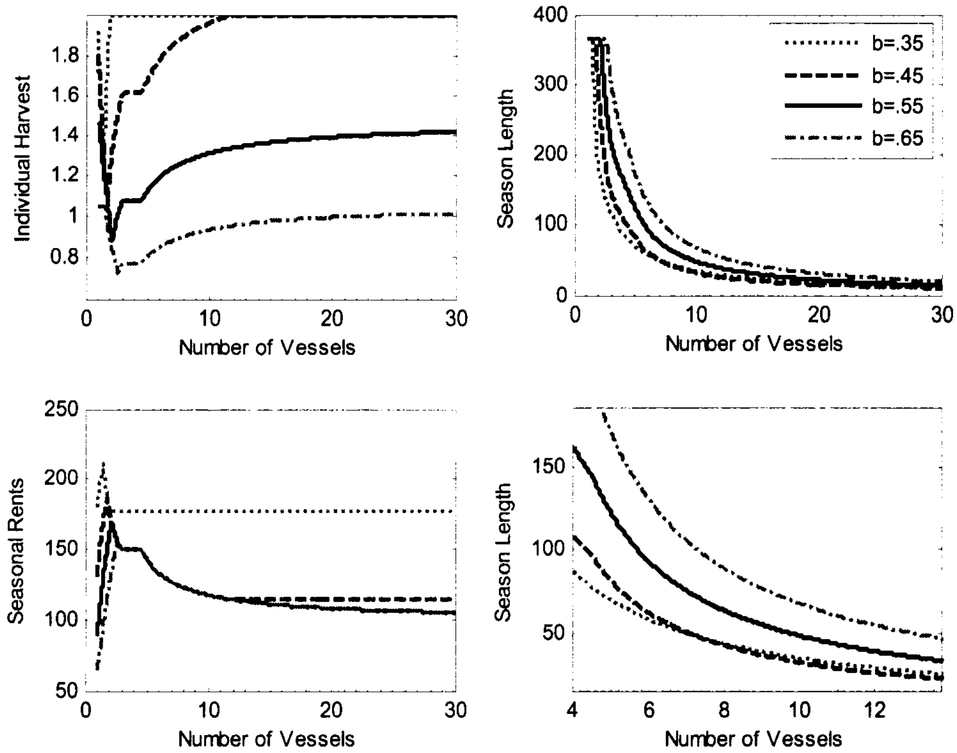

Figure 3.6: Nash Equilibrium Harvest, Season Length, Rents, and Season Length (detail) for Differing Values of $b$

The effect of increased selectivity on rents is similarly mixed. Consider when $N>5$ in Figure 3.6. If $b$ is sufficiently large to cause $h_{\max} = h_{\pi \max}$ then marginal improvements in harvesting efficiency (as when $b$ falls from .65 to .55) yield no improvement in rents – the increased harvest and lowered costs of discard are exactly offset by the reduction in season length. However, if the improvement in bycatch efficiency is large enough to drive the equilibrium harvest rate to its maximum level for a particular $N$, then average rents may increase.

The implications for fishery management may be summarized as follows. First, when starting with very "dirty" technology, mandating a small improvement in efficiency/selectivity will, at best, yield a modest increase in average rents and result in a shorter season. Second, moderate improvements from a low level of efficiency may yield some increase in average rents but usually only for fisheries with a reasonably large number of participants. Third, the larger the proposed increase in efficiency, the greater the range of fishery sizes that will exhibit an increase in rents. Finally, these increases in rents are somewhat artificial because they are due to the constraining effects of the physical limits on harvest that prevent agents from fully equalizing marginal benefits and costs and thus fully dissipating the potential gains from the new harvesting technology. If the marginal benefits substantially outweighed marginal costs in equilibrium, then we might expect increased investment in harvesting capacity in the future in an attempt to capture these potential rents.

This discussion of rents also ignores the additional costs of purchasing and operating the new technology which may overwhelm any increase in variable rents. Ward (1994) utilized a dynamic, multi-fleet model to show that decreases in bycatch species catchability are likely to exhibit few long-run benefits due to the compensating effects of increased effort in the targeted fishery for the bycatch species. Our results complement this conclusion by suggesting that technological improvements may be of limited utility even when considered from a short-run perspective and where no targeted fishery for the bycatch species exists. Furthermore, the ultimate lack of any improvement in rents from widespread adoption of more efficient gears suggests that there may be limited incentive for rational, forward-looking fishermen to invest in or assist in the development of such technologies.

The results for perturbations of $\alpha$, as shown in Figure 3.7, are similar in many respects to those for $b$. This similarity is driven by the fact that both $b$ and $\alpha$ have a positive effect on the marginal cost of harvest. As a result, increases in $\alpha$ (at least for moderate to large fisheries) result in decreases in daily harvests and thus longer seasons. A notable difference, however, between this case and that for $b$ is that rents actually *increase* rather than decrease in $\alpha$.

What is the real-world analog to changing $\alpha$? On first glance it seems difficult to imagine a modification of fishing gears that does not confound a change in $\alpha$ with what is more adequately and intuitively captured by a simple change in $b$. In real-world situations, however, the quantity and composition of catch are a result of interaction between the production possibilities of the gear and the "raw materials" supplied to this production process by the ecological system the gear is utilized within. Perhaps then, $b$ and $\alpha$ may be roughly decomposed along these same lines with $b$ representing the intrinsic efficiency of a particular fishing gear and $\alpha$ capturing the effect of intrinsic characteristics of the physical/biological system – particularly those aspects associated with the spatial cross-correlation of species densities.

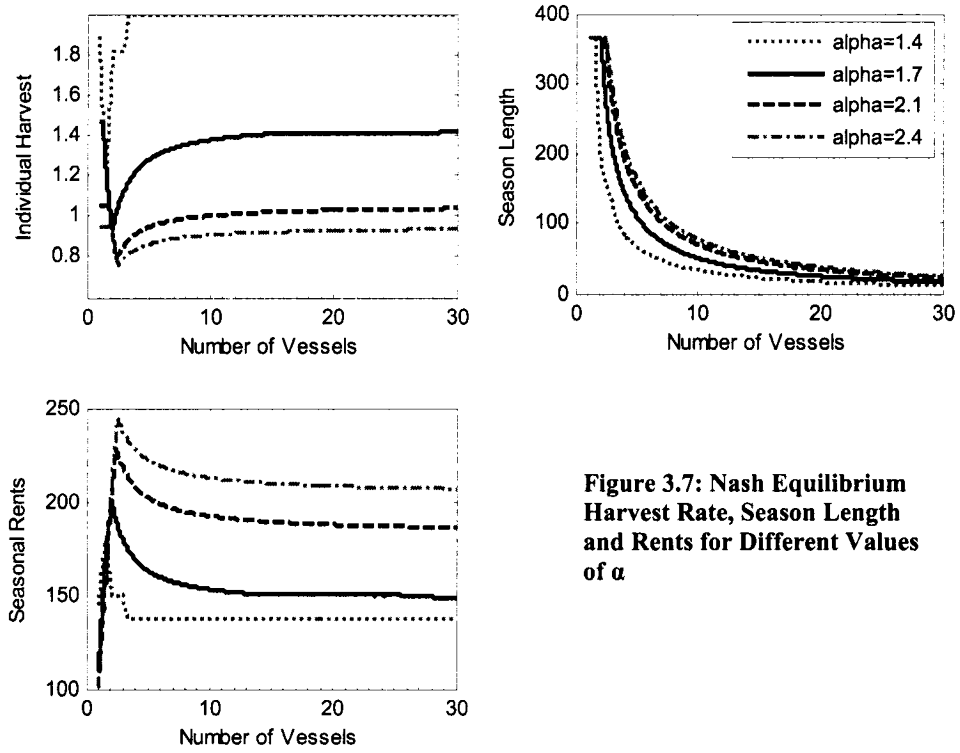

**Figure 3.7: Nash Equilibrium Harvest Rate, Season Length and Rents for Different Values of $\alpha$**

Consider Figure 3.8. Note how when $\alpha$ is large that high daily harvests of the target are associated with very large bycatch rates whereas bycatch rates at low harvest levels are actually quite low. If a fisherman can be expected to fish in a single locality for any given day then the bycatch rate and harvest recorded for that day are indicative of the relative biomass of the species at that point. It therefore follows that large values of $\alpha$ coincide with high degrees of spatial cross-correlation in bycatch and target densities; on average unusually large bycatch densities are associated with especially dense concentrations of target species and vice versa.

Surprisingly, this spatial autocorrelation in bycatch and targeted species turns out to be a positive characteristic that leads to more conservative harvest behavior and increased rents. The pursuit of attractive "clusters" of target in a high-$\alpha$ situation carries with it the strong possibility that the harvest of those clusters will result in significant costs to oneself. Low $\alpha$ fisheries, those with less clustering together of bycatch and target species assemblages, weaken this behavioral nexus since, on average, the penalty for exploiting high-density areas is lower.

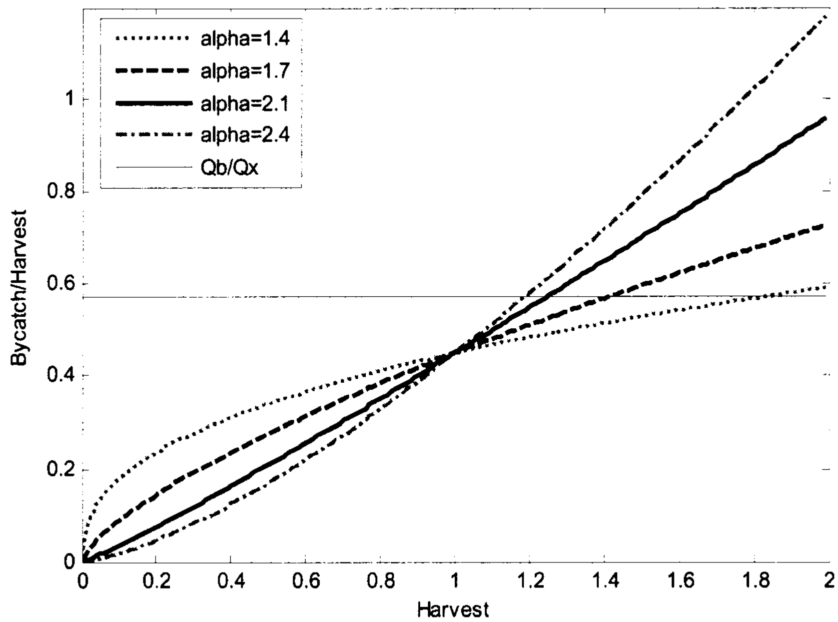

Figure 3.8: Comparison of Bycatch Rates as α Changes.

### 3.3.3 Changes in quota allocations

Given the short-run nature of this model, the technological parameters ($b$, $\alpha$ and $\bar{h}$ ) are intrinsically dependent upon the quantity and distribution of biomass for bycatch and targeted species. In most (but not all) modern industrialized fisheries the total allowable catch (TAC) is predetermined based on biological criteria and competing fleets expend substantial time and resources lobbying regulators over how to divide this fixed pie (or, rather, a series of such pies). It is of some value then to ask what would happen if a fleet obtained more or less quota apart from any underlying changes in the biomass that would justify such an alteration.

Since bycatch is the limiting factor for even comparatively generous allocations of $Q_X$ and "clean" fishing technologies, we limit our discussion to the impact of changes in $Q_B$. Figure 3.9 shows the results of three different quota allocations, one more liberal than in our base specification and another less so. It should be noted that the highest allocation of $Q_B$ is so large that it is no longer technologically feasible for the bycatch quota to bind at any level of harvest.

The result of increasing the quantity of bycatch quota is to (weakly) increase the harvest rate for any fishery size – this despite the fact that for all but the smallest $N$ the optimal harvest rate should be invariant with respect to $Q_B$ (see Theorem 3.1). Note, however, that moderate increases in quota (those that preserve the possibility of bycatch binding) lead to no differences in harvest behavior for fisheries of sufficient size. If $Q_B$ is raised to the point where it can no longer bind, then target quota binds for all fishery sizes and fishermen are driven to exert even larger amounts of effort than they would have otherwise.

The impacts on equilibrium rents and season lengths are ambiguous for a limited range of fishery sizes; an increase in quota could lead to an equilibrium with lower rents and a shorter season than the status quo! Nevertheless, as the size of a fishery grows, a clear pattern of increased rents with increases in bycatch quota emerges; otherwise, we would be hard-pressed to explain the pervasive desire of fishermen to expand their bycatch quota. This loosening of the constraints on fishermen does narrow the gap between optimal and non-cooperative rents, but the potential for improvement is limited. Once bycatch quota is sufficiently plentiful that it can no longer bind, increased allocations yield no behavioral effect and the noncooperative outcome remains suboptimal for virtually all fishery sizes.

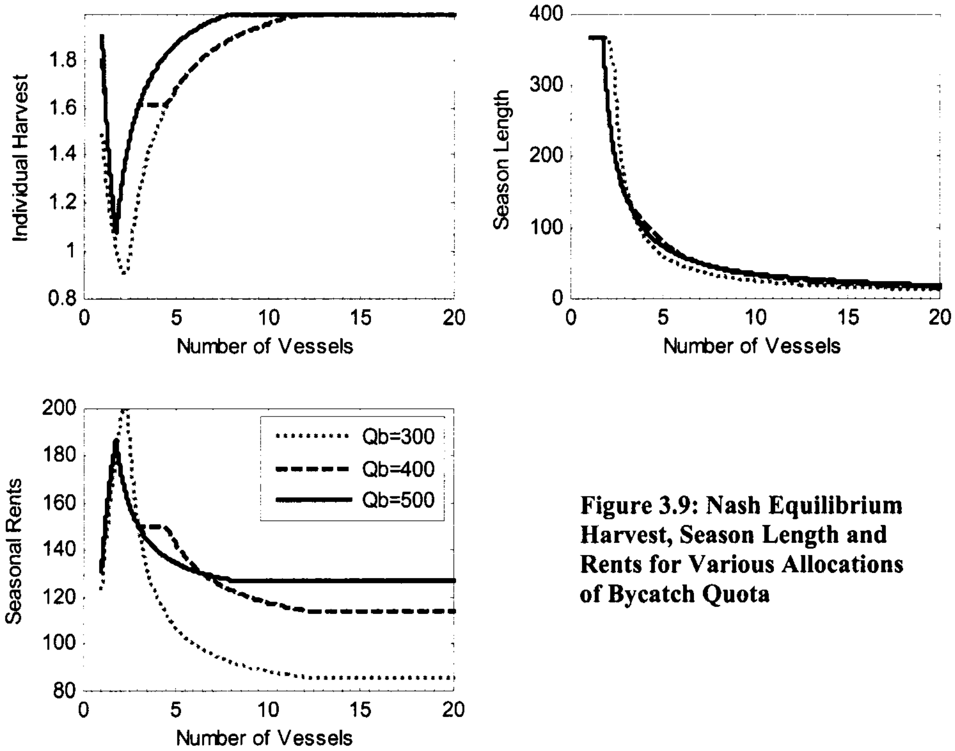

**Figure 3.9: Nash Equilibrium Harvest, Season Length and Rents for Various Allocations of Bycatch Quota**

### 3.3.4 The optimal penalty for bycatch

A cursory examination of the necessary conditions in Table 3.1 suggests that the effects of an increase in *c* and a decrease in *p* are qualitatively the same. This is indeed the case, and so we do not consider the effects of fluctuations in this parameter. Rather, we examine how *c* might be exploited as a policy instrument.

We have motivated *c* as the internal "production" cost of bycatch due to sorting and discards, but any cost of bycatch that is born on a per-unit basis will exert an equivalent effect. Consider then an "effluent penalty" $\tau$ on bycatch so that the full personal cost of bycatch is $c + \tau$. At what level must this penalty be set to cause the Nash equilibrium to mimic the social planner's solution? How do changes in economic, technical and regulatory parameters alter the penalty?

For the sake of brevity, we consider only the case where the fishery is large enough such that $Q_X$ binds for the social planner.[62] The task then is to adjust the penalty so that the conditions for the equilibrium described in the second row of Table 3.1 are always satisfied. The minimum penalty required to accomplish this feat is, not surprisingly, the Pigouvian tax where the marginal benefits of increased harvest just equal the personal marginal costs (penalty included) at the optimum season length of $\bar{T}$ (i.e. at the transition between the first two equilibria in Table 3.1). Setting $\hat{T} = \bar{T}$ and solving for $\tau$ yields:

$$\tau = \frac{p\left(1 - \frac{1}{N}\right)}{b\left(\alpha - \frac{1}{N}\right)}\left(\frac{\bar{T}N}{Q_X}\right)^{\alpha-1} - c\,. \tag{3.7}$$

This penalty is increasing in the price of the targeted species and decreasing to the extent that high costs of sorting and discard already supply some disincentive to high bycatch rates. Relatively inefficient gears (those characterized by high values of $b$) actually necessitate lower unit penalties since the disincentive toward more rapid harvest is magnified via $b$ in the marginal cost function. An increase in the allocation of target quota will also lead to a decrease in the optimal $\tau$ for a given fishery size. Not surprisingly, the optimal bycatch penalty is increasing in the number of fishery participants; the decreased "internalization" of the season-length externality with increased $N$ ensures this result.

In this discussion we have acted as if there is a single optimal penalty for a particular situation, and yet this is not the case. There are actually a range of penalties in excess of (3.7) that would work equally well in inducing optimal behavior, although (3.7) does so at least cost to the fishermen. The indeterminate nature of the optimal penalty occurs because all that is needed is a sufficiently large penalty to cause the season length constraint to have a non-negative shadow value at the optimal harvest rate (in other words, to cause the marginal costs of additional harvest

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[62] Little is lost by this simplification; the case for $Q_B$ binding is quite similar. Moreover, in practice $Q_X$ typically begins to bind for very small values of $N$ at a variety of reasonable parameter values (for $N > 1.19$ for the parameter values in Table 2).

to exceed the marginal benefits). One offshoot of this result is that penalties that are set a bit high for the current situation are then robust (in the sense of maintaining optimal behavior) for slightly larger or smaller fisheries or for local variations in parameters.[63]

Throughout this discussion we have utilized the term "penalty" instead of "tax". This is intended to highlight the fact that although this penalty clearly resembles the classic Pigouvian tax, we need not limit ourselves to it exclusively. Indeed, given the assumptions of the model, the bycatch penalty could be assessed via other mechanisms and that yield the same result. For instance, fishermen could be compelled to purchase quota for every unit of bycatch they expend and $\tau$ would represent the appropriate quota price (and the market equilibrium price in a perfectly competitive quota market). Alternatively, $\tau$ could represent the monetary equivalent of the mutual "social pressure" that must be brought to bear by their peers on individual vessels for each excess unit of bycatch in order to induce optimal harvest and bycatch behavior (where fishermen perfectly observe each other's catch and can be relied upon to administer the proper punishment). Finally, a cooperative could be formed where equal allocations of target and bycatch quota are distributed among members according to their harvest of each species in the optimal solution. It can be shown that atomistic behavior on the part of fishermen will then lead to the optimal outcome.[64] Figure 3.10 shows the harvest rate, optimal penalty and total rents for the Nash equilibrium solution when the optimal penalty is applied and the revenues collected from the penalty are re-distributed in an incentive compatible fashion to fishermen. Note the now perfect correspondence between the optimal and Nash equilibrium solutions.

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[63] There is a limit to this robustness. If a penalty is set too high then the argmax of the daily profit function may fall below the minimum level needed to exhaust $Q_X$ in $\overline{T}$. This would result in leaving behind unfished quota at the end of the year which is clearly suboptimal.

[64] All of these instruments have focused on penalizing bycatch and have ignored the fact any penalty instrument on bycatch has an equivalent instrument for the targeted species due to the precise nature of their complementarity in this model. We have chosen to ignore this since such a relationship would cease to exist in many real-world situations where multiple bycatch species are associated with a single target. In these cases, a single instrument on the target would be inadequate to induce efficiency unless the bycatch species were all perfectly complementary with one another.

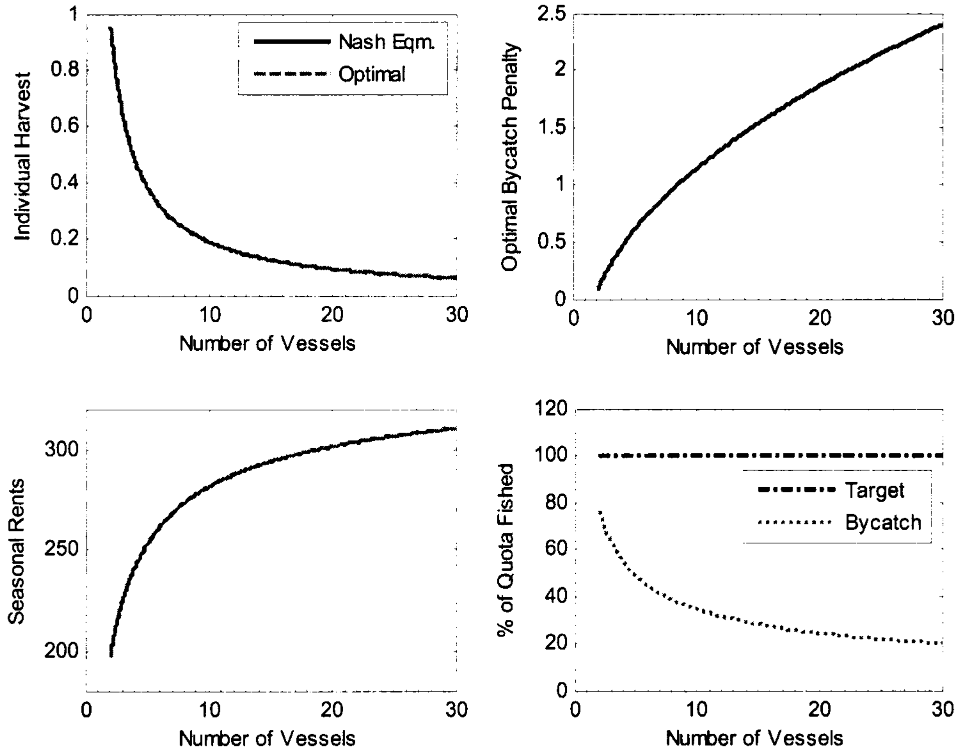

Figure 3.10: Nash Equilibrium Harvest, Rents and Quota Utilization Compared Against Social Planner Levels when the Optimal Bycatch Penalty is Assessed.

## 3.4 Conclusions

The yellowfin sole fishery in the Bering Sea is but one example of many multispecies fisheries in the world currently governed under the common quota system for both target and bycatch species. Many fisheries for cod, rock sole, various flatfish species and rockfish in Alaska and elsewhere are governed by similar regulatory systems and have been plagued by many of the same problems. These fisheries are mostly license-limited, with species and gear “endorsements” that permit vessels to pursue various target/bycatch combinations in specific areas and at specific times with specified gear. Such fisheries range in size from small (eg. wreckfish fishery with 4 vessels, atka mackerel with 6 vessels, the pre-coop pacific whiting fisheries with 4 companies) to medium (pre-coop Bering Sea pollock fishery with 8 companies, the pacific cod hook/line catcher vessel fishery with 5-15 vessels), to larger (pacific cod catcher/processor with 40). With numbers of participants in these size ranges, it is clearly plausible to conjecture that decision making may be strategic rather than atomistic.

We have developed a model that explains characteristics of these and other similar fisheries governed by multiple common pool quotas. The model shows how changes in key parameters can change the nature of Nash equilibrium harvest, season length and rents – generating predictions that point the way to testable empirical hypotheses and providing further insights into the linkages between behavior, technology, regulations, and fishery performance. An important insight from this exercise is the identification of yet another form of rent dissipation associated with insecure harvest privileges. In this case, there is a "race for fish" in a joint production setting that triggers common pool regulation reactions by regulators. These regulations are well intentioned in the sense that they are designed to prevent biological overharvesting of both the target and bycatch species, and common pool quotas and season closure instruments are generally successful in this regard when properly monitored with timely information dissemination.[65] However, while common pool quotas may be effective in addressing biological objectives, they exacerbate rather than solve the fundamental economic problem of insecure harvesting privileges to both catch and bycatch stocks. The fruit of this system is rent dissipation on a number of fronts, from wasted target quota, high discard costs, and shortened seasons (which we have modeled here) to more far-reaching effects such as congestion costs, losses in the product market from reduced product quality, skewed product mixes and flooding of the market.

Our model ultimately raises the question of how to best regulate bycatch in complex multispecies fisheries. A look through most of the fisheries science and management literature would persuade the reader that the problem is really a technical problem, solvable mainly by the development of alternative gear. But our model suggests that observed bycatch is actually a

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[65] Of course, this success is only valid when viewed from a single-species paradigm of management. If quotas are obtained with the goal of managing assemblages of species, then harm may arise on an ecosystem scale from substantial underfishing of some quotas relative to others.

much more complicated outcome of gear design, spatial ecology, regulations, and ultimately, of human strategic behavior. Furthermore, to the extent that private incentives are required to develop and adopt "clean" harvesting technologies, we have found analytical support for the hypothesis that such incentives are probably lacking under systems with insecure harvest rights. All this suggests that the range of policy options must encompass strategies that go beyond simple technological options and that further analytical and empirical work is needed to assess the merits and drawbacks of incentive-based approaches including individual bycatch quotas, fishing cooperatives, and voluntary group sanctions. In the final analysis, the bycatch policy problem poses an important fundamental question: namely, how much of the problem is inherently technological and how much of it is behavioral or institutional? This is an issue that has not been adequately researched, and so we address it in the empirical analysis of Chapter 5 and Chapter 6.

# Chapter 4

# Data Sources

The analysis contained in the next two chapters depends on the synthesis of a number of databases from both federal and Alaskan sources. Some are freely available; however, a few, particularly onboard observer records, are not typically released in an unaltered form to outside researchers due to privacy concerns.[66] As with any empirical undertaking, it is critical to understand the underlying rationale for the data and the methods by which it is collected. The following paragraphs catalog the data sources drawn upon in this dissertation and provide some assessment of their strengths and limitations. These data include:

1. Weekly Processor Reports
2. Annual Price and Product Recovery Rate Data
3. Federal and State Vessel Characteristics Data
4. Quota Tracking and Time/Area Closure Information
5. Meteorological and GIS Data
6. NORPAC Observer Records.

## 4.1 Weekly Processor Reports

All catcher processor and mothership vessels in the groundfish fisheries of the North Pacific are required to file a report at the end of any week in which they have been active. This report requires the skipper to detail the weight of total *production* (as opposed to catch) for each species and product combination along with the type of gear used and the three-digit reporting

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[66] Due to the stipulations of our information sharing agreement with NMFS, we are strictly limited in our ability to share this information in its raw form. Accordingly, there are times when the display of results is restricted so as to protect the anonymity of individual vessels or fishermen.

area where the species was caught.[67] They are also required to offer similar reporting for any discarded groundfish catch. This information is utilized by regulators at the Alaska Regional Office, along with observer and product recovery rate (PRR) data, to estimate total catch of each species and trigger time/area closures as the season progresses.

Given that these reports are filed by the fishermen, one may wonder if incentives are conducive to honest reporting. Indeed, it is doubtful that fishermen do fully report them due to the fact that quota accounting in the BSAI is invariant to the final disposition of the catch and it therefore makes sense to avoid being assessed catch for which no compensating revenue is received.[68] Given the possibility of moral hazard in weekly reporting and its relatively coarse spatial resolution, we have limited the use of this data to two areas for which it should be quite reliable. Firstly, we employ it to identify broad temporal trends in fishery output and relative production of each species. Secondly, we utilize the weekly reports to identify the allocation of production across particular products for a given species.

## 4.2 Price Data

Obtaining accurate information on ex-vessel prices for the groundfish fleet is difficult due to the fact that catcher processor vessels are, with a few exceptions, not legally obligated to file landings tickets when they unload their catch. Furthermore, those vessels that do file Alaska fish tickets for the species we consider (being mostly catcher vessels) deliver catch designated for predominately low-valued products such as whole fish or fish meal that are not representative of the more capital intensive but higher-valued products favored by the catcher processor fleet. The best alternative source of information on prices is obtained from the Commercial Operator's Annual Reports (COAR) which are filed with the Alaska Department of Fish and Game (ADFG)

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[67] All the reports used by fishermen and directions for their completion are available online at the NMFS Alaska regional office website: http://www.fakr.noaa.gov.

[68] Vessels with significant observer presence may have considerably less leeway to misreport their production and discards as the observer data serves as an independent source of verification.

at the end of each season. Fishermen who file this report must give the total weight of each species/product combination and the total value they received for it. The average annual ex-vessel price for each catcher processor can therefore be obtained from these data. Unfortunately, however, we are unable to obtain vessel-specific prices for each vessel in our sample due to the fact that catcher processors operating in the U.S. EEZ were not required to file COAR reports until 2002. However, a substantial number of vessels, both within our sample and without, apparently filed COAR reports despite the lack of a legal mandate to do so (65 FR 78131).[69] Accordingly, we draw upon a NMFS database that summarizes the COAR reports for the offshore sector (catcher processors and motherships) by weighting the price for each species and product combination by each vessel's share of production as calculated from Weekly Production Reports to yield a measure of the average ex-vessel price for the year.

Although one would obviously prefer a measure of ex-vessel price that is both vessel specific and time-disaggregated, there are compelling reasons that the use of a weighted annual average may serve as an acceptable substitute. First of all, unlike many small coastal fisheries where fishermen interact directly with their ultimate buyers, groundfish fishermen in the EEZ typically move their product through a network of brokers to distant domestic and foreign markets. These brokers establish delivery contracts with fishermen (i.e. "deliver X tons of species Y at a price of $Z by such-and-such date") that often shelter fishermen from short-term fluctuations in market prices.

Secondly, fishermen in the H&G fleet typically deliver commoditized products for which there is fairly little scope for differentiation. The imports of flatfish and other H&G products have been dominated, particularly in the last decade, by Asian markets such as China which import the product for processing into fillets or fish sticks and then export much of it back to western markets. Furthermore, fishermen in this fleet must compete in a global "whitefish"

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[69] Such voluntary filing is frequently observed in fisheries where the anticipation of rationalization causes vessel owners to seek to establish a documented production history in the fishery.

market with the Russian, European and New England fleets. Given the nature of these target markets, it is unlikely that any particular processor would command a substantial premium for its products.

Thirdly, despite the varying catchability of groundfish across the year due to meteorological, biological and regulatory factors, the fact that virtually all of the H&G fleet's immediate output is frozen enables wholesalers to smooth supply throughout the year via storage. As a result, one might expect less seasonality in expected ex-vessel prices than would be evidenced in a purely fresh-fish market. Each of these explanations suggest that the use of fleet-wide annual average prices is likely appropriate.[70]

## 4.3 Vessel Characteristics Data

Data on vessel characteristics are gleaned from both state and federal sources. The state of Alaska requires that all vessels operating in their waters be licensed on an annual basis by the Commercial Fisheries Entry Commission (CFEC). As part of this licensing process, owners submit a variety of characteristics of their vessels including the length, horsepower, gross and net tonnage, hold capacity, the age of the vessel as well as some limited information on the owning company.[71] The federal permit data is considerably less informative but does contain corroborating information on vessel length and tonnage.

Ultimately, we have chosen to focus on vessel length, horsepower, hold capacity and age in this analysis. Measurements of gross and net tonnage, while often employed in empirical fishery applications, are plagued here by inaccuracies that are not resolvable between the two databases, and it is arguable that much of the volumetric information contained in gross and net

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[70] In an attempt to use seasonally varying prices, we obtained wholesale price data from the Tsukiji central market in Tokyo for both yellowfin and rock sole. Ultimately, however, this data was discarded due to the lack of equivalent data for all other target species. Simple time series analysis also failed to show any significant linkage (lagged or otherwise) between Alaska flatfish production and Japanese prices, suggesting that the wholesale price may not be closely tied to the price received by fishermen.

[71] The CFEC database is searchable online: http://www.cfec.state.ak.us/.

tonnage is adequately captured by information on length and hold capacity.[72] Measurements of other vessel characteristics are considerably less problematic. On some occasions one or more vessel characteristics were missing from the CFEC data for a particular vessel and year. In these cases a reasonable value was imputed. The manner in which this was accomplished varied from case to case and was often made clear by the particular context. In some cases this involved replacing the missing CFEC data with the equivalent information from the federal permit database. However, on most occasions, the obvious solution was to simply impute a value from the previous or successive year. Characteristics such as horsepower or vessel length rarely vary widely from year to year to due the high costs of investment and disinvestment, and, indeed, most observed vessel characteristics were quite stable from year to year.

## 4.4 Quota Tracking and Time/Area Closure Data

In order to monitor and enforce the complex system of multispecies quotas and time/area closures, fishery managers at the Alaska regional office of NMFS require a considerable amount of information, particularly for the apportionment of PSC catch across target species categories. To meet this challenge, managers combine information from weekly processor reports and observer data to provide the best possible weekly estimates of groundfish and PSC catch by target fishery, management zone and gear on a weekly basis. This catch accounting is publicly available for PSC species for the early 1990s forward through the Alaska Regional Office's website. These measurements are undoubtedly prone to error, but this is mostly irrelevant to our analysis as the relevant catch assessment to fishermen is what the regulator *thinks* it is.[73] We then supplemented this quota tracking data with historical information from the Alaska Regional

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[72] Measurements of tonnage (particularly net tonnage) are highly variable depending on the manner on which they are calculated. Also, unlike vessel length which is easily measurable, tonnage is not so readily verified.

[73] The catch quantities reported in the data have undergone some historical corrections, so they may be a bit more accurate than the information available to regulators at the end of a particular week. Nevertheless, they do closely mimic the information available for in-season management.

Office's archives and the Federal Register to build a comprehensive database of time and area closures and other regulatory changes for the period of this study.

## 4.5 Meteorological and GIS Data

Given the fearsome reputation of the Bering Sea and the substantial distances from port to fishing grounds, it is likely that current and anticipated meteorological conditions are likely to play a large role in a skipper's decision of whether and where to fish – a supposition that is supported by informal conversations with fishermen (Hezel, 2006). The ideal dataset would include a long time series of wave height and wind speed observations from a scattered network of weather buoys; however, a survey of the NOAA National Data Buoy Center's database reveals that there was only one moored buoy in the Bering Sea during the period of this study, and it is located at the bounds of international waters, well away from the vast majority of fishing activity.[74]

Given this lack of detailed ocean conditions data, we have instead relied on time series data of daily surface atmospheric observations (particularly average wind speed) from the National Climatic Data Center.[75] Given the lack of significant sheltering features throughout much of the Bering Sea, wave height and intensity are primarily driven by the direction of prevailing winds and their velocity. Surface observations from St. Paul Island in the Pribilofs are ideal measurements of these factors due to the proximity of the island to many fishing grounds, its small size and limited natural wind cover and its exposure to the direct brunt of the surrounding maritime climate by virtue of its central location on the continental shelf.

Many of the graphics as well as a considerable amount of the empirical work in this dissertation rely on the synthesis of multiple geographic layers within a GIS environment. ArcView shapefiles of regulatory boundaries (including the perimeter of spatial closures) were

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[74] This limited coverage is presumably due to the extensive icing of continental shelf waters in the Bering Sea during the winter and early spring months.

[75] Available online: http://www.ncdc.noaa.gov.

provided by personnel at AFSC or ADFG. The only significant GIS sources not provided by AFSC are those related to the bathymetry of the Bering Sea. In this case, we have chosen to use depth contours developed by the United States Geological Survey's (USGS) Alaska Biological Science Center (Alaska Biological Science Center, 1997). These shapefiles provide a high degree of resolution (1:250,000) for depths of up to 200m at a contour level of 10m and a lower level of resolution (1:2,500,000) at 400m intervals for depths beyond 200m.[76] These contours were synthesized from a large number of preexisting paper and digital sources based primarily on soundings data and are more than adequate for the spatial scale and degree of accuracy required for this analysis.[77] In a (very small) number of cases where depth information was missing for a particular area, values from paper nautical charts were interpolated in their place.

## 4.6 Onboard Vessel Observer Data

Ultimately, the single most important data source for this research derives from the North Pacific Groundfish Observer Program (NPGOP). The use of onboard observers in the North Pacific has its origin in the early 1970s when Japanese fleets invited a small team of scientists onboard their vessels to monitor halibut bycatch. The passage of the Magnuson Act in 1976 mandated the use of observers on foreign vessels while legislation passed between 1988 and 1990 required observer coverage for domestic vessels as well and created the NPGOP as it is known today. As of 2001, the program retained 350-400 observers overseen by a staff of 36 (North Pacific Groundfish Observer Program, 2003).

The structure of the NPGOP is unique. NMFS provides operational oversight for the program, bearing the cost of its administration, providing certification training, defining observer duties and sampling methods and verifying and managing the resulting data. The vessel owners

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[76] Although 400m contours may seem coarse on initial impression, they are actually quite closely spaced due to the fairly steep gradient along the continental slope.

[77] Raster bathymetric information derived from satellite altimetry measurements (Smith and Sandwell, 1997) appeared promising at first but was ultimately discarded due to problems with missing observations and inconsistencies between the raster data and known features on high-resolution nautical charts.

actually bear the direct cost of observers and contract through one of several providing companies to meet the coverage requirements. The level of coverage for catcher processors varies based upon the length of the vessel. Vessels under 60 feet have no observer requirements while those between 60 and 124 feet must have an observer onboard for at least 30% of fishing days. Vessels 125 feet and larger must have an observer onboard at all times when fishing.

Observers are required to have an undergraduate degree in natural science and to have completed some coursework in mathematics and statistics. Once hired, they must undergo a three day training program before deployment and are required to abide by the requirements of an approximately 400 page manual (North Pacific Groundfish Observer Program, 2006) that provides details of their responsibilities, expected conduct and sampling and reporting methods when onboard. After each cruise, observers must undergo a debriefing in order to verify the quality of their data and sampling methods. Personnel are also briefed at the beginning of each cruise to stay abreast of any new regulations or responsibilities that are relevant to their work.

The duties performed by observers are many and varied and not fully detailed here, but one of their foremost duties is the collection of detailed information on fishing effort and total catch and the careful random sampling of hauls for species composition and the quantity of PSC catch.[78] The variables collected include the spatial location of gear retrieval (to the minute of latitude and longitude), the duration of each tow, fishing depth and several others. In performing these duties, observers are required to uphold high methodological standards of sampling in order to ensure that their data is as bias-free as possible. The decision of which hauls to select for species composition sampling is typically determined by the use of a sampling table that randomizes the decision based on an observer's anticipated workload, thus minimizing the crew's

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[78] Observers must also record all vessel interactions with marine mammals and certain seabirds and gather specimens and conduct measurements for stock assessment and other research purposes. They are also required to note and report any violations of fishery regulations although enforcement is delegated to NMFS personnel and the U.S. Coast Guard.

ability to anticipate a sampled haul and thus potentially alter the catch composition in some manner.[79]

After selecting a haul for sampling, observers must then obtain a random sample from the haul for purposes of assessing its species composition. The methods for doing this have remained fairly consistent since the introduction of the random haul table in 1992 (Berger, 2006). For fisheries with very homogeneous catch (such as the mid-water pollock fishery) observers are expected to sample either the entire catch or a large portion of it; however, in many groundfish fisheries with more heterogeneous catch composition (such as those for flatfish) they must take smaller, more manageable samples due to time constraints (a process known as "basket sampling").[80] Observers are encouraged to conduct their sampling as far forward in the processing line as possible so as to minimize the chance for unobserved discards by the crew. For some vessels (e.g. where catch is very mixed or the vessel has little bin space in the processing facility) this may involve random spatial sampling from the emptied codend on deck before the catch has been sorted. In many cases, however, the codend is directly emptied into the processing plant below, in which case there are temporal measures in place for sampling at the head of the processing line. Regardless of the method, the final result of this sampling is weighted proportions for each species in the sample. These proportions, when applied to the vessel's record of total catch or the observer's own estimate, yield statistically reliable estimates of the species breakdown of a particular haul. Finally, after conducting their sampling and recording the results, observers are required to relay their information to NPGOP officials in Seattle on at least a weekly basis; however, improved information on vessels has made it such that many observers are now able to perform this transfer on a daily basis.

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[79] Observer rest patterns are, much like the vessel's crew, at the mercy of the fishing schedule of the ship. Observers are expected to sample based upon a random mechanism around the clock.

[80] Observers may also occasionally select a larger sample (or the entire haul) for the presence of PSC species due to their special importance for management and their relatively low prevalence in a typical haul.

The NPGOP is widely extolled as a success. It is the largest fisheries observer program in the world and compares favorably in both design and implementation with any other program, whether in the U.S. or internationally (MRAG Americas, 2000). The data provided by observers has facilitated the successful biological management of groundfish stocks in the North Pacific for over 15 years. Nevertheless, there are significant areas for improvement. The lack of direct hiring and oversight of observers by NMFS opens up the possibility of conflicts of interest and corruption on the part of observers. Rough weather and cramped working conditions do not always lend themselves to the best of sampling outcomes. Pre-sorting and discarding of catch by crew members may prevent an observer from obtaining an accurate tally of each species. Finally, those vessels with only 30% coverage requirements are free to choose when to bring an observer onboard, suggesting that the data obtained on such occasions may not be typical of those on unobserved fishing days.

Each of these problems have been addressed to some degree by the NPGOP. For example, incentive problems on the part of fishermen are curbed to a significant degree by extensive debriefing on the termination of a cruise as well as by electronic logic checks on all submitted data. Furthermore, vessel operators or fisheries observers that knowingly misrepresent catch or bycatch information are subject to hefty civil and criminal penalties.[81] Although anecdotal evidence of sampling problems and conflicts of interest do exist, the overall impression of an independent review of the program was that there was little evidence of any systematic bias (MRAG Americas, 2000). Information provided by observers has been employed in numerous studies by well qualified scientists as well as for day-to-day management purposes. Indeed, for fisheries data, which are often of low temporal and spatial resolution and often directly reported

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[81] In 2005 the owners of one vessel were levied $500,000 in fines and damages, served 18 months of probation and lost two weeks of fishing privileges for intentionally deceiving observers as to their halibut bycatch. (The captain and first mate both spent four months in jail.) Also, an observer was sentenced to a felony and spent 12 months in prison in 1996 for under-reporting halibut bycatch.

by fishermen with scant opportunity for outside verification, NPGOP data are some of the best available.

Having established the properties of our various data sources, we now embark upon our empirical analysis.

# Chapter 5

# An Empirical Analysis of Fishing Location Choice and Bycatch Avoidance

The analysis of Chapter 3 has shown how the use of common-pool catch quotas on both targeted and bycatch species may create substantial incentives for fishermen to undervalue the catch of bycatch species due to the inability of fishermen to fully capture the benefits of their conservation efforts. When the number of fishermen is small relative to the available quota, then this incentive is curbed somewhat, but as the number of fishermen grows, the implicit willingness to trade bycatch for target catch falls until, at some threshold level of participation, the Nash equilibrium bycatch rate coincides with that predicted by a model in which fishermen act as if they have no discernible impact on equilibrium season length (i.e. atomistic competition).

Despite the power of the noncooperative game framework for uncovering the inner mechanism of individual incentives, the model of Chapter 3 does not readily translate into direct empirical application for a variety of reasons. First, the relatively small group of fishermen actively pursuing the targeted species combined with the considerable losses of rents resulting from rampant competition open up the possibility for cooler heads to prevail and to form either an implicit or explicit compact to avoid bycatch to an extent that is cognizant of the true marginal value of the bycatch as a complement to the fleet-wide harvest of groundfish. The implication for our empirical approach is that any model of the fishery must embrace the potential for both noncooperative and cooperative behaviors within its structure.

Secondly, the game theoretic model neglects many salient features of the applied problem in the interest of tractability and clarity. Whereas fishermen in the game theoretic model were assumed to pursue a single target species, in reality fishermen pursue an entire portfolio of species with varying emphases on particular targets throughout the season as biological, market and regulatory factors dictate. Fishermen were also considered uniform in terms of their harvesting technology and preferences, whereas in actuality substantial heterogeneity may prove significant due to differences in vessel capital and ownership, fishing experience and numerous other factors. Also, the tradeoff of bycatch and targeted catch, while considered as a static phenomenon in Chapter 3, may fluctuate substantially over the course of a season due to varying current conditions (and individual expectations) concerning the relative scarcity of bycatch quota, one's horizon for remaining active in the fishery, regulatory actions and numerous other causes.

Thirdly, the game theoretic framework, although grounded in the spatial reality of fishing, does not directly lend itself to modeling the choice of where to fish. This decision is paramount for the reason that, barring major changes in fishing gear or methods, the primary short-run determinant of fishermen's catch composition and variable cost expenditure, and thus their profitability and bycatch rates, is often their location choice.

In order to model this spatial choice behavior in a manner that is inclusive of both cooperative and noncooperative behavior, multispecies targeting, vessel heterogeneity and time-varying incentives for bycatch avoidance, we specify a random utility model (RUM) of fishing ground choice at the individual haul level to address the following question: how does the combination of binding common property bycatch quotas, costly bycatch avoidance and competition between a relatively small number of vessels affect the spatial aspects of fishermen's behavior?

## 5.1 A Random Utility Model of Fishing Location

The use of random utility models in the analysis of fishing supply over space or fishery is now over two decades old and finds its genesis in the analysis of Bockstael and Opaluch (1983).[82] These models are beginning to find significant applied use and have proven to be especially useful for the prediction of fishermen's behavior and the welfare losses from spatially explicit management tools such as marine reserves (Curtis and Hicks, 2000, Smith, 2001). Typically, such models are motivated in terms of expected utility theory where the expected utility of selecting a particular fishery or fishing site is expressed as a linear function of the expected economic returns (typically variable profits) from fishing in a site and, on some occasions, their variance (Mistiaen and Strand, 2000). Since direct measures of variable costs for assessing a site are rarely available from existing data sources, costs are typically assumed to vary as a (linear) function of the distance to a site from the location of origin.[83]

In this particular application, we model the utility of the primary decision-maker (typically the skipper) aboard a vessel *conditional* on their actually deciding to fish in the Bering Sea using bottom trawl gear. By restricting our attention to a subset of fishermen's total spatial allocation problem, we are able to construct a more complete specification than would have otherwise been possible. Such an approach will yield consistent estimates of the model parameters in at least two circumstances: 1) fishermen decide whether to fish, the broad fishery zone (e. g. Bering Sea or Aleutian Islands), and their choice of location in a sequential manner and do not revisit the first two decisions between trips to port, or 2) fishermen do revisit the choice of whether to fish and the general geographic area between port berths but the choice of

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[82] Other significant papers that have employed RUM models to analyze fishery supply behavior are Eales and Wilen (1986), Dupont (1993), Larson et al. (1999), Holland and Sutinen (1999, 2000), Smith and Wilen (2003), Smith (2005), Curtis and Hicks (2000) and Curtis and McConnell (2004).

[83] This assumption is typically justified by the observation that in most fisheries (conditional on a vessel going to sea) the primary physical cost of fishing is due to fuel consumption which is roughly a linear function of the distance traveled. (Labor is typically paid on a share system of revenues less some portion of costs and so its usage is rarely of concern with respect to the choice of fishing location.) The physical characteristics (e.g. horsepower, tonnage, vessel length) of a vessel also affect fuel consumption and may enter into the specification of the cost of distance through interaction terms.

specific fishing location can be viewed as the terminal nest in a nested logit model of all three dimensions of choice (Train, 2003). The very different characteristics of the Bering Sea fishery from those in the Aleutian Islands or Gulf of Alaska combined with the significant distances between the fishing grounds in each of these zones and vessels' limited fuel capacity all lend support to our conditional approach.[84]

Our basic utility specification (suppressing subscripts for individual agents) is as follows:

$$U_{nt} = \beta * E\left(\frac{REV_{nt}}{HR}\right) - \gamma * DIST_{nt} - \lambda * E\left(\frac{HALIBUT_{nt}}{HR}\right) + \delta' X_{nt} + u_{nt}, \qquad (5.1)$$

where $n$ denotes the particular site and $t$ denotes the temporal unit over which location choices are made. Given the high temporal resolution of the observer data and the likelihood that profit-maximizing and bycatch-averting decisions are revisited on a nearly constant basis in this competitive fishery, we have chosen to define $t$ at the level of the individual haul.[85] Note that both expectations variables enter in terms of productivity per hour of trawling. This normalized measure is desirable since the duration of tow may vary substantially across hauls and is itself, in some aspects, a choice variable.[86] By defining expectations in productivity units we are able to control for this issue without modeling the duration decision. Control variables to account for various other aspects of the choice scenario and the decision makers are incorporated into the vector $X_{nt}$ while influential factors that are unobserved by the analyst but are nevertheless known by the skipper are represented by $u_{nt}$.

The coefficients in equation (5.1) have useful economic interpretations as the marginal utilities (or disutilities) of their associated characteristics. The coefficient on the expected

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[84] Indeed, an analysis of the transition probabilities between the Bering Sea and Aleutian Island fisheries suggest that each zone constitutes a near "absorbing state". Fishermen participate in both zones but, having committed to a zone, they typically persist in fishing there for a substantial number of hauls.

[85] The NPGOP data does not provide the actual time at which a haul was completed; rather, it gives the date on which a tow was completed and a variable indicating the order of the hauls.

[86] Fishermen often tow until they achieve a total catch that is consistent with the capacity of their gear, the size and power of their vessel and their desired product quality – less crowded nets frequently entail a less damaged and more valuable product (Hezel, 2006). However, fishermen may terminate a haul prematurely if a site is not sufficiently productive.

revenue productivity, $\beta$, is especially important in that it represents the marginal utility of a dollar increase in hourly returns from fishing. By dividing other coefficients by the estimated value of this coefficient, we are able to obtain the dollar-denominated "shadow value" of a change in a particular characteristic. In particular, we are able to obtain the implicit shadow cost of halibut and the implied marginal cost of steaming distance between sites. This second term may itself depend upon the characteristics of the vessel, current fuel prices and characteristics of the marine environment (such as wind speed) and we account for these and other factors in the ensuing discussion of model specification.

## 5.2 Model Specification

The process of specifying the RUM model is quite involved and requires that a considerable number of decisions are made prior to ensure meaningful results. This specification process is represented in flowchart form by Figure 5.1. The process begins by defining the time period and vessels over which to conduct our estimation. We must then define the spatial set over which choices will be defined. Having done this, we then confront the issues of how to specify the expectations terms in (5.1), how to cope with the large size of our choice set (using a procedure known as sampling from alternatives), and, how to specify the implicit cost of distance and halibut coefficients of (5.1) in a manner that allows us to test a variety of interesting behavioral hypotheses about the effects of the common property quota system on individual incentives.

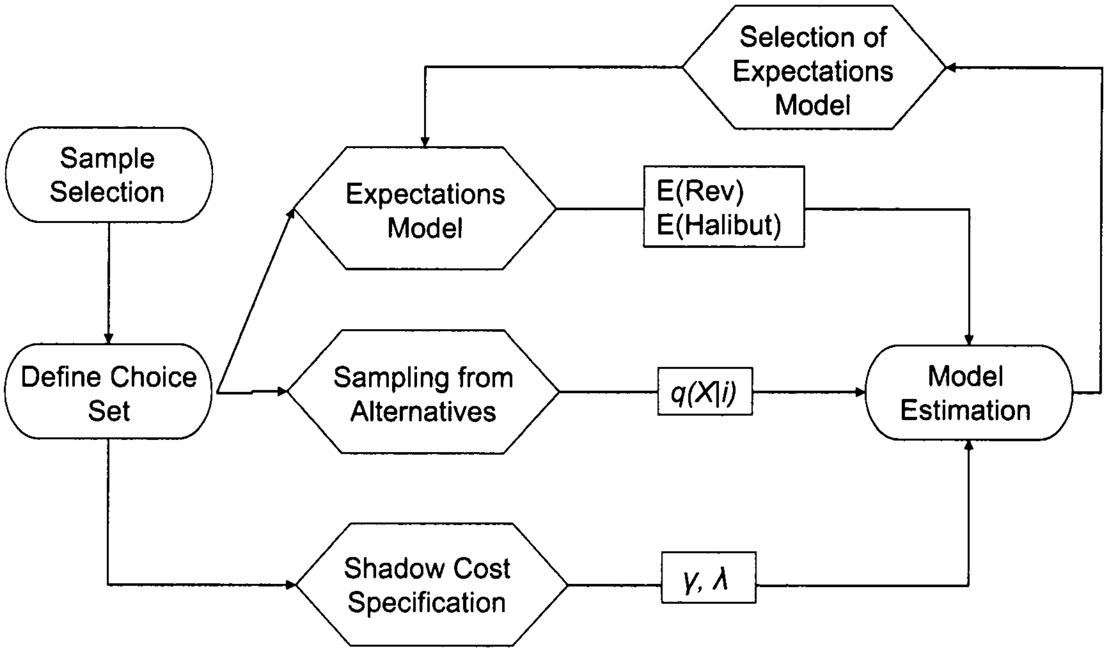

Figure 5.1: Flowchart of Model Specification Process

### 5.2.1 Sample Selection

The years selected for this study are from 1994-2000. As depicted in Chapter 2, these years constitute a dynamic era in the history of the fishery with numerous closures due to bycatch as well as the designation of several new spatial closures. This period also spans the implementation of a cooperative program of bycatch avoidance in both the rock sole and yellowfin sole fisheries in 1995 – a fact that proves salient for the extension of this model in Chapter 6. The decision to truncate the sample at 1994 was largely driven by loopholes in the standards for "directed fishing" in previous years that make the calculation of retainable quantities of species (and thus expected revenues) difficult if not impossible.

Although fishing for groundfish occurs in the Bering Sea as early as the last two weeks of January, we restrict our sample to the period after April 15th of each season. The rationale for this truncation is largely driven by the nature of the winter groundfish fishery. As described in Chapter 2, much of the effort in the Bering Sea in these months is devoted to the pursuit of female rock sole (along with cod and, to much lesser degree, flathead sole) for the purposes of their valuable roe. Unfortunately, observer data rarely provide an estimate of what percentage of the sole catch is roe-bearing (or even female). Furthermore, the prices recorded in NMFS for "roe in" head and gut product are likely far removed from the prices ultimately received by the vessel owners due to the presence of "roe bonuses" that are contingent upon a variety of factors such as product quality and the price the product fetches in foreign markets. Altogether, these factors seriously curtail the reliable calculation of expected revenues for these months. However, by mid-April the targeted fisheries for roe-bearing females have typically ended due to the natural subsidence of the spawning period.

Our sample is limited to 19 bona fide participating vessels that satisfy the vessel length requirement for 100% observer coverage. Those vessels that fall below the 124 foot threshold are only required to have an observer onboard for 30% of fishing days. The timing of this coverage is largely left to the vessel management, and it is therefore highly doubtful that observations for these data constitute a representative sample. The 19 vessels were owned by nine distinct companies with holdings ranging from one to six vessels.[87] These vessels represent a large portion of the Groundfish Forum (GFF) membership over the sample period, an industry group representing the interests of the head and gut fleet in the North Pacific. In all, six vessels with substantial and consistent patterns of participation in the fishery and membership in the GFF were eliminated from our sample due to a lack of full observer coverage.

In order to ensure that our measures of distance between sites are accurate, it is necessary that we successfully identify the point of origination for a haul. Since fishing trips are often long events composed of, often overlapping, periods of fishing and processing, in most cases the point of origination can reasonably be inferred from the previous location of gear retrieval in an effort

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[87] Industry restructuring as well as exit and entry led to some variation in the number and ownership of vessels through time. For instance Tyson Seafood Group transferred ownership of two of its vessels to separate companies between 1997 and 1998 while another of their vessels was retired from the fishery over the same period. U.S. Seafoods introduced a large (295 ft.) trawler to its fleet in 1999. Also, a couple of sporadic participants in the fishery left the fishery in the early years of our sample for economic reasons. These vessels are not included in our sample.

sequence. However, when a substantial amount of time elapses between hauls, it becomes increasingly unlikely that such logic continues to apply; the vessel may have returned to port, taken shelter from inclement weather, engaged in search behavior without completing a haul, or simply have paused its fishing operations in order to allow the processing facility to catch up.[88] To purge the data of such cases, we eliminated hauls from our sample when indicators in the data suggested the previous recorded location may be suspect. Several detailed criteria were used but the key indicators are: 1) a new observer cruise is started (observers typically embark and disembark in port) or 2) more than a full day has passed since the last recorded position for the vessel.

After making these adjustments to our sample selection criteria, we arrived at a sample of 45,200 choice occasions. Given that these choices are allocated over only 19 vessels, we have at our disposal an unusually detailed dataset of the repeated choices of fishermen.

### 5.2.2 Choice Set Definition

As discussed at length in Chapter 2, fishermen conduct their operations over a vast and diverse ocean habitat where one's choice of fishing location depends, in part, upon the desired target species and its seasonal distribution. For instance, fishermen may trawl over the sandy flats below 50m in depth to target yellowfin sole or over the steep slopes and canyon rims of the shelf break (~200m) in pursuit of rockfish or turbot. To operationalize our RUM model, we must somehow carve this continuous plane into a variety of discrete zones – a process for which the literature offers little guidance.[89] At the most basic level, the objective is to divide space in a way that mimics the "mental maps" fishermen employ to guide their decision making. Not having access to this invaluable information, we adopt the following guiding principles:

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[88] The NORPAC data for this period do not contain reliable indicators of when a vessel is in port although there are often substantial clues and regularities in the data that often make this judgment possible. Both these observations and outside information suggest that port berths occur on a roughly fortnightly basis.

[89] In some cases where target species are sedentary or patchy in their distribution (e.g. scallops or sea urchin) this discretization may be relatively straightforward. However, the mobility of the target species combined with the largely homogeneous nature of the substrate habitat over large areas of the continental shelf (McConnaughey and Smith, 2000) makes discretization considerably more difficult in this case.

1. Variations in the areas and shapes of sites should be minimized wherever expedient to minimize biases in the choice probabilities due to differences in the size or spatial configuration of sites;
2. Sites should reflect a minimal degree of habitat heterogeneity in regards to substrate, bathymetry, etc.;
3. The boundaries of spatial alternatives should coincide wherever possible with the boundaries of regulatory zones and spatial closures in order to facilitate the reflection of the effects of management on the returns to fishing;
4. Sites must be large enough to provide sufficient data to reliably estimate expected values of catch and bycatch throughout the season.

Each of these principles is, to some degree, inconsistent with the demands of the others, thus necessitating an informed judgment call. Ultimately we chose a grid based on the Alaska Department of Fish and Game statistical reporting areas for fish tickets (See Figure 5.2). The open-ocean areas of this grid are one degree of longitude by ½ degree of latitude which coincides with roughly 60x60km in area. Due to the features of the coastline and the needs of ADFG for fine spatial reporting within their 3 mile jurisdiction, reporting areas are often quite small and irregularly shaped about the coast. To remedy this feature, we aggregated these areas to form zones of roughly the same size and configuration as the surrounding grid. Note that only those grid areas that experienced positive reported visitation in our sample period or in the two years prior to it and which were deemed reasonable (i.e. not wholly contained within a prohibited area or in waters so deep that bottom trawling is simply infeasible) were included in the choice set. All told, there are 165 total alternatives in the choice set with a combined area of around 540,000 square kilometers.

In order to specify our model, we require a measure of distance from a fisherman's current location to his designation. In the case of the chosen alternative this might be well approximated by the terminal point location of the previous and subsequent hauls as revealed in the observer data. However, an exact spatial location of the haul for alternatives that were not chosen is, of course, not available. As a result we utilize ArcMap GIS software to place a centroid in each of the sites and calculate the distances between alternatives utilizing the centroids as representative points within these sites.[90] This procedure is ubiquitous in the economic, transportation studies and quantitative geography literatures on spatial choice.

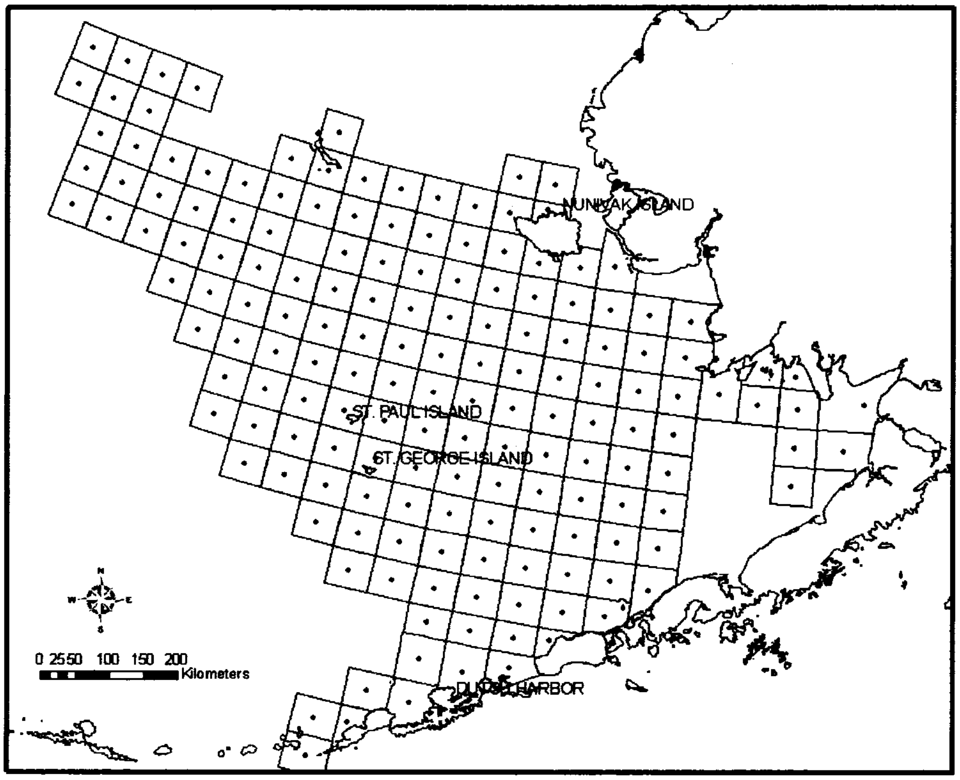

Figure 5.2: Choice Set Grid and Centroids

### 5.2.3 The Specification and Prediction of Expectations

A glance at equation (5.1) reveals that two of the most important parameters of our model (the marginal utility of wealth and the marginal disutility of bycatch) are attached to variables that are latent to the analyst. This property is ubiquitous to practically all fishing location choice

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[90] Given the fairly small size and regular shapes of our sites, it is difficult to imagine how this procedure would systematically bias any of our estimation results. Possible alternatives might be to utilize the exact distance for the chosen alternative and the centroid distance for all others or to replace geographic centroids with "visitation centroids" based upon the mean center of each vessel's observed fishing history within each site.

models as fishermen's catch expectations are inherently subjective, temporally unstable, state dependent and potentially heterogeneous due to varying levels of skill, experience or divergent stochastic realizations from fishing at particular sites. Attempts to directly elicit subjective measures of expectations à la Manski (2004), while valiant, are likely to face significant challenges due to the substantial cognitive burden for fishermen of translating detailed spatiotemporal information to a quantitative format as well as substantial incentive hurdles that make truthful revelation highly unlikely.

Given these difficulties, it is of little surprise that economists have primarily turned to actual historical catch data to form estimates of expectations. Typically the methods applied to this data have been fairly simple. In many cases revenue and catch expectations have been devised by taking backward-looking averages or rolling averages over the returns of the entire fleet (Mistiaen and Strand, 2000, Smith, 2005, Smith and Wilen, 2003) while others have made efforts to account for heterogeneity in fishing power by standardizing revenues according to observable vessel characteristics (Holland and Sutinen, 1999, 2000). Other studies such as Curtis and Hicks (2000), Curtis and McConnell (2004), Dupont (1993) and Eales and Wilen (1986) utilize more sophisticated time series methods to infer future returns based on past realizations of catch and/or prices – often at a fairly broad temporal scale. Nearly all these studies rely on the assumption that expectations are common knowledge across the fleet.[91] They also ignore much of the intrinsic complexity of multispecies fisheries by modeling the expected revenues from fishing rather than the individual catch of targeted species (Holland and Sutinen, 1999, 2000).

There are serious issues with the direct application of such methods to our case. First, unlike most previous models where the goal has usually been to generate robust predictions of future behavior over relatively coarse temporal and spatial scales, our primary aim is to generate

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[91] Curtis and McConnell (2004) is an exception in that they consider whether fishermen's expectations in the Hawaii longline fishery are reflective of new information from their own and their competitors' catch in the interim since their last trip to port. They select from three hypotheses based on their capacity to predict site location behavior and find support for updating based on one's own information but not the information of one's competitors.

consistent estimates and conduct reliable inferences on the primitive parameters of the choice problem. It is reasonable to presume that greater attention to specification of expectations will be necessary in this case to avoid biases whereas such care may generate little payoff in terms of out-of-sample predictions.

Second, the temporal and spatial resolution of our model exceeds that of much of the previous literature. When modeling fishing location at a coarse scale or at the trip level or higher, broad averages may explain behavior quite well; however, in modeling the location of individual hauls over a fine grid it is quite likely that decisions are driven to a much greater degree by relatively ephemeral and idiosyncratic information obtained at the individual vessel level or transmitted through fishermen's information networks. In such cases, divergence of recent experience and the resulting heterogeneity of information may matter to a much higher degree in explaining behavior than some smoothly evolving fleet-wide average.

Third, the complex restrictions on the retention of individual species that characterize the North Pacific system are not easily accommodated within a simple model of expected revenues. To be able to track the effects of regulations on expected revenues and their distribution over space we must develop a model that separately predicts the expected catch of each major target species and then "filters" these predictions through the relevant regulations for a particular season and location to produce reasonable estimates of regulation-reflective expected catch and revenues.

Fourth, the methods previously utilized in the literature do little to approximate the complex synthesis of information from multiple sources and spatial and temporal scales that is likely to truly reflect the expectations-formation process. There is substantial theoretical support (Clark and Mangel, 1986, 1984, Wilson, 1990) and bolstering field observation (Andersen and Wadel, 1972, Gatewood, 1984) that suggest an environment in which cooperative sharing of information among fishermen is interspersed with deliberate withholding of information or even deception. Furthermore, both theory and our discussions with fishermen suggest that they base their decision making on both "coarse" and "fine" grained information (Hezel, 2006, Wilson, 1990). Coarse grained information is defined at a lower level of spatial and temporal resolution than fine grained information and is thus both less variable and more likely to be common-knowledge to experienced fishermen. Previous approaches to expectations modeling have avoided these issues of exactly what information fishermen might possess, how they weight these potentially contradictory data and how they blend knowledge of broad seasonal patterns with more recent and spatially precise information.

In an attempt to address these concerns, we model the catch of 7 targeted species and halibut bycatch using observer data for those hauls which were species-composition sampled from 1992-2000.[92] We take as our basic premise that, given various pieces of information $I_j$ (*j*=1,...*J*) on expected catch at a site *i* at time *t*, a fishermen assimilates this information according to a rational expectations weighting rule:

$$E(CATCH_{it} / HR \mid d(i,t)_1 I_1,\ldots,d(i,t)_J I_J) = \exp\begin{pmatrix} \psi_0 + \psi_1(d(i,t)_1,\ldots,d(i,t)_J) * I_1 \\ + \ldots + \psi_J(d(i,t)_1,\ldots,d(i,t)_J) * I_J \end{pmatrix} \tag{5.2}$$

where the $d(i,t)_j$ are indicator (0,1) variables of whether a particular piece of information is available to the fisherman at that moment in time. This notation is useful since it is likely that a skipper may lack certain fine grained information (e.g. yesterday's own-catch at site A or the catch of vessel B at site A) due to the fishing history of the vessel or the limitations of its information sharing arrangements. The weight ascribed to a particular piece of information is therefore a function of the total information availability, a very flexible arrangement. The specification of the expected catch as an exponential function is motivated by the necessity of bounding expected catch in the positive domain.[93]

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[92] Given the complexity of our approach, we are unable to provide the details of the expectations specifications or the associated estimation results within this chapter. However, all such material is available in Appendix B.

[93] Most species are present in areas with at least a small positive probability. However, as discussed in Appendix B, we do modify this specification somewhat to allow for zero expected catch for species with highly specific habitat preferences.

Upon defining the sources of information that fishermen draw upon to predict expected catch, we can then proceed to estimate the weights in (5.2). We utilize dummy variable interactions to account for all possible information-availability scenarios – thus allowing for a highly flexible estimation of this relationship. We estimate these equations over our entire dataset for each species using single-equation Poisson quasi-likelihood methods that are robust to misspecification of the underlying stochastic data-generation process (i.e. that the Poisson distribution is in fact the appropriate likelihood). By utilizing the entire dataset we are presupposing that the optimal rule for combining information is stable over both time and individuals (i.e. that the informational merit of various "signals" is essentially unchanged with the passage of time and that individuals all process these signals in the same way). This is not unduly restrictive, however, as varying catch and visitation histories induce heterogeneity in expectations across skippers despite the common weighting rule.

Of course, deciding which pieces of information to include in the specification is problematic. Our use of dummy variables can quickly lead to a situation where even our large sample is incapable of adequately identifying the multitude of parameters, and so parsimony is key. Ultimately we model expected catch of a particular species as dependent on the natural logarithms of five variables:

1. Recent fine grained information (today and previous day's catch observations)
2. Older fine grained information (average catch for the period spanning the day before yesterday and back another week)
3. Oldest fine grained information (same as number 2 but a week beyond in age)
4. "Logbook" data (a moving 2-week symmetric average from last year's catch record)

5. "Coarse grained" info (a site's expected catch based on a more aggregated spatial and seasonal scale).[94]

The exact content of variables 2 and 3 is allowed to vary somewhat depending upon assumptions about the extent and temporal diffusion of information sharing across the fleet. For instance, these variables could include only vessel-specific information or they may reflect broader averages over the entire fleet or a subset of the fleet. We ultimately estimate a variety of information-processing rules under a range of plausible assumptions and then combine these estimates to simulate several plausible information-sharing scenarios. We explore these scenarios and how we select between them econometrically in Section 5.3.3 below.

Having estimated the appropriate information-processing rules for all species, we can then "filter" these catch expectations through the regulatory closures and retention restrictions that were in place at various points in time to gain a measure of the approximate retainable quantities of each species per hour of towing. It is then a relatively simple matter to combine these quantities with annual data on prices for each species and product combination and weekly records of each vessel's product allocation by species to produce a final measure of site-specific expected revenue productivity that is based on a sophisticated model of information processing, allows for significant individual heterogeneity in expectations and is reflective of regulatory constraints on revenues.

### 5.2.4 Managing a Large Choice Set

Given the substantial number of choice occasions and the large dimensionality of our choice set, it should come as no surprise that computational considerations in estimation are of substantial importance. Dimensionality affects estimation in two ways. First, the computational complexity of the numerical log likelihood maximization procedure is effectively determined by

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[94] This expectations signal is itself derived from a model estimated on the data and is meant to approximate the broad recurring spatial and temporal and trends at a far broader level than the scale of spatial decision making. It also captures annual shocks to the abundance of each species as captured in the observer data.

the product of the number of choice occasions by the number of alternatives per choice. As the number of alternatives per choice occasion increase so too does the length of the summations that are evaluated for each choice occasion at every iteration of the log likelihood maximization procedure. Secondly, the prediction of expected revenues and halibut bycatch as described in the previous section entails the calculation of numerous individual, group and site-specific catch history variables for each species of concern. Given the irregular temporal spacing of observations within a cross sectional unit (subsequent or preceding hauls may be either days or hours apart), we are forced to utilize computationally demanding looping procedures to recreate these histories. Performing such an operation over 45,200 choice occasions and 165 alternatives could take many days to complete and there is no guarantee that the likelihood maximization would even be tractable for such a high-dimensional problem.

Fortunately, a technique known as "sampling from alternatives" provides an escape from these difficulties. This technique appears to have received its first explication in McFadden (1978) for the case of models with type I extreme value distributions on the error term (i.e. the conditional logit model) and has been used on many occasions since to estimate RUM models with large choice sets.[95] A detailed account of the conditions required to attain consistency with this method as well as the details of our own procedure is contained in Appendix C; the basic idea is quite simple, however. A subset of the total choice set is selected by the analyst according to some probabilistic criterion. Depending on the criterion and the underlying distribution of the error term in the RUM model, this selection procedure may result in biases in the coefficients of the model if not properly accounted for. When the errors follow a generalized extreme value (GEV) distribution and the selection probabilities possess an easily satisfied regularity property, then these biases can be eliminated through the addition of "location shifters" to the choice probabilities. In practical terms, this entails the addition of individual and alternative-specific bias correction terms to the observed utility component of (5.1). Estimation in this context is

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[95] Train et al. (1987) is a particularly sophisticated and well-motivated example.

accomplished through constrained maximum likelihood methods where the coefficient on the bias correction terms is held equal to one.

In our case, we select five alternatives for each choice occasion in addition to the one that is chosen. Rather than choose these alternatives in a purely random manner, we actually utilize a probability rule that sequentially selects sites according to their visitation histories over the entire sample period. The advantage of such a selection procedure is that it, on average, selects those alternatives with desirable attributes to the fishermen. We are therefore able to obtain a greater degree of information on the value of changes in important attributes for a particular number of alternatives than would have been likely under a purely random scenario. This should help to offset some of the loss of efficiency that arises from utilizing a subset of the full choice set (Train, 2003).

### 5.2.5 Specification of Shadow Cost Terms

The coefficients on the marginal disutility of distance and the disutility of halibut in equation (5.1) are portrayed as constants. There are nevertheless substantial reasons, originating both in our observation of the fishery and from theory, that cast doubt on such a simple specification and suggest one in which these "parameters" are themselves functions of theoretically relevant variables. We detail our rationale for our specification of these functions below.

#### *5.2.5.1 The Marginal Disutility of Halibut*

The marginal disutility of halibut, $\lambda$, measures the extra aversion to fishing in an area on the part of a skipper when he expects to harvest one more kilogram of halibut than in an otherwise identical area. The model of Chapter 3, although aspatial, suggests that this quantity (when divided by the marginal value of revenues) is bounded from below by the out-of-pocket marginal cost of discard. However, to the extent that agents have relatively few competitors, then we might expect a greater degree of internalization of the season length externality and an attendant rise in the implicit cost of halibut. Also, to the extent that cooperative norms or the credible threat of punishment from one's competitors encourages still further internalization, we may observe even higher implicit costs for halibut bycatch. Despite these important guidelines, the structure of our game theoretic model offers little direct guidance as to our specification. We therefore list a variety of factors below that made our final specification for $\lambda$ and the arguments for their inclusion. A full list of the variables in our model is presented in Table 5.1.

First, we consider the effects of the availability of halibut mortality quota on the implicit cost of halibut by including the percentage utilization of halibut quota measured at the beginning of the current week (the finest temporal resolution for which we possess quota-tracking data). However, as discussed in Chapter 2, fishermen can allocate halibut bycatch, via their targeting and discard behavior in a particular week, to one of two primary target allocations – that for rock sole and other flatfish or that for yellowfin sole.[96] As a result, we linearly enter the utilization for each quota category into our specification but also include their interaction to account for the fact that a reduction in available quota for one category when the other is in short supply may entail a very different behavioral response than when the other quota is available in abundance. It is difficult to speculate on exactly what the overall effect of tightening quotas may have on halibut avoidance – either increased or reduced avoidance seem plausible. However, it is reasonable to expect that the effect of the tightening of one quota category will likely increase the present value of the remaining quota in the other category and reduce the proclivity of a skipper to accrue bycatch against it. In other words, the sign of the quota utilization cross-effect is likely to be positive.

A factor that played a key role in the avoidance of bycatch in Chapter 3 was the anticipated bycatch of one's competitors. If this bycatch is relatively low then the marginal effect of one's own conservation on the equilibrium season length is amplified and so is the personal

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[96] There are halibut PSC allocations for other targeted species in this fishery (e.g. cod and various deepwater flatfish). However, very little halibut bycatch is amassed against these categories by the flatfish fleet.

incentive to avert bycatch. To account for the effects of expected bycatch we linearly enter the observed mortality of halibut in the previous week against the two primary halibut quota allocations. To the extent that past mortality is utilized by fishermen to project future mortality, we should expect that the coefficients on these terms be negative since the greater the bycatch mortality of one's competitors the more one's efforts at bycatch avoidance are immediately undone by one's competitors. We might also expect that the coefficient attached to the anticipated mortality of halibut against the yellowfin sole allocation may be more strongly negative than that of rock sole due the greater degree of targeting on yellowfin sole within the fishery over much of the season.

Another factor that may significantly impact a particular skipper's avoidance of halibut is his anticipated participation in the fishery. If, at the beginning of the season, a skipper believes that he will only participate in a fishery to a minimal degree, then there is ostensibly a reduced private incentive to avoid bycatch as less of the potential benefits of constraint will accrue to his vessel than would be the case if he were planning on remaining active in the fishery until it closes. In an analogous fashion, as the season progresses and a vessel draws near to the point of leaving the fishery, it is reasonable that the personal incentive for avoidance of bycatch would diminish somewhat. To capture this effect we include the actual number of remaining active days for the vessel in question within the current halibut quota allocation.[97] By tracking participation over the current remaining halibut allocation, we acknowledge the short horizon over which fishermen are likely to "save" halibut for future use. In other words, since seasonal halibut allocations are typically exhausted, it stands to reason that fishermen would adjust their own planning horizon to reflect this fact.

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[97] One may object that what is in fact required here is the *expected* participation due to concerns of measurement error or potential endogeneity. However, developing such a measure would require the synthesis of contemporaneous information on numerous alternative fisheries and the estimation of an economic model of entry/exit behavior – a considerable task. Furthermore, despite the status of participation as an endogenous choice to fishermen, we have found it difficult to devise a convincing case for actual participation being systematically correlated with the unobserved variation in random utility.

As described in Chapter 2, when regulators close a targeted fishery due to PSC catch, fishermen are not usually prohibited from continuing to fish; however, they do face significant restrictions on the quantities of targeted species they are allowed to retain so that any remaining PSC bycatch must be accrued against some other target species for which a closure is not in effect.[98] The obvious effect is simply to reduce the average revenue productivity of hauls (an effect already accounted for in our model of expected revenues). However, closures may also have implications for the individual incentive to avoid halibut given the fact that they have the effect of both reducing fishermen's options for how they allocate any future halibut bycatch as well as potentially diverting fishermen to target species for which halibut bycatch quota is not a limiting factor. To account for these effects we include dummy variables for yellowfin sole and rock sole/other flatfish closures in our specification of the marginal disutility of halibut.

Many of the previous variables are intrinsically time-varying, both on an annual scale and within the individual sub-seasons. In order to ensure that we capture the effects of changes in these variables and not merely other exogenous variation, we include a quadratic annual trend as well as dummy variables for the intra-seasonal allocations of halibut to yellowfin sole (accounting for an increase in the number of sub-seasons from 1996 onward) and sub-seasonal trends for each yellowfin sole halibut allocation period.[99]

#### *5.2.5.2 The Marginal Disutility of Distance*

Past analyses of spatial choice behavior have overwhelmingly treated the cost of distance as essentially "technical" in nature and have therefore specified it as a constant (with possible

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[98] For many fishermen, these restrictions do have the effect of ending their Bering Sea fishing season (particularly when the closure is a late-season closure for yellowfin sole and there are few alternative fishing targets).

[99] As an example of why these temporal controls are necessary, consider the following. Suppose fishermen know at the beginning of a sub-season that bycatch will be harder in the near future due to anticipated changes in its location vis a vis the target species – then they may attempt to reduce their capture of halibut early in the season to "bank" it for when the cost of halibut avoidance will be higher. Such behavior could cloud the effects of changes in available quota or participation due to their clear collinearity with the progress of time and the underlying spatiotemporal patterns.

seasonality due to varying fuel prices) or, in the most sophisticated cases, have treated it as a linear function of fuel-efficiency-related vessel characteristics. There is an apparent problem with this approach, however, that lies in the fact that the distance between sites is clearly monotonic in the consumption of time spent in activities other than fishing. We should expect that this time would bear an opportunity cost and that this cost should reflect the interim consumption of scarce resources by one's competitors. Given that halibut bycatch typically limits the fishery well before target species quota, the marginal disutility of distance should not only reflect direct economic costs of travel but also the perceived value of the losses of future target catch due to one's competitors' interim bycatch.

Given that this opportunity cost of distance should be dependent upon one's current implicit valuation of halibut bycatch and the interim capture of halibut by one's competitors is likely proportionately related to the steam time incurred between sites (and thus the distance between them), we intuit that the perceived cost of distance should be influenced by the same variables that enter into the marginal disutility of halibut bycatch. In addition, we also include vessel length and the interaction of vessel length and horsepower in order to account for vessel-specific factors influencing both direct and opportunity costs. We also include the average daily wind speed in order to account for increased fuel usage as well as greater physical risk due to turbulent wind-blown seas.[100]

### 5.2.6 Control Variables

In addition to the detailed specification of the shadow cost terms, we also include a number of control variables. Many derive their motivation from their uniform significance in the literature, yet still others are included due to the special characteristics of the case study and our data.

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[100] The bearing of the wind relative to the travel vector under consideration might also be of some relevance (i.e. traveling with the wind vs. against it) but we do not consider it here.

It is quite likely that distance is relevant to fishermen's decision making in ways that are not adequately captured by the distance between alternatives alone. For instance, it is quite likely that alternatives that are in close proximity to one's home port are more likely to be visited than those that are relatively close, all other things equal. Such behavior may occur due to safety concerns but may also be rooted in a dynamic pattern of decision making under hold constraints or delivery contracts.[101] For this reason we include the distance from the primary port in the region (Dutch Harbor) to the centroid of the alternative in our specification. We also interact this measure with the hold capacity of the vessel to account for the extra "degree of freedom" of large vessels over small vessels in terms of their range from port.

Beginning with the work of Bockstael and Opaluch (1983), several studies have noted that fishermen's future choice behavior depends in a significant fashion on their past choices. This "state dependence" is typically positive, meaning that fishermen often prefer those sites they have visited in the past to a degree that is not fully explained by their expected payoffs. Possible explanations for such behavior include heterogeneity in expectations arising due to divergent experiences at locations, positive returns to experience at a particular site, risk-avoiding behavior (familiar sites possess less risk due to their reduced "sampling variance"), and simple inertia or adherence to tradition. Regardless of the cause, accounting for state dependence is important for the reason that, if left alone, it can masquerade as heterogeneity in the parameters of the RUM model (Smith, 2005).[102] To accomplish this we utilize three measures of state dependence as control variables. First, we include a simple dummy variable to indicate whether a site was fished by the vessel immediately prior to the current choice occasion. Secondly, we include the number

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[101] The estimation of dynamic discrete choice models (cf. Rust (1994)) is still rather limited in the dimension of the choice set (i.e. state space) that can be considered (Smith and Provencher, 2003). Hicks and Schnier (2006) offer a solution that is relatively tractable under restrictive assumptions on the nature of expectations over future states. The size of our choice set and the complexity of expectations calculations preclude the use of such methods in our case given the current state of technology.

[102] Our specification of expectations, unlike those currently used in the literature, allows for current expectations to diverge across agents due to their heterogeneous histories (to the extent that incompletely-sampled observer data captures this heterogeneity). Therefore, our state dependence variables should be less affected by this cause of state dependence than previous studies.

of fishing hours and the number of fishing hours squared at a site in the past day as well as the same quantities for the week beforehand. This measure captures the effect of different horizons of experience on choice as in Holland and Sutinen (2000), but does so in a continuous fashion so that the effects of the quantity of past experience is also captured.

Although our model of expectations formation allows fishermen to share information, it does not incorporate the signals dispersed to astute fishermen by considering the locations of their competitors apart from any other information. Economic models (Banerjee, 1992, Bikhchandani, et al., 1992) and laboratory studies (Anderson and Holt, 1997) suggest that emulating the previous behavior of agents may be individually rational when making decisions under conditions of uncertainty – even when one's own information about the optimal choice differs from that indicated by previous decisions. In many cases this can trigger a "cascade" wherein agents sequentially converge to the same choice despite their own better judgment. To account for possible "herding" behavior in our model we include variables indicating the number of vessels that fished in a site over daily intervals from one to three days prior to the current date. This approach lets us investigate the informational decay of location data over a short-term horizon.[103]

In addition to trapping valuable targeted species, trawls also catch a large number of species or grades of fish that are frequently discarded for either economic or regulatory reasons. The unit cost of sorting and discarding this catch may be small; however, large quantities of such catch may prove sufficiently onerous so as to motivate fishermen to avoid areas where significant discards are anticipated. Walleye pollock is one such species that, although processed and landed in relatively small quantities, is often discarded by fishermen, when they are free to do so, due to relatively poor prices and limited markets for head and gut pollock products. To account for this effect we include the expected catch of pollock as a regressor in the utility specification.

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[103] To rigorously investigate the presence of herding behavior and informational cascades would necessitate the inclusion of such variables in the revenue expectations model in addition to the RUM model. However, for the sake of simplicity and in order to focus our analysis on bycatch-related behavior, we avoid this step. Comparison of the two approaches on preliminary results suggests that this decision had very negligible effects on our results.

Furthermore, to account for regulatory changes in 1998 that required the full retention of pollock catch, we interact the expected catch variable with a dummy variable for the period after the change.[104] In addition to economic discards such as pollock, fishermen are often required to discard large portions of their catch due to retention restrictions. As detailed in Chapter 2, fishermen are not forced to follow retention restrictions at the level of the level of the individual haul so it is possible that targeting and discard behavior follow a complex dynamic process across a sequence of hauls (although, as noted, this tendency is likely curbed by both regulatory and economic factors). Nevertheless, in order to obtain a rough estimate of the effects of anticipated discards on location choice behavior, we utilize the expected catch of each species at a site and combine this with our information on retention restrictions to form estimates of expected discards *as if* compliance with these restrictions was instantaneously imposed after each haul.

In designing our choice set, we endeavored to minimize, subject to several other goals, the variation in area of our alternatives. To account for the remaining variation, we incorporate the area of the choices into our model. We choose to do this by using the natural logarithm of surface area in square kilometers as a control variable in equation (5.1). In the simple case of the conditional logit, the odds of one choice versus another can then be represented as follows:

$$\frac{P_i(n)}{P_i(m)} = \frac{\exp(V_{in} + \gamma \ln(Area_n))}{\exp(V_{im} + \gamma \ln(Area_m))} = \frac{\exp(V_{in}) \times Area_n{}^{\gamma}}{\exp(V_{im}) \times Area_m{}^{\gamma}}. \tag{5.3}$$

In the special case where $\gamma = 1$, the relative odds of choosing $n$ over $m$ are proportional, ceteris paribus, to the relative areas of the two sites. This is a reasonable hypothesis that we are able to nest via our specification.

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[104] Increased retention/improved utilization legislation (IR/IU) required that fishermen process 100% of their pollock and cod catch and that the resulting products meet a minimal utilization percentage of this catch. This legislation was superficially motivated by the impetus to reduce the "wasteful" discards of non-target catch by the head and gut fleet but seems to have also been driven by political maneuvering by the (pollock and cod-targeting) AFA cooperative fleet in an attempt to achieve higher future allocations of their target species. We do not account for cod in our specification since its relatively high value in our sample period largely curtails its extensive discard.

## Table 5.1: Variables in Random Utility Model (all terms enter linearly)

| |
|---|
| *Marginal disutility of distance -- all variables interacted with distance (100s km)* |
| Vessel dummies |
| % utilization yfs halibut quota |
| % utilization rs/of halibut quota |
| % utilization yfs halibut quota * % utilization rs/of halibut quota |
| Future vessel participation within yfs season (weeks) |
| Halibut mortality from yfs in previous week (mt) |
| Halibut mortality from rs/of in previous week (mt) |
| Closure dummy: yfs |
| Closure dummy: rs/of |
| Horsepower (1000s) |
| Horsepower (1000s) * Vessel length (100s ft) |
| Average Wind Speed (mph) |
| Seasonal dummies* |
| Annual trend |
| Annual trend^2 |
| Seasonal trends (# days remaining in full season * seasonal dummy)* |
| *Marginal disutility of halibut bycatch -- all variables interacted with expected halibut catch productivity (mt/hr)* |
| Constant |
| % utilization yfs halibut quota |
| % utilization rs/of halibut quota |
| % utilization yfs halibut quota * % utilization rs/of halibut quota |
| Future vessel participation within yfs season (weeks) |
| Halibut mortality from yfs in previous week (mt) |
| Halibut mortality from rs/of in previous week (mt) |
| Closure dummy: yfs |
| Closure dummy: rs/of |
| Seasonal dummies* |
| Annual trend |
| Annual trend^2 |
| Seasonal trends (# days remaining in full season * seasonal dummy)* |
| *Control Variables* |
| Expected revenue productivity (1000s $/hr) * Vessel dummies |
| Distance from Dutch Harbor (100s km) |
| Distance from Dutch Harbor (100s km) * hold capacity (1000s ft^3) |
| Vessel dummies * state dependence dummy (=1 if alternative is location of previous haul) |
| # fishing hours at site -- today & yesterday |
| (# fishing hours at site -- today & yesterday) ^ 2 |
| # fishing hours at site -- 1 week prior to yesterday |
| (# fishing hours at site -- 1 week prior to yesterday) ^ 2 |
| Number of vessels in site -- 1 day previous |
| Number of vessels in site -- 2 days previous |
| Number of vessels in site -- 3 days previous |
| Expected pollock catch (mt) |
| Expected pollock catch (mt) * dummy(=1 if year>=1998) |
| Expected regulatory discards (mt) |
| Natural logarithm of Area (km^2) |

*Seasonal dummies are based on yellowfin sole halibut allocation periods. For our sample period there are two seasonal allocations for the years 1994-1995 and three for 1996-2000. The first seasonal dummy for the 1994-1995 period is dropped for identification purposes (except when used in interacted form, in which case no period is dropped).

## 5.3 Model Estimation

In order to estimate the parameters of the indirect utility function, we must first make some decisions concerning the degree of parameter heterogeneity across vessels as well, the stochastic representation of the unobserved factors of choice and the selection of the proper characterization of revenue and bycatch expectations.

### 5.3.1 Parameter Heterogeneity

The consideration of preference heterogeneity across agents in discrete choice models has increased substantially in recent years, due in no small part to computational advances in simulation methods that allow the tractable estimation of models such as the mixed logit (McFadden and Train, 2000, Train, 1998). These methods, which have found some use in models of fishing location choice (Mistiaen and Strand, 2000, Smith, 2005) and recreation demand (Chen and Cosslett, 1998, Herriges and Phaneuf, 2002, Provencher, et al., 2002, Train, 1998) are quite useful in that they parsimoniously capture heterogeneity by specifying the coefficients of the RUM as random variables that are dependent upon a small number of estimable parameters.[105]

Despite the utility of this approach, it is ultimately a poor substitute for actual knowledge of the individual parameters. If we possess sufficient data on the repeated choices of individuals to consistently estimate their unique preferences, then it is clearly more flexible and informative to do so than to rely on a low-dimensional approximation to preference heterogeneity in the population.[106] Given that we possess between 435 and 4836 choice occasions per vessel in our sample, the consistent estimation of individual-level parameters seems reasonable (Smith and Wilen, 2005).

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[105] For instance, a parameter that is expected to have both positive and negative values in the population can be specified as a normal distribution where the mean and standard deviation are estimated.

[106] An exception to this assertion might occur in the case where the sample is a random subset of the population and the model is intended for predictive use. In such a case, prediction at the population level would be hampered by the more general approach we describe here.

Notwithstanding the length of our panel dataset, the estimation of a fully heterogeneous model is infeasible from the vantage of both computational and statistical efficiency. We therefore focus our attention on three key parameters. First, we allow the marginal utility of expected revenues to vary across vessels due to its central importance (both theoretical and empirical) as a driver of location choice.[107] Some skippers may be highly driven by the prospect of small gains while others may be more relaxed in their approach to profit maximization. Second, we allow for unobserved variations in the underlying technology of the vessel or the preference of the skippers that affect the implicit costs of steaming between sites. Finally, we allow the state dependence dummy variable to exert a different effect for each vessel. This decision was prompted by pre-test results that indicated that a substantial degree of heterogeneity in the "inertia" or "momentum" of vessel movements was indicated.[108]

### 5.3.2 Stochastic Assumptions

Since we utilize the "sampling from alternatives" solution to cope with our large choice set, we are required (for the sake of consistent estimates) to limit our specification of the unobserved component of utility to the generalized extreme value (GEV) family (Bierlaire, et al., 2003). This family of distributions is fairly flexible and encompasses a number of distributions such as the conditional logit, the nested logit and the overlapping nested logit (Train, 2003). In the following analysis, we restrict our specification to the conditional logit form.[109] This model has the benefit of computational simplicity, an important consideration given the large number of

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[107] Allowing the marginal utility of "wealth" to vary is relatively rare in the literature due to the use of random parameters models. In such models, the population distribution of the shadow values of choice characteristics (the ratio of the characteristic coefficient to the marginal utility of wealth) is often difficult to characterize when the marginal utility of wealth is allowed to vary over individuals.

[108] We initially considered heterogeneity in the coefficient on expected halibut. Likelihood ratio tests rejected the hypothesis of equality across all 19 coefficients ($\chi^2(18) = 35.05$, 1% critical value = 34.80), but the estimated values were nevertheless quite similar in value and the majority of the individual-specific parameters were insignificant from zero at conventional levels of statistical significance. Our results are not sensitive to the homogeneous characterization of preferences for halibut avoidance.

[109] Our use of the term "conditional logit" coincides with the nomenclature popularized by McFadden,. meaning a model of multinomial choice wherein the utility from choices is a function of the attributes of

choice occasions in our dataset and the highly-specified nature of our model.

Of course, the conditional logit has serious potential shortcomings due to the fact that the stochastic "error terms" are assumed to be independently and identically distributed. In other words, unobserved utility is assumed to be both homoskedastic and serially uncorrelated. A side effect of these properties is the "independence of irrelevant alternatives" (IIA) wherein a favorable (adverse) change in the characteristics of one choice results in equi-proportional substitution away from (toward) the other alternatives.

Notwithstanding these limitations we are able to considerably loosen the restrictive assumptions of the conditional logit by careful specification of the observed component of utility – a pursuit facilitated by the volume of data for each vessel in our sample. Indeed, as in any econometric model, it is preferable to account for as many important factors via the covariates as possible and thus drive the unobservable factors toward something closely approximating "white noise". By estimating vessel-specific parameters, we eliminate (or reduce) possible serial correlation in the error terms due to idiosyncratic vessel responses to covariates. The extensive specification of state dependence and herding variables also provide multiple well-motivated linkages between current choices and past decisions – further reducing the degree of correlation in the errors. The fact that our expectations predictions are regularly updated based on new information also aids in this regard.

In addition to accounting for parameter heterogeneity and serial correlation, the properties of our dataset allow us to consider a form of heteroskedasticity not usually encountered in conditional logit models. It is commonly known that the parameters in a conditional logit (or any other RUM model for that matter) are only identified up to a scale parameter, $\sigma$, since utility

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the choices rather than of the characteristics of the agents exclusively (which do not change over alternatives). Such a model is frequently known as a "multinomial logit" outside the economics literature.

is an immeasurable, unitless concept.[110] The scale of the model and the parameters are jointly determined in an inseparable fashion to achieve the logit variance of $\pi^2/6$. Consider, however, the choice probability of agent $i$ when the utility parameters ($\beta^*$) are homogeneous across agents but the scale parameters differ across vessels:

$$P_i(n) = \frac{\exp(V_{in}/\sigma_i)}{\sum_j \exp(V_{ij}/\sigma_i)}. \tag{5.4}$$

Two implications immediately follow. First, failure to account for differences in scale across agents may lead to findings of significant heterogeneity in the coefficients of the utility function when none is actually present (Swait and Louviere, 1993). It is advisable then to jointly model scale and coefficient heterogeneity when working with panel data.[111] Secondly, the scale parameters are not identifiable without some form of normalization. This normalization is easily accomplished by setting the scale of one of the vessels to one – the estimated scale parameters for the remaining vessels are then interpretable as relative to this normalized vessel. Note that the joint estimation of the relative scale factors and heterogeneous utility parameters is not possible if all the parameters are allowed to vary over vessels; however, given that we limit heterogeneity to only a few key variables, identification conditions are easily satisfied.

The careful specification of observed utility, judicious selection of heterogeneous parameters and care to differences of scale help to loosen many of the restrictions of the conditional logit model. Indeed, by estimating both heterogeneous slope and scale parameters, this specification is actually more general than most commonly-employed random parameters specifications which fail to address issues of scale. The effect of these changes is to maintain the

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[110] The scale parameter is a measure of the influence of unobservable factors in driving choice. The higher the scale parameter, the greater the variance in unobservable factors, and the less choices are driven by factors that are known by the analyst.

[111] The consideration of scale heterogeneity is actually quite rare, particularly in the applied econometrics literature. One notable exception is in the combination of stated and revealed-preference data for environmental valuation (Adamowicz, et al., 1994). Much of this seeming indifference is likely driven by necessity – few panel datasets are sufficiently long within cross-sections to identify scale differences.

IIA assumption (conditional on the model regressors) within each cross-section but not over the fleet as a whole. Given our primary goal of estimating and conducting inference on ratios of coefficients and the oft-noted robustness of logit parameter estimates for such purposes under various misspecifications, we feel our stochastic specification is sufficient.[112,113]

### 5.3.3 Selection of the Expectations Model

As described previously, our process for estimating expectations relationships allows us to define rational expectations rules for information assimilation conditional on the data possessed by fishermen. Unfortunately, the actual information sets of fishermen (i.e. the structure of their information-sharing networks) is largely hidden to us.[114] As a solution to this problem, we utilize an approach similar in spirit to that of Curtis and McConnell (2004) and combine the predictions from our expectations models to construct a small number of reasonable informational hypotheses. We then utilize predictions from these constructed variables to estimate multiple versions of the RUM model and then "let the data decide" the best approximations to the actual revenue and halibut expectations models.

Given a nearly unlimited number of alternative hypotheses on information sharing, we utilized a couple of key facts from close observation of the fishery to simplify our search. First, given the obvious incentives to hide or misrepresent one's bycatch in a competitive system and the introduction of Sea State in 1995 to counter this very incentive, it seems a safe hypothesis to assume that sharing of fine-grained halibut bycatch data would not have existed in any substantial form prior to 1995 and that the extent of such sharing is limited thereafter to Sea State

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[112] This robustness is an empirical regularity ascertained from observation of numerous published results. There is no formal result to guarantee such robustness although Train (2003) notes a similar regularity.

[113] If our model were intended for predictive use, then it is quite likely that allowing for correlation of alternatives over space would generate substantially improved predictions, particularly at the vessel level. Such correlation can be tractably accommodated within the GEV framework (Bhat and Guo, 2004) although few applications have gone beyond the (potentially unrealistic) nested logit formulation.

[114] Discussions with fishermen (Hezel, 2006) suggest that they do maintain information sharing partnerships with a small number of other vessels. The size and extent of these partnerships fluctuates with conditions on the grounds and there is some diffusion of information across groups due to common membership. This information, while useful, is not sufficiently precise to inform sharp "priors" on the structure of information sharing arrangements.

participants. Second, there is strong anecdotal data indicating that a handful of vessels from the one company that opted out of Sea State in its early years were quite isolated in terms of their pooling of information. We utilize these observations to construct six simple hypotheses which are presented and described in Table 5.2. Please note that "sharing" in this context implies the transmission of slightly aged fine-grained information (types 2 and 3 as described in Section 5.2.3). It is arguably less incentive-compatible for vessels to truthfully reveal nearly contemporaneous fine-grained information, and the purely ordinal nature of our data within a day precludes the modeling of such arrangements.

The selection of the appropriate expectations model involves the comparison of intrinsically non-nested hypotheses and is thus open to a variety of statistical methods, none of which are uniformly favored by the scientific community. Curtis and McConnell compare the in-sample predictive performance of various information assumptions by looking at the "percent correctly predicted" by their model. Such an approach lacks a rigorous theoretical foundation, however, and we also found that the predictive performance of our alternative models were quite similar.

Ultimately, we elected to use information criteria, specifically the Bayesian Information Criteria (BIC) to select the preferred expectations model. The BIC is simply a transformation of the maximized log likelihood of the RUM model with an additional penalty for model dimension and can be represented as follows:

$$BIC = -2 * \log \ell(\hat{\theta}_{MLE} \mid D) + K * \log N, \tag{5.5}$$

where a smaller value of the BIC is preferred. The BIC has a rigorous grounding in the statistical literature as a useful, if somewhat crude, asymptotic approximation to Bayesian methods of model selection (Kass and Raftery, 1995, Raftery, 1995), and the recognition of its utility is slowly growing in the environmental economics literature (Haynie, 2005, Layton and Lee, 2006).[115]

The results of estimating our model for all six expectation hypotheses are displayed in Table 5.2.[116] It is immediately apparent that expectations hypotheses that dramatically curb sharing of information perform relatively poorly in our analysis; furthermore, models that suggest widespread and extensive sharing (e.g. model 1 and 2), although better in their predictions by comparison, fall short as well. Indeed, the best model according to the BIC criteria is model 3. This model suggests a sharp bifurcation in the information sets of fishermen and provides strong support for the anecdotal prior evidence provided to us by those close to the fishery. The evidence in favor of this informational hypothesis is compelling. BIC differences of over 10 are typically regarded as "very strong" evidence in favor of one hypothesis over another (Raftery, 1995), and the next best hypothesis is defeated by a margin of over 20. Indeed, if the BICs were used to construct posterior model weights in an approximate form of Bayesian model averaging (Buckland, et al., 1997, Layton and Lee, 2006), model 3 would receive over 99.9% of the weight! For this reason, we feel justified in the utilization of model 3 without further consideration of model uncertainty.[117]

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[115] In the comparison of two models, the approximate Bayes factor of model 1 vs. model 2 is $\exp\left(-BIC_1/2\right)/\exp\left(-BIC_2/2\right)$. The asymptotic properties of this approximation are somewhat crude – -1/2*BIC approximates the logarithm of the integrated log likelihood with an *O(1)* error – but Raftery (1995) provides compelling arguments that suggest that the degree of error in practice is frequently negligible.

[116] We should note that we treat this problem as one of "variable selection" without regard to the number of parameters required to estimate the various expectations hypotheses. This implies that the penalty term in the BIC has no substantive bearing on model selection since all models are of the same dimension. This assumption is warranted by the fact that expectation formation is assumed exogenous to choice behavior within our framework.

[117] Notwithstanding this strong result, the predictive abilities of each model were startlingly similar as measured by the "percentage correctly predicted" as also were most coefficient estimates. This suggests that all of the candidate expectations models were sufficiently close approximations to the "true" model to preserve the ordinal ranking of alternatives in most cases.

Table 5.2: Comparison of Expectations Hypotheses for RUM Model

| *Expectations Model* | *Description* | *BIC* | *BIC-BICmin* |
|---|---|---|---|
| 1 | Full sharing of target catch and halibut data for entire sample period. | 41,509 | 21 |
| 2 | Full sharing of target catch data for entire sample, no sharing of halibut prior to Sea State (SS), sharing according to Sea State participation status thereafter. | 41,529 | 41 |
| 3 | Full sharing of target catch data across initial SS and non-SS vessel groups (but none between groups), halibut sharing arrangement same as 2. | 41,488 | 0 |
| 4 | Full sharing of target catch data for initial SS group, no sharing of target catch data for initial non-SS group, halibut sharing arrangement same as 2. | 41,646 | 158 |
| 5 | No sharing of target catch data for initial SS group, full sharing of target catch data for initial non-SS group, halibut sharing arrangement same as 2. | 41,537 | 49 |
| 6 | No sharing of target catch data, halibut sharing arrangement same as 2. | 41,696 | 208 |

## 5.4 Estimation Results

We estimate the RUM model described above using a constrained likelihood maximization routine coded in GAUSS software. All told, we estimate 130 free parameters utilizing 45,200 observations. A complete reporting of parameter estimates and standard errors is presented in Appendix D along with a discussion of interesting, but for our purposes, peripheral, results on the control variables. It should be noted, nonetheless, that the vast majority of variables are not only highly statistically significant but also of the "correct" sign as dictated by both theory and previous studies.

Table 5.3 presents some key results concerning the fit of the RUM model as well as simple summaries of the heterogeneous parameters within the model and a battery of hypothesis tests on the model specification. A quick glance reveals that the model appears to fit the data quite well as evidenced by the high value of pseudo $R^2$.[118] This evidence of a strong fit is given

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[118] The pseudo $R^2$, also known as the "likelihood ratio index", is defined as one minus the ratio of the log likelihood of the model in question to one in which all parameters are zero and measures the improvement in the explanatory power of the model relative to one based on purely random guessing. Although the

further credence by the high percentage (nearly 85%) of correct predictions generated by our model (where a "correct" prediction is defined as an instance in which the alternative with the highest predicted probability coincides with the alternative that was actually chosen).[119] This prediction is defined, of course, over our subset of six alternatives, not the full choice set; however, a purely random model would guess correctly about 16.7% of the time, so the model still offers a substantial improvement.

The results of several likelihood ratio tests to test nested restrictions on the model are also given in Table 5.3. We find that each of the proposed restrictions is strongly rejected beyond all conventional levels of significance, the "weakest" rejection having a p value of $1\text{x}10^{-13}$. The results are thus supportive of a model where heterogeneity in both preferences and scale is important, where past own and competitor behavior influence current choices and where anticipated bycatch enters the spatial calculus of decision makers.

A glance at the summary statistics for the heterogeneous parameters is quite revealing. As predicted by theory, all vessels exhibit positive and significant attraction to areas with higher expected revenues; however, the degree to which skippers are "money driven" does vary somewhat in our sample – the most sensitive vessel has an attraction to spatial rent gradients that is over three times greater than that of the least sensitive vessel. A likelihood test rejects the equality of vessel-specific effects for the marginal disutility of distance; however, Table 5.3 also reveals that none of the vessel specific dummies for the marginal disutility of distance were individually significant. This result is likely indicative of the inclusion of vessel characteristics in our specification of the marginal disutility of distance; an earlier version of this

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value achieved here is quite high relative to many studies, there is little basis for the comparison of this statistic across different datasets or sets of alternatives (Train, 2003).

[119] Using a predictive $R^2$ to gauge model fit is not without its problems as it ignores the probabilistic nature of the model predictions (Train, 2003); it is, nonetheless, a commonly-reported and useful tool for assessing the predictive success of a model.

model without these characteristics did generate significant vessel-specific effects.[120]

The estimation results on the relative scale parameters are telling. Although a joint test of equality of scale is rejected, we nevertheless find a fairly narrow range of variation in the estimated values. We also find that four of the vessels have estimated scale values that cannot be statistically distinguished from the base vessel. These findings suggest that the remaining latent heterogeneity is fairly minimal and that each of the vessels is more or less comparable in their "predictability" given the covariates. This provides further confirmation of our choice of variables and the parsimonious specification of vessel/skipper heterogeneity.

Having established the appropriateness of our model, we now examine the key results of our model with respect to halibut avoidance and the implicit cost of distance.

Table 5.3: Summary of Key Estimation Results from RUM Model

| | Mean | Minimum | Maximum | Standard Deviation | Number Significant at 5% level* |
|---|---|---|---|---|---|
| Scale Parameter | 1.3021 | 0.9724 | 1.5416 | 0.1807 | 14 (of 18) |
| Marginal utility of revenue productivity | 0.5351 | 0.2724 | 0.8919 | 0.2033 | 19 (of 19) |
| Marginal disutility of distance -- constants | -0.6197 | -2.6789 | 3.9809 | 1.3860 | 0 (of 19) |
| State dependence dummies | -1.1026 | -3.0282 | -0.0570 | 0.8170 | 16 (of 19) |
| *Summary Stats* | | | | | |
| *N* | 45,200 | | | | |
| Number of Estimated Parameters | 130 | | | | |
| Log-likelihood | -20,027.29 | | | | |
| Pseudo $R^2$ | 0.7843 | | | | |
| Predictive $R^2$ | 0.8478 | | | | |

| *Likelihood Ratio Tests* | Chi-Square** |
|---|---|
| H0: Homogeneous Scale Parameters (dof=18) | 189.04 |
| H0: Homogeneous MU of Revenue Productivity (dof=18) | 112.10 |
| H0: Homogeneous State Dependence Dummies (dof=18) | 283.24 |
| H0: Homogeneous (Unobserved) Marginal Disutility of Distance (dof=18) | 101.84 |
| H0: No State Dependence Variables (dof=23) | 3854.04 |
| H0: No Herding Variables (dof=3) | 228.60 |
| H0: No Halibut Variables (dof=20) | 185.84 |

* These counts are based on two-sided z-statistics. The null hypothesis for the scale parameters is a value of 1.

** All of the chi-square values are well beyond the critical values at the 1% significance level.

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[120] It should be noted that this seeming insignificance in the vessel-specific distance effect is not indicative of insignificant total distance effects for any particular vessel. Indeed, as demonstrated in a later section, distance is a uniformly significant "bad" for all vessels in our sample.

### 5.4.1 The Marginal Implicit Cost of Halibut

The extensive specification of the marginal disutility of expected halibut bycatch combined with the difficulty of interpreting the unitless parameters of the RUM model combine to complicate our analysis. To overcome the second problem, we monetize the parameters of the marginal disutility of expected halibut bycatch by dividing them by the vessel-specific estimate of the marginal utility of expected revenue productivity. Since both expected revenues and halibut are specified in productivity terms, the effect is to produce the estimated marginal effects on the implicit cost of halibut from changes in each of the factors listed in Table 5.1. However, this procedure also generates 19 individual marginal effects for each covariate due to the varying marginal valuations of vessel rents. In an attempt to concisely summarize these marginal effects, Table 5.4 reports the median, minimum and maximum shadow costs (along with the standard error over the 19 vessels) of characteristics in terms of their influence on the implicit marginal cost of halibut bycatch. Asymptotic *z* statistics, calculated using the delta method (Greene, 2003), are also included in parentheses below the shadow cost estimates.

One of the first findings to arise from Table 5.4 is that the marginal effect of an increase in halibut quota scarcity for one quota allocation always acts to raise the marginal cost of a change in the scarcity of the other allocation (i.e. the coefficient on the quota scarcity cross-product term is positive as predicted). At high levels of quota availability for both quota categories it appears that an increase in halibut quota utilization for one target species (say yellowfin sole) may actually lead to a reduced shadow cost of expected halibut bycatch (i.e. less avoidance). In general, however, as both primary quota allocations grow "tighter" with the passing season, the "pure" effects of quota scarcity (which are both negative) are eventually overcome such that an increase in utilization of a particular quota category leads to *increased* halibut avoidance. Of course, the ability to verify the veracity of these claims is somewhat limited by the relatively low levels of significance on the linear quota utilization terms. This lack of significance is in large part due to the collinearity of the evolution of quota scarcity with the temporal trend controls in our model. However, to the extent that we hope to separate quota-driven influences on halibut avoidance from other time-varying factors, the trends are necessary.

The marginal influence of increased vessel participation is far more apparent. Vessels with a greater "stake" in the current halibut allocation (as measured by their future weeks of fishing within the current yellowfin sole PSC allocation) place a higher implicit cost on the bycatch of halibut and this avoidance is reflected by greater avoidance in their spatial decision making. Equivalently, fishermen have a greater tendency, ceteris paribus, toward greater halibut avoidance at the beginning of a season than toward the end. This finding is consistent with a model, such as that in Chapter 3, in which fishermen believe that their bycatch avoidance has some effect on the season closing date; otherwise, we would expect no substantial difference in bycatch avoidance based on anticipated participation. Fishermen seem willing to forego halibut bycatch in the present in order to "bank" it in hopes of utilizing it to enable the catch of target species in the future. However, as one grows nearer to exiting the fishery (either voluntarily or due to an anticipated closure) the impetus for such "investment" diminishes and so halibut avoidance diminishes.

The effect of an increase in the previous week's halibut mortality attributable to the yellowfin sole allocation is to reduce the implicit marginal cost of halibut in the current week. This result is sensible to the extent that mortality in the previous week serves as a forecast of the intensity of bycatch by one's competitors in the current week and perhaps even further into the future. In this case, a high current bycatch rate by one's competitors will undermine one's own efforts toward conservation of bycatch quota and so bycatch avoidance decreases as a rational response to these poor incentives.[121]

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[121] This effect is only found for halibut mortality accrued against the yellowfin sole allocation. Reasons for the insensitivity of halibut avoidance to competition for halibut in the rock sole/other flatfish allocation may be due to high collinearity between mortality in the two quota allocations or the fact that the primary value of this allocation over much of the season is as a "backstop" for when the yellowfin sole PSC allocation grows scarce.

Table 5.4: The Marginal Effects of Changes in Characteristics on the Implicit Marginal Cost of Expected Halibut Bycatch ($/kg)*

| | Median | Minimum | Maximum | Standard Deviation |
|---|---|---|---|---|
| Constant | $54.21 | $27.59 | $90.32 | $20.40 |
| | (1.75) | (1.77) | (1.77) | |
| % utilization yfs halibut quota | -$77.18 | -$128.59 | -$39.28 | $29.04 |
| | (-1.83) | (-1.86) | (-1.86) | |
| % utilization rs/of halibut quota | -$28.46 | -$47.41 | -$14.48 | $10.71 |
| | (-1.17) | (-1.18) | (-1.17) | |
| % utilization yfs halibut quota * % utilization rs/of halibut quota | $88.42 | $44.99 | $147.31 | $33.27 |
| | (2.14) | (2.20) | (2.17) | |
| Future vessel participation within yfs season (weeks) | $1.31 | $0.67 | $2.19 | $0.49 |
| | (2.64) | (2.74) | (2.67) | |
| Halibut mortality from yfs in previous week (mt) | -$0.10 | -$0.16 | -$0.05 | $0.04 |
| | (-2.16) | (-2.20) | (-2.26) | |
| Halibut mortality from rs/of in previous week (mt) | $0.01 | $0.01 | $0.02 | $0.00 |
| | (0.25) | (0.25) | (0.25) | |
| Closure dummy: yfs | -$19.59 | -$32.65 | -$9.97 | $7.37 |
| | (-3.54) | (-3.48) | (-3.78) | |
| Closure dummy: rs/of | $2.09 | $1.06 | $3.48 | $0.79 |
| | (0.72) | (0.72) | (0.72) | |
| Seasonal dummy: pre-96_season2 | $73.06 | $37.18 | $121.72 | $27.49 |
| | (3.31) | (3.64) | (3.36) | |
| Seasonal dummy: post-96_season2 | -$16.25 | -$27.08 | -$8.27 | $6.11 |
| | (-1.28) | (-1.29) | (-1.28) | |
| Seasonal dummy: post-96_season3 | -$19.37 | -$32.26 | -$9.85 | $7.29 |
| | (-1.65) | (-1.66) | (-1.67) | |
| Seasonal dummy: post-96_season4 | -$9.11 | -$15.17 | -$4.63 | $3.43 |
| | (-0.70) | (-0.70) | (-0.70) | |
| Annual trend | -$6.62 | -$11.02 | -$3.37 | $2.49 |
| | (-1.18) | (-1.17) | (-1.20) | |
| Annual trend^2 | $0.49 | $0.25 | $0.82 | $0.18 |
| | (0.85) | (0.86) | (0.84) | |
| Seasonal trend: # days remaining * pre-96_season1 | -$0.46 | -$0.77 | -$0.23 | $0.17 |
| | (-3.02) | (-3.02) | (-3.15) | |
| Seasonal trend: # days remaining * pre-96_season2 | -$0.75 | -$1.26 | -$0.38 | $0.28 |
| | (-3.95) | (-4.01) | (-4.41) | |
| Seasonal trend: # days remaining * post-96_season2 | $0.07 | $0.03 | $0.11 | $0.03 |
| | (0.26) | (0.26) | (0.26) | |
| Seasonal trend: # days remaining * post-96_season3 | $0.06 | $0.03 | $0.10 | $0.02 |
| | (0.72) | (0.72) | (0.71) | |
| Seasonal trend: # days remaining * post-96_season4 | -$0.10 | -$0.17 | -$0.05 | $0.04 |
| | (-1.32) | (-1.33) | (-1.33) | |

*Z Statistics are included in parentheses and are all derived using standard errors calculated by the delta method.

The effect of closures on the incentive to avoid halibut bycatch is telling. In the case of rock sole/other flatfish closures the effect is insignificant. Given the fact that these closures typically occur while the yellowfin sole targeted fishery remains active, it seems reasonable that the news of a closure would have little or no additional behavioral effect beyond the scarcity cross-effects we have already discussed. By contrast, the effect of yellowfin sole closures on the marginal cost of halibut bycatch is both large and negative. This diminished bycatch avoidance in the wake of a yellowfin sole closure is provocative and demands an explanation. One rationale that seems quite likely is motivated by the way bycatch is allocated to targeted species in the wake of closures and the nature of fishermen's alternative targets within the Bering Sea. Once yellowfin sole is closed to directed fishing, only a small proportion of its total catch can be retained for landing. This restriction, usually coincident with preexisting closures for rock sole/other flatfish, leads to changes in targeting and discard decisions that result in the accrual of halibut bycatch against alternative targets that either rarely face bycatch-driven closures or lack a PSC halibut allocation altogether.[122] As a result, the formerly binding quota constraint may go "slack" in the minds of fishermen so that the unintended effect of a PSC-induced closure is to foster *less* avoidance than immediately beforehand – a perverse result of the bluntness of retention restrictions as curbs on fishing behavior in a complex multi-species setting.[123]

The examination of the marginal impacts of covariates on the marginal cost of halibut, while useful, does little to illuminate the prevalence of bycatch avoidance behavior in our sample. To accomplish this we calculated the shadow cost of halibut over the unique vessel/day combinations in our dataset (a day being the finest temporal resolution of any of the covariates in the expression for the marginal disutility of halibut) and then calculated 2 standard error confidence intervals for these estimates using the delta method. A summary of these results is presented in Table 5.5.

Ultimately, we found that of the 10,657 unique vessel/day combinations, 5,240 (49%) had insignificant marginal costs of halibut bycatch with the sign of the estimated marginal cost

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[122] For instance, fishermen may forsake trawling the continental shelf waters with its high concentrations of "closed" species and instead target rockfish and turbot along the deeper waters of the continental slope.

[123] This criticism must be tempered by the observation that such closures encourage many fishermen to temporarily exit the fishery or dramatically curtail their participation so that the reduced incentive to avoid bycatch is often countered by the reduced effort in the fishery.

(benefit) of halibut being fairly evenly divided.[124] Perhaps more interesting, however, is the fact that 3,340 vessel/days (over 31%) had estimates of halibut shadow costs that were both positive and significant according to 2 standard error criteria.[125] Overall, there is weak evidence that skippers avoid halibut to a limited degree – the average implicit cost of halibut is $3.30/kg – but the dispersion of our estimates and the plurality of insignificant estimates suggests that bycatch avoidance is not a consistent feature of fishing behavior.

Table 5.5: Summary of the Marginal Shadow Costs of Expected Halibut Bycatch ($/kg)

| Criteria | Mean | Median | Min | Max | Standard Deviation | Count |
|---|---|---|---|---|---|---|
| Insignificant | -$1.01 | -$1.05 | -$22.18 | $17.22 | $5.25 | 5,240 |
| Positive & Significant | $20.95 | $15.36 | $3.21 | $102.41 | $16.42 | 3,340 |
| Negative & Significant | -$14.21 | -$11.45 | -$61.47 | -$2.88 | $9.18 | 2,077 |
| Entire Sample | $3.30 | $0.89 | -$61.47 | $102.41 | $16.76 | 10,657 |

Given the seasonally varying nature of many of the covariates that enter the marginal disutility of halibut, it is worthwhile to ask whether bycatch avoidance (or the lack thereof) fluctuates throughout the season. Figure 5.3 and Figure 5.4 show the monthly breakdown of the estimated marginal cost of halibut by sign and statistical significance; the years 1994-1995 and 1996-2000 are considered separately due to the subdivision of the January to August and August through December halibut allocations in 1996 to smaller seasons spanning (with some variation from year to year) January to April, April to early-May, early-May to mid-August, and mid-August to December. For both periods, there is a clear tendency toward the increased prevalence of bycatch avoidance (i.e. a greater proportion of positive and significant shadow cost estimates) in the late summer and fall months – a period which always coincides with the last PSC allocation

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[124] 2,950 were negative and insignificant while 2,290 were positive and insignificant.

[125] Of course this implies that there were 2,077 (19%) vessel/days where the marginal implicit cost of halibut was negative and statistically significant – thus indicating *targeting* of halibut bycatch over a limited portion of our sample. We lack a convincing explanation for such behavior, but at least some of these values can be attributed to our flexible, but unbounded, linear specification of the marginal disutility of halibut.

period for yellowfin sole. This pattern is especially strong in 1994 and 1995 where significant halibut avoidance is ubiquitous in the later months of the season and is largely driven by the effects of seasonal dummies and trends for this period of analysis (see Table 5.4).[126]

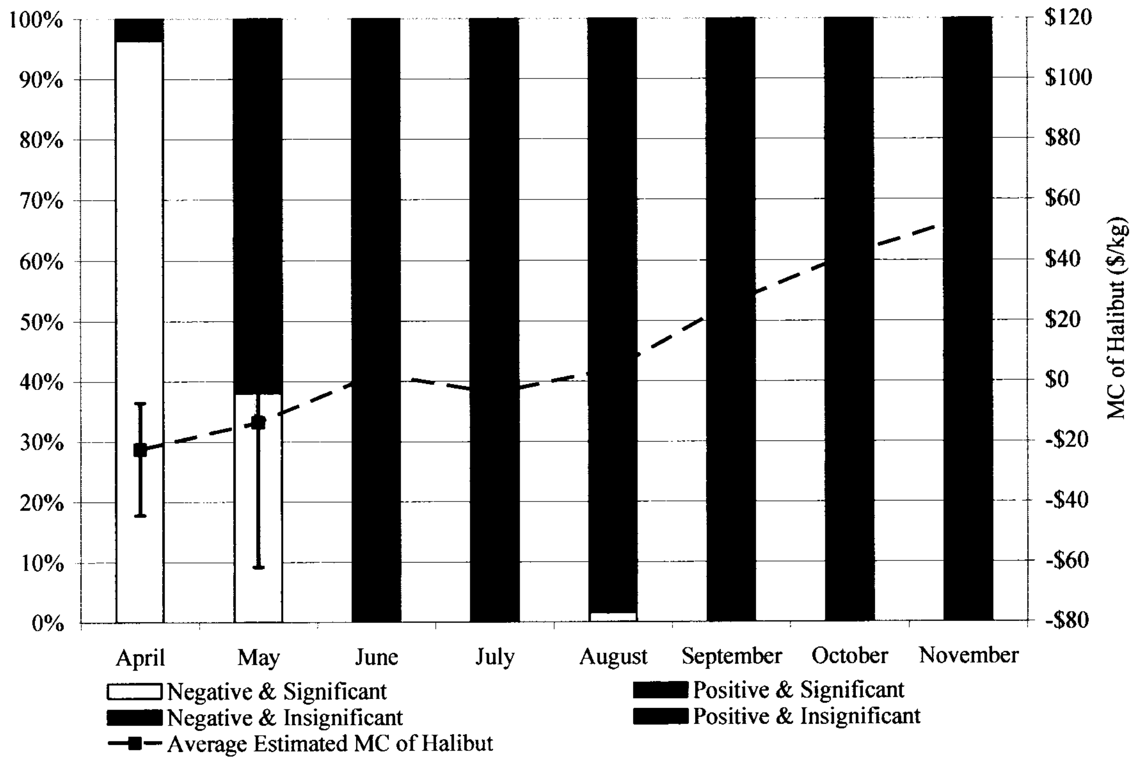

Figure 5.3: Monthly Breakdown of 1994-1995 Marginal Costs of Halibut Bycatch with Average Estimated MC and Minimum/Maximum Envelope

The pattern of bycatch avoidance for the years 1996 to 2000 shares some of the same regularities as for the earlier years – namely, a strong tendency in the fall months toward widespread avoidance of halibut at the cost of expected revenues with weak or nonexistent evidence of avoidance in the prior months. However, there are some notable differences. The strong evidence of almost immediate bycatch avoidance in the final season of the 1994-1995 period is supplanted by gradually increasing evidence of avoidance and an upward trajectory in the estimated shadow cost of halibut as the season progresses. Furthermore, although the paths of

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[126] The reason for this unusually strong end-of-season avoidance behavior in the early years of our study is uncertain.

the average monthly shadow cost of halibut for the two periods share the same qualitative trend, the strength of avoidance evinced in the early years is not shared for 1996 to 2000 – again largely due to the lack of a significant exogenous seasonal effect in this period.

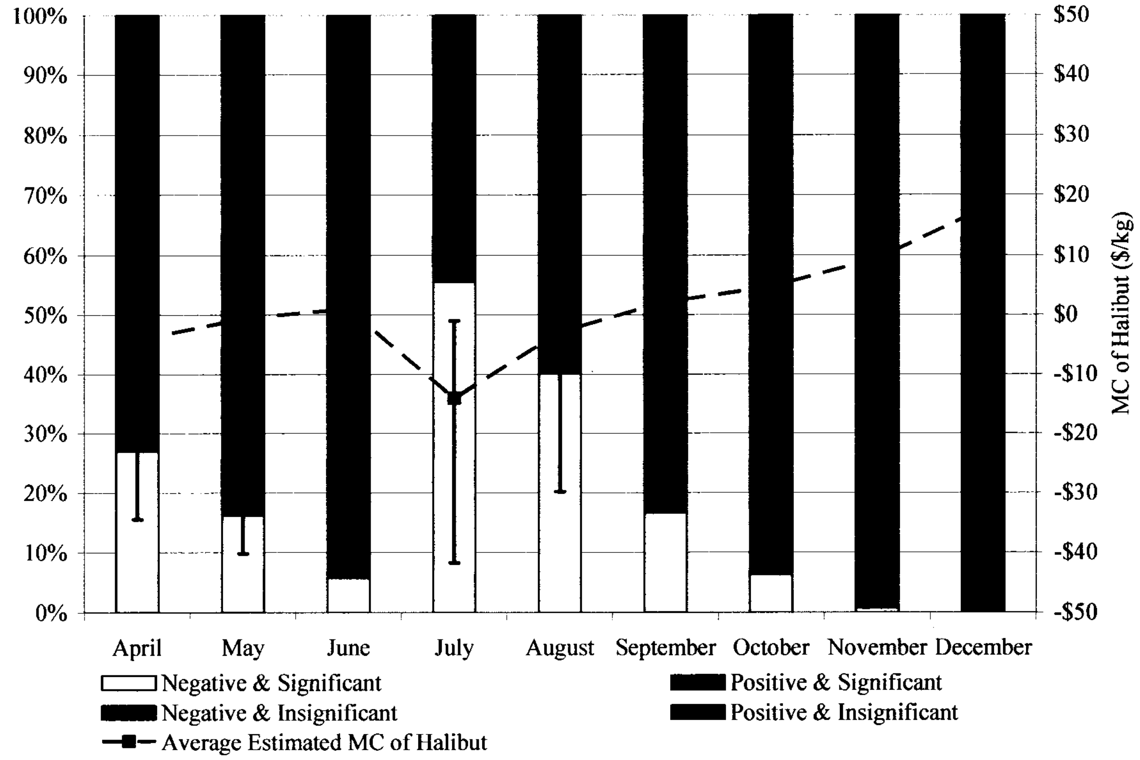

Figure 5.4: Monthly Breakdown of 1996-2000 Marginal Costs of Halibut Bycatch with Average Estimated MC and Minimum/Maximum Envelope

To illustrate the effects and relative importance of drivers of intra-seasonal movements of the implicit cost of halibut and thus better understand the motivating forces behind bycatch avoidance, we consider the path of the estimated implicit marginal cost of halibut for a typical vessel in the year 2000.[127] Figure 5.5 shows the evolution of this cost over a season (gaps in the time series are due to days of inactivity) while Figure 5.6 breaks this cost into its additive parts. One can obtain the total marginal cost of halibut (indicated in red diamonds) by summing the remaining effects.

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[127] Note that, due to the lack of a vessel-specific effect in the marginal disutility of halibut, the temporal paths of halibut shadow costs will all follow the same trends with the numerical values differing only due to the heterogeneous marginal utility of revenues.

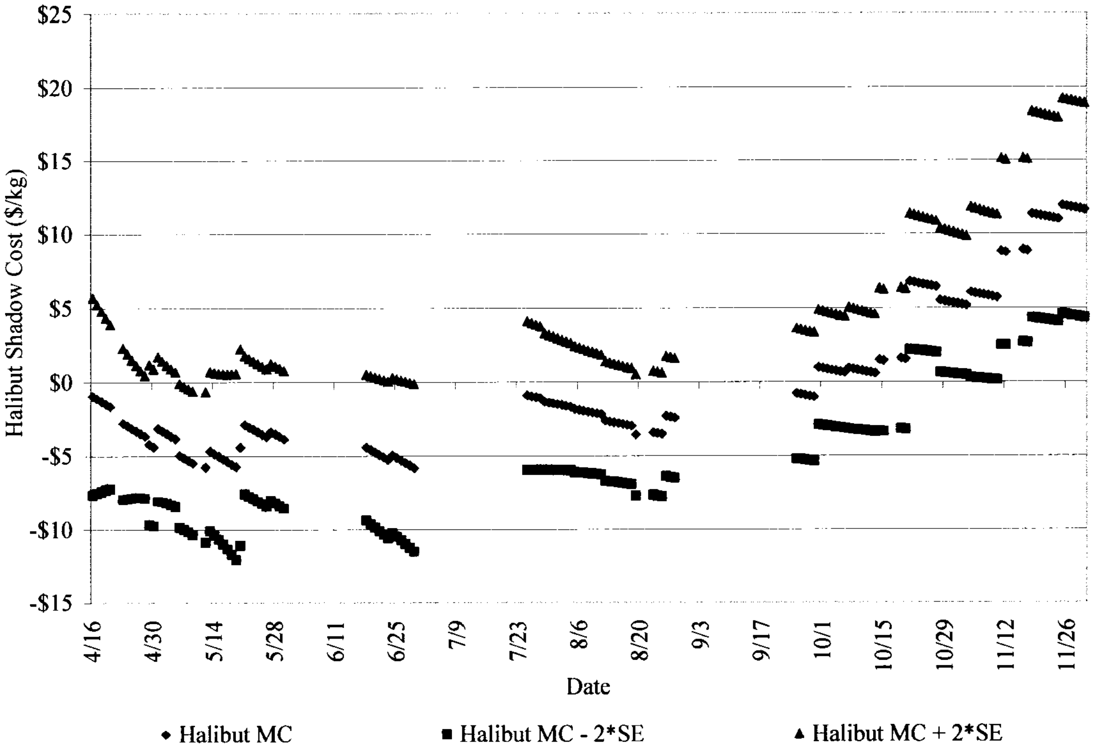

Figure 5.5: Daily Evolution of Estimated MC of Halibut for a Particular Vessel in 2000

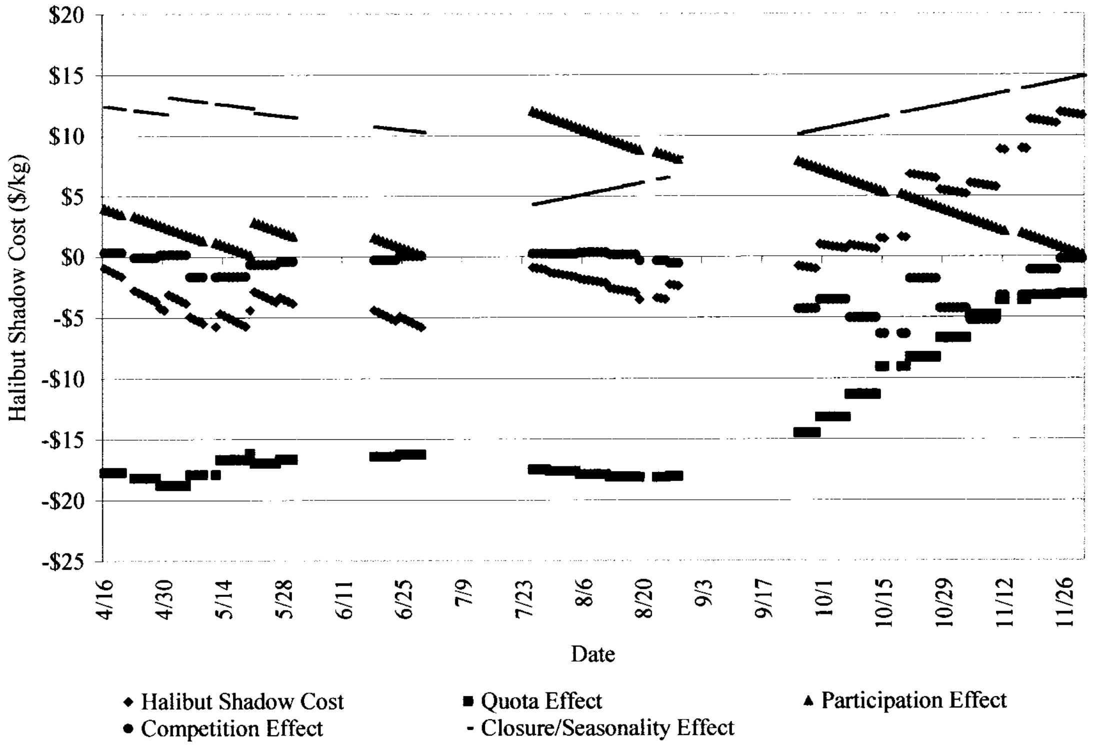

Figure 5.6: Components of Estimated MC of Halibut for a Particular Vessel in 2000

An examination of the "structural" components of the implicit cost of halibut (i.e. every factor aside from the seasonal trends) is enlightening in a number of ways. First, the magnitude of the quota scarcity and future participation effects are quite large when quota is relatively plentiful in a joint sense or when the horizon of remaining participation is quite long, respectively. Despite these large effects, the magnitude and movements of these two factors are often countered by residual seasonal effects so that the estimated marginal cost of halibut (whether positive or negative) is often quite small. Second, the effect of the strength of anticipated competition for halibut quota in a particular week, while statistically important, is often quite small; however, when recent experience suggests bycatch mortality will be particularly strong (as in the final weeks of the season), then this "competition effect" can significantly curb halibut avoidance behavior. Finally, the strong cross-effect that occurs with the joint tightening of remaining yellowfin and rock sole halibut quota can serve to increase the implicit cost of halibut to fishermen over a period of just a few weeks. It is primarily this "quota scarcity effect" that drives the observed late-season increase in halibut avoidance behavior in 2000, and it has similar effects for other years as well (although its relative importance is less for the 1994-1995 period). Given that marked halibut avoidance is primarily a late-season phenomenon, it appears that the primary driver of halibut avoidance, at least since 1995, lies in skipper perceptions of quota scarcity.

### 5.4.2 The Marginal Implicit Cost of Distance

To produce a monetary measure of the perceived marginal cost of distance and the effects of various covariates on this cost, we begin, as with the marginal cost of halibut, by dividing the estimated coefficients of the marginal disutility function by the vessel-specific marginal utility of revenue. However, since the costs of travel between sites are accrued over the total number of hours spent fishing a tow while the marginal utility is in productivity terms, we must deflate the resulting coefficients by the expected duration of fishing. To do this, we simply divide our estimates by the average duration of haul observed in our sample – 3 hours.

The combined effect of the covariates on the marginal cost of distance is quite clear and consistent with prior expectations from the economic literature. Of the 10,657 unique vessel/day combinations in our data, every estimated marginal cost is positive and distinguishable from zero at the 1% level – providing strong evidence that distance is a "bad" in all circumstances. However, the aversion to distance is quite variable in our sample. The frequency distribution of estimated implicit costs is given in histogram form in Figure 5.7. On average, an extra kilometer of travel commands an implicit cost of $26.25 with estimates ranging between $11.30 and $42.96. Explaining this considerable latitude leads to a serious reappraisal of exactly what is hidden in the cost terms of models of spatial choice and the relative importance of technology and regulations in shaping these costs.

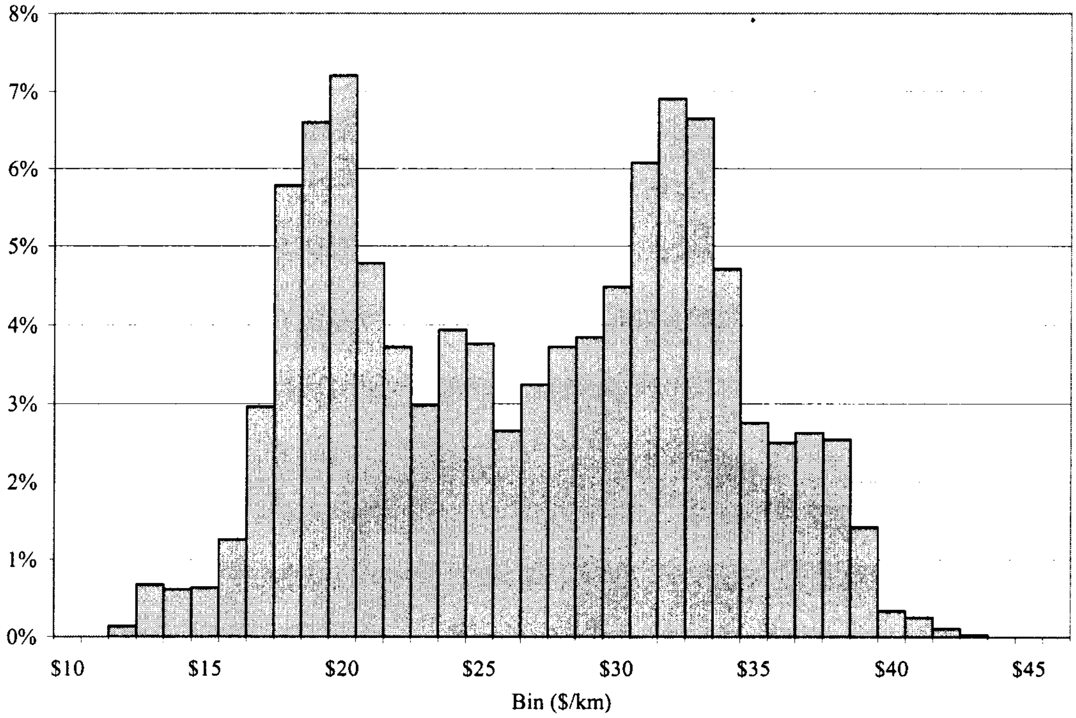

Figure 5.7: Histogram of Estimated MC of Distance for Entire Sample

Table 5.6 reports the marginal effects of vessel characteristics and fishery conditions on the marginal implicit cost of an extra kilometer of travel between fishing sites. The results for horsepower and the product of horsepower and vessel length, although not uniformly significant, are suggestive of a simple and logical technological relationship. The effect of an increase in the length of a ship on the costs of travel are uniformly positive due to relatively inflexible linkages between length and the mass of a vessel and, ultimately, the energy consumption needed to reach and maintain cruising speeds. The effects of increases in horsepower are not quite so simple – they appear to depend critically upon the length of the vessel. Nevertheless, all vessels in our sample are all of sufficient size that an increase in horsepower is estimated to *increase* the marginal cost of travel.[128] In other words, any cost gains due to reduced travel time from increases in power are more than offset by the additional operation costs. Furthermore, the magnitude of these incremental costs is amplified by increases in the size of the vessel.

Despite these results, very little of the variation apparent in Figure 5.7 can be attributed to cross-vessel heterogeneity. A simple regression of the estimated marginal costs of distance on the component attributable to observed vessel characteristics (this being the sum of the horsepower and horsepower/vessel length interaction terms) explains less than 1% of the variation around the sample mean, and the maximum divergence in per-mile costs across vessels in our sample that is attributable to observed vessel characteristics is approximately $4.80.[129] Furthermore, an examination of the range between the maximum and minimum marginal cost of distance for each particular vessel and year combination revealed that these varied from between $6 to $9 – suggesting that costs can vary substantially over a fine temporal scale and this variation can outweigh cost differences due to variations in vessel characteristics.

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[128] One can imagine that there is an optimal (i.e. variable cost minimizing) horsepower for each vessel length, thus necessitating the inclusion of a squared term for horsepower. However, this term proved highly insignificant in previous specifications and so was dropped it from the model.

[129] A similar regression which included *unobserved* heterogeneity in costs as well yielded practically identical results.

A quick glance at Table 5.6 suggests an explanation for the in-season variation. The three terms that reflect quota scarcity are all of substantial magnitude and statistical significance. The pure effect of increases in quota scarcity (represented by the two linear terms) is to *increase* the cost of distance while the joint effect of this increase (represented by the cross-product term) is to offset these pure effects somewhat. The effect of an increase in quota utilization for the yellowfin sole allocation of halibut on the marginal cost of travel is consistently positive over the sample but diminishing as joint scarcity increases. A similar effect seems to hold true for the rock sole/other flatfish allocation as well, although we cannot preclude the possibility that the effect of increased scarcity in this allocation may be to *decrease* the cost of distance for particularly high levels of quota utilization in the yellowfin sole allocation.[130]

Interestingly, the signs of these three terms are precisely the opposite of their counterparts in Table 5.4 for the marginal cost of halibut bycatch. In other words, movements in quota scarcity that act to lower (raise) the implicit value of halibut bycatch tend, on many occasions, to raise (lower) the marginal cost of distance. This effect is understandable via the following competitive mechanism. Suppose that joint quota scarcity is such that an increase in the scarcity of one quota allocation causes everyone to exert more care in avoiding halibut than before.[131] Knowing this, each fisherman will now anticipate lower bycatch rates from their competitors in any unit of time. The result is to lower the opportunity cost of time spent in activities other than fishing – thus lowering the cost of steaming between sites. In other words, the qualitative effects of quota scarcity for the marginal implicit cost of halibut and distance should be mirror images of one another since one's competitors are assumed to act according to the same personal incentives as face each individual fisherman. The importance of quota scarcity on the movement of the marginal perceived cost of distance should not be underestimated. A simple regression of the estimated marginal costs of distance on the quota scarcity component reveals that more than 51%

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[130] This coincidence of tight yellowfin quota and slack rock sole/other flatfish halibut quota is not an empirical reality in our data, however.

[131] The same argument works in reverse if an increase in quota scarcity causes *less* avoidance.

of the variation in marginal costs about the mean can be explained by variations in available quota alone.

The effects of future participation and bycatch competition, unlike those of quota scarcity, seem to have at best a minor role to play in the explanation of movements in the cost of distance. Since vessels with greater anticipated participation have been found to place higher values on halibut bycatch, one would perhaps expect their opportunity cost of distance to increase in participation; however, the effect of participation is found to be trivial in magnitude and highly insignificant (not to mention of the wrong sign). Similarly, one might surmise that the fleet-wide decrease in halibut avoidance that arises from high competition for bycatch in the yellowfin sole allocation in the previous week would cause the opportunity cost of time engaged in non-fishing activities to rise. However, precisely the opposite effect is found (although it is of small magnitude).

Explaining these results is a challenging task. Although the overarching model of spatial choice is structural in its conception, the specification of the shadow cost terms, while informed by economic theory, is ultimately a flexible reduced-form approximation to a complex dynamic and strategic process. As such, it suffers from the problems of interpretation endemic to such models. Nonetheless, a reasonable explanation of the contrary sign on the bycatch competition term can be ventured by careful consideration of the countervailing effects of fleet-wide movements of the implicit marginal cost of bycatch. When the implicit value of bycatch declines (as from high anticipated bycatch mortality rates), overall avoidance declines, raising the expected foregone bycatch (and thus future target catch) per unit of steam time. However, the personal marginal valuation of each unit of this lost bycatch also declines. Which effect dominates is an empirical question; our analysis suggests the latter, although the overall effect is quite small.[132]

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[132] A similar logic may be behind the insignificant results for vessel participation.

Perhaps the most telling result of our analysis is reflected in the negative and significant effect of a closure in the yellowfin sole fishery due to halibut bycatch. The simple triggering of a closure in this fishery has the instantaneous and highly statistically significant effect of diminishing the incremental cost of distance by anywhere from $2.55 to $8.35 per kilometer. As mentioned in the previous section, the closure of the directed yellowfin sole fishery often has the effect of driving those fishermen that remain active in the fishery into the targeting of species for which PSC allocations of halibut are either nonexistent or not typically binding. The effect is dramatically lessened halibut avoidance; however, in such situations the bycatch of one's competition is no longer relevant as there is now plenty of bycatch "pie" to spread across the remaining (smaller) fleet. As a result, the implicit cost of distance declines substantially in response to the closure.[133]

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[133] Note that potentially collinear seasonal and quota scarcity effects are thoroughly accounted for in our specification so that this effect is indeed quite likely triggered by the closure itself and not some unobserved correlated factor.

Table 5.6: The Marginal Effects of Changes in Characteristics on the Implicit Marginal Cost of Distance ($/km)

| | Median | Minimum | Maximum | Standard Deviation |
|---|---|---|---|---|
| Constant | -$5.30 | -$15.77 | $15.08 | $7.15 |
| | (-0.94) | (-0.96) | (2.18) | |
| % utilization yfs halibut quota | $35.66 | $18.14 | $59.41 | $13.42 |
| | (3.15) | (3.15) | (3.39) | |
| % utilization rs/of halibut quota | $21.67 | $11.03 | $36.10 | $8.15 |
| | (3.10) | (3.10) | (3.33) | |
| % utilization yfs halibut quota * % utilization rs/of halibut quota | -$28.46 | -$47.41 | -$14.48 | $10.71 |
| | (-2.87) | (-3.04) | (-2.85) | |
| Future vessel participation within yfs season (weeks) | -$0.01 | -$0.02 | -$0.01 | $0.00 |
| | (-0.09) | (-0.09) | (-0.09) | |
| Halibut mortality from yfs in previous week (mt) | -$0.03 | -$0.05 | -$0.02 | $0.01 |
| | (-2.59) | (-2.78) | (-2.64) | |
| Halibut mortality from rs/of in previous week (mt) | $0.00 | -$0.01 | $0.00 | $0.00 |
| | (-0.52) | (-0.52) | (-0.52) | |
| Closure dummy: yfs | -$5.01 | -$8.35 | -$2.55 | $1.89 |
| | (-3.64) | (-4.08) | (-3.72) | |
| Closure dummy: rs/of | $0.17 | $0.09 | $0.29 | $0.07 |
| | (0.25) | (0.25) | (0.25) | |
| Horsepower (1000s) | -$5.18 | -$8.63 | -$2.64 | $1.95 |
| | (-1.47) | (-1.50) | (-1.48) | |
| Horsepower (1000s) * Vessel length (100s ft) | $4.44 | $2.26 | $7.39 | $1.67 |
| | (3.02) | (3.06) | (3.25) | |
| Average Wind Speed (mph) | $0.10 | $0.05 | $0.16 | $0.04 |
| | (2.33) | (2.35) | (2.43) | |
| Seasonal dummy: pre-96_season2 | -$7.73 | -$12.88 | -$3.93 | $2.91 |
| | (-2.55) | (-2.64) | (-2.56) | |
| Seasonal dummy: post-96_season2 | $1.05 | $0.53 | $1.74 | $0.39 |
| | (0.40) | (0.40) | (0.40) | |
| Seasonal dummy: post-96_season3 | $3.18 | $1.62 | $5.30 | $1.20 |
| | (1.39) | (1.39) | (1.41) | |
| Seasonal dummy: post-96_season4 | $4.90 | $2.49 | $8.16 | $1.84 |
| | (1.75) | (1.74) | (1.79) | |
| Annual trend | -$3.79 | -$6.32 | -$1.93 | $1.43 |
| | (-2.64) | (-2.76) | (-2.62) | |
| Annual trend^2 | $0.38 | $0.19 | $0.63 | $0.14 |
| | (2.48) | (2.47) | (2.58) | |
| Seasonal trend: # days remaining * pre-96_season1 | $0.04 | $0.02 | $0.07 | $0.02 |
| | (1.33) | (1.33) | (1.35) | |
| Seasonal trend: # days remaining * pre-96_season2 | $0.08 | $0.04 | $0.13 | $0.03 |
| | (3.05) | (3.04) | (3.22) | |
| Seasonal trend: # days remaining * post-96_season2 | $0.28 | $0.14 | $0.46 | $0.10 |
| | (2.90) | (2.89) | (3.06) | |
| Seasonal trend: # days remaining * post-96_season3 | -$0.03 | -$0.05 | -$0.01 | $0.01 |
| | (-1.56) | (-1.58) | (-1.58) | |
| Seasonal trend: # days remaining * post-96_season4 | -$0.001 | -$0.002 | -$0.001 | $0.0005 |
| | (-0.07) | (-0.07) | (-0.07) | |

*Z Statistics are included in parentheses and are all derived using standard errors calculated by the delta method.

## 5.5 Conclusion

We have successfully specified and estimated a sophisticated model of fishermen's choice of fishing location when the attractiveness of a potential fishing site depends not only on well-known factors such as expected revenues and the direct monetary costs incurred in reaching the site, but also upon the expected bycatch at the site and the cost of the lost future fishing opportunities due to interim bycatch by one's competitors. We develop a sophisticated model of expectations formation that combines multiple data sources over diverse temporal and spatial scales in a manner that is consistent with their informational value, and we utilize this model in combination with an efficient sampling from alternatives algorithm to tractably estimate our model over an unusually fine temporal and spatial scale.

Our estimates of the implicit marginal cost of halibut bycatch suggest that halibut avoidance may be negligible for a significant portion of the season – a finding consistent with the multi-product "tragedy of the commons" modeled in Chapter 3. However, we also uncovered substantial evidence inferring that halibut avoidance (or the lack thereof) is a highly fluid phenomenon and responds in economically sensible ways to factors such as a vessel's participation horizon, the intensity of recent bycatch mortality in the fishery and, most importantly, the scarcity of remaining bycatch quota. There is particularly robust evidence of marked halibut avoidance behavior in the waning moments of the fishery that is driven by the erosion of the scarcity effects as quotas tighten and, in earlier years, by unexplained seasonal trends.[134]

Despite the presence of significant halibut avoidance behavior at points during the season, the implicit marginal cost of halibut to fishermen is nevertheless well below its value to the fleet as a whole. Simple ratio estimates of the average quantity of revenue generated per kilogram of

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[134] The observed exogenous trend toward heightened avoidance in the late season may be driven in part by the very few outside fishing opportunities at this time of year. In other words, fishermen may avoid halibut to a greater degree in the fall because they lack economically viable outside opportunities if they fail to do so.

halibut suggest an estimate in the range of $200 is appropriate for much of this time period. This estimate is clearly distorted by the poor marginal incentives presented to fishermen and is thus a crude underestimate of the marginal value of a unit of halibut in a model of quasi-rent maximization (see Larson, et al. (1996)); nevertheless, it provides an average indication of how much revenue (before the subtraction variable costs) can be obtained from an extra unit of halibut. Although netting out average variable costs of harvest and production would diminish this quantity somewhat, it is quite clear that an average implicit cost of bycatch of approximately $3 is clearly subpar from the vantage point of fleet-wide rent maximization subject to quota constraints.

The findings concerning the perceived marginal cost are likewise quite revealing. In addition to variations in costs due to observed and unobserved vessel heterogeneity, there appears to be a substantial additional cost to travel between sites that is inherent to the common property system of management. An initial reasonable estimate of the per-mile deadweight loss would be at least $5 – this being the instantaneous median reduction in travel costs when fishermen are no longer constrained by the PSC allocation on yellowfin sole. This being said, our specification provides substantial evidence that this loss is highly flexible over the course of a season and is well explained by movements in quota scarcity, so that this initial estimate may be an underestimate.

This additional cost of distance suggests that fishermen under a common property management regime are likely to show a greater degree of inertia in their spatial behavior than is justifiable by either their direct costs or from state dependence. This inertia constitutes a uniquely spatial symptom of common property management, and has not, to our knowledge, been mentioned in previous theoretical or empirical work.

The results of this behavior could be far-reaching and are worthy of further investigation. For instance, given that bycatch composition is often driven by spatial behavior, the added inertia from the "common property effect" could serve to further hamper the economic feasibility of bycatch avoidance by dampening the sensitivity of fishermen to spatial gradients in relative revenues and bycatch rates. This sluggishness could also exacerbate problems of habitat loss and localized depletion due to excessive "mining" of fishing grounds on a repeated basis.

# Chapter 6

# The Effectiveness of a Cooperative Program of Bycatch Avoidance

> *"Unless the number of individuals in a group is quite small, or unless there is coercion or some other special device to make individuals act in their common interest, rational, self-interested individuals will not act to achieve their common or group interests."* – Mancur Olson (1965)

This statement from *The Logic of Collective Action*, provocative at the time of its publication, effectively summarizes much of the received wisdom from noncooperative game theory on the prospects for cooperation in the provision of public goods or the management of common property resources. Indeed, the sustenance of cooperative behavior among rational and narrowly self-interested agents has been the subject of theoretical research by economists and political scientists for decades with the now commonplace finding that cooperation is typically only sustainable within the class of infinitely repeated games, and then only when agents are sufficiently forward-looking in their outlook (i.e. their discount rate is not too high).

Notwithstanding this gloomy prospect, there are innumerable real-world examples of successful cooperative management of common property resources by the resource users themselves – often with little or no external coercion.[135] The Ejido forests of Mexico (Arnold, 1999), the pastures of Törbel in Switzerland (Ostrom, 1990) and the lobster fisheries of Maine (Acheson, 1987) have all been successfully managed at local levels under common property regimes. Furthermore, there is substantial evidence from laboratory experiments (e.g. Ostrom et al. (1994), Ostrom et al. (1992) and Walker et al. (1990)) which suggests that while collective behavior may fall short of the social welfare maximizing solution, people are often far more

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[135] Ostrom (1990) and McCay and Acheson (1987) consider a number of these cases. An extensive bibliography on common property research can be found at http://dlc.dlib.indiana.edu/.

cooperative in their behavior than predicted by narrow self interest alone. This experimental and anecdotal evidence has spawned extensive research among social scientists on the theoretical justification for collective action and the evolution of social norms for cooperative resource use.[136]

The predictions and findings from the previous chapters have been broadly consistent with the view of the world embodied in the "tragedy of the commons". In Chapter 5 we discovered that fishermen undervalue halibut bycatch in their spatial decision making relative to its overall value to the fleet as an unavoidable complement of target catch. Nonetheless, fishermen do frequently exhibit a positive willingness to pay for the avoidance of halibut, and the strength of this avoidance is responsive to conditions on the grounds such as quota scarcity, the horizon of participation and the recent level of competition for bycatch TAC. If we rule out purely altruistic behavior as a cause, these findings suggest a model in which fishermen perceive that their behavior influences the equilibrium outcome and their optimal strategy depends upon the behavior of their competitors. In other words, head and gut fishermen interact in a *strategic* manner with one another.

Given the small number of vessels (and even smaller number of companies) involved in the fishery and the stable patterns of participation over the years, it is entirely possible that fishermen may band together in a cooperative manner to avoid bycatch. This cooperation could take a range of forms such as sharing of information (either passively in the process of independent fishing or actively through coordinated search behavior), the forming of implicit or explicit agreements to avoid bycatch hot spots or an agreement to reward or punish defectors (in spite of the positive costs of doing so) for their "dirty" fishing behavior.

The voluntary implementation of the Sea State program in 1995 appears to combine all of these elements of cooperation. Only participating vessels were made privy to rapidly updated bycatch rate information. Receipt of this information often led to informal arrangements among

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[136] Ostrom (2000) provides a concise introduction to this literature.

skippers to avoid fishing in certain areas (although fleet-wide teleconferences and explicit agreements did not develop until relatively recently). Also, the spatial display of daily bycatch rate information, while technically anonymous, when combined with radio communications and visual observations often allows captains to identify the bycatch rates of their competitors and to monitor their own behavior relative to their competitors while potentially utilizing this knowledge to encourage "dirty" fishermen to change their behavior.[137]

In this chapter we utilize observer data to consider the success of Sea State in curbing bycatch for the head and gut fleet for the April-November fishery targeting yellowfin sole and several other groundfish species. The first section uses summary statistics and simple reduced form models to consider the success of Sea State in curbing bycatch *outcomes* (as measured by weekly bycatch rates). The second section expands upon the structural model of Chapter 5 to determine if fishermen who joined Sea State exhibit markedly different implicit costs of halibut in their spatial decision making than those who did not. The third section comments upon our findings and provides a comparison between the success of Sea State in the yellowfin and rock sole roe fisheries.

## 6.1 Did Sea State Lower Bycatch Rates?

In addressing the success of Sea State, it helps to be more precise in defining the question. First of all, our primary measure of improvement for the fishery is the bycatch rate of halibut relative to other total groundfish (measured in kg/mt). We believe that groundfish catch provides the appropriate denominator in this context given the range of targeting practices demonstrated in Chapter 2. Secondly, we wish to define an improvement in bycatch rates in a counterfactual sense, meaning that ideally we would like to compare the bycatch rates of Sea State participants across time to the unobserved bycatch rates they would have exhibited had they not participated.

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[137] Given the extra-legal nature of cooperation in the fishery, fishermen are limited in their ability to impose costs upon one another. The primary economic deterrent appears to be the withholding of valuable information on the distribution of targeted species.

For example, simply showing a downward trend in bycatch after the implementation of Sea State is not sufficient to prove its success – other temporally varying factors may be behind the improvement. Conversely, even if bycatch rates increase in the wake of Sea State, it may nevertheless be the case that bycatch rates are lower than they might have been in the absence of the program.

In approaching this counterfactual we are aided by the fact that participation in Sea State was not initially unanimous across the head and gut fleet. One company of four to six active vessels opted out of the program for a period of several years until joining sometime around the 1999 season.[138] As such they were not directly privy to the information given to fishermen through Sea State. It is also highly unlikely that significant information leakage between Sea State and non-Sea State vessels occurred given the assertions of fishermen (Hezel, 2006) and the findings from our own tests of informational hypotheses in Chapter 5 which support a clear bifurcation of revenue sharing between the two vessel groups. By utilizing the non-participatory vessels as a comparison group before and after the advent of Sea State we can actually gain some insight into the counterfactual. Before embarking on this analysis, however, a simple comparison of summary statistics for the two groups is useful.

### 6.1.1 Summary Statistics

The data employed in this chapter are the species composition-sampled hauls from onboard observers for 18 vessels from 1992 to 2000. This sample consists of 12 Sea State participants and 6 that initially did not join.[139] As in the previous chapter, we limit our attention to vessels with 100% observer coverage due to the potentially unrepresentative nature of the observer data for smaller, partially-covered vessels. This results in the exclusion of 6 Sea State

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[138] Our attempts to establish the exact date of Sea State participation for these vessels have not been successful; however, the estimate of 1999 is based on information from a reliable industry source (Gauvin, 2006). Also, we conduct our analysis in a way that is robust to this uncertainty.

[139] Each of these vessels participated in the fishery before and after Sea State. There is one less vessel in our sample than in Chapter 5 because one vessel, the Seafreeze, did not enter the fishery until 1999. We eliminate it due to our inability to control for its behavior before Sea State.

member vessels from our sample (but complete coverage of non-participants). Strictly speaking, our conclusions can only be applied to the vessels in our sample, although the sampling of Sea State vessels is likely sufficient to support more general conclusions. Finally, we limit our attention to the period between April and November in order to focus on the fishery for yellowfin sole and the avoidance of halibut. We eliminate December from our sample since very few hauls occur in this month due to closures and weather concerns.

In order to dampen the role of random variability in our sample, thin the proportion of zero bycatch rates and eliminate a large degree of serial correlation between successive hauls, we choose to aggregate bycatch rates on a weekly basis. Table 6.1 presents summary statistics of these bycatch rates by year and by the participatory and non-participatory groups. The distribution of bycatch rates is predictably skewed with a significant mass at zero (particularly in the earlier years of our sample) and a long right tail (as revealed by the substantial difference between mean and median rates in most years).[140] These statistics suggest that the central tendency of bycatch rates is typically quite low, particularly in the early and mid 1990s, and that the mean bycatch rate is determined by a small percentage of "dirty" hauls, regardless of which group a vessel belongs to.[141] Of course, in extrapolating this aggregate result to individual vessels we risk committing the "ecological fallacy". Heterogeneous central tendencies in bycatch rates across vessels could produce a similar pattern; however, the regression analysis of the next section suggests that vessel specific effects are not particularly important in defining the aggregate distribution of bycatch rates.

Considering the evolution of bycatch rates over the years, it seems clear that there is an overall upward trend in bycatch rates over this time period. This trend is especially noticeable

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[140] We should stress that these are *estimated* bycatch rates. Some incorrect zero values are the inevitable result of a random sampling protocol. Accidental oversampling of PSC catch may also occur, leading to inflated estimates of halibut bycatch.

[141] We do not attempt to identify "dirty" and "clean" weeks since this classification is highly dependent upon the context. Also, a "clean" bycatch rate for one target classification may be unacceptable for another. Unfortunately, the target of a week's hauls can be manipulated by retention and targeting decisions late in the week and is therefore likely to be driven by recent bycatch outcomes.

beginning in 1996; however, there is some evidence of upward creep in the higher quantiles of the frequency distribution of bycatch rates in the preceding years. The upward trend accelerates in the last three years of our sample with median bycatch rates doubling or even tripling the rates in preceding years. This finding may support the claims of fishermen that the abundance of halibut in the Bering Sea has grown significantly over recent years (Hezel, 2006).

Table 6.1: Quantiles and other Summary Statistics for Weekly Halibut/Groundfish Bycatch Rates (kg/mt)

| Year | | 10% | 25% | 50% | 75% | 90% | Mean | Wilcoxon Rank-Sum z Statistic |
|---|---|---|---|---|---|---|---|---|
| 1992 | Sea State | 0 | 0 | 0.9 | 6.5 | 16.8 | 5.8 | |
| | Non-Sea State | 0 | 0 | 2.1 | 7.3 | 16.6 | 6.1 | 1.04 |
| | All | 0 | 0 | 1.4 | 7.2 | 16.7 | 5.9 | |
| 1993 | Sea State | 0 | 0.4 | 2.4 | 7.4 | 16.5 | 6.0 | |
| | Non-Sea State | 0 | 0 | 2.0 | 13.5 | 31.3 | 10.7 | 0.64 |
| | All | 0 | 0.1 | 2.2 | 9.1 | 21.5 | 7.9 | |
| 1994 | Sea State | 0 | 0 | 1.6 | 8.1 | 21.1 | 8.9 | |
| | Non-Sea State | 0 | 0 | 1.1 | 9.5 | 27.7 | 12.3 | -0.06 |
| | All | 0 | 0 | 1.5 | 8.2 | 25.1 | 10.4 | |
| 1995 | Sea State | 0 | 0 | 1.9 | 11.3 | 30.2 | 12.0 | |
| | Non-Sea State | 0 | 0 | 1.2 | 17.1 | 31.6 | 10.9 | -1.02 |
| | All | 0 | 0 | 1.4 | 11.8 | 30.3 | 11.7 | |
| 1996 | Sea State | 0 | 0.7 | 5.6 | 13.8 | 31.0 | 11.8 | |
| | Non-Sea State | 0 | 0 | 2.9 | 13.2 | 27.4 | 9.3 | -1.76* |
| | All | 0 | 0.2 | 4.5 | 13.3 | 30.0 | 10.9 | |
| 1997 | Sea State | 0 | 1.0 | 3.8 | 10.7 | 28.9 | 9.9 | |
| | Non-Sea State | 0 | 0.7 | 3.8 | 11.6 | 26.1 | 9.7 | -0.54 |
| | All | 0 | 0.9 | 3.8 | 10.8 | 27.4 | 9.8 | |
| 1998 | Sea State | 2.0 | 5.7 | 12.6 | 21.0 | 34.3 | 19.7 | |
| | Non-Sea State | 0 | 0.2 | 3.9 | 10.7 | 22.7 | 7.9 | -7.2** |
| | All | 0 | 2.5 | 8.8 | 17.5 | 30.4 | 14.7 | |
| 1999 | Sea State | 2.0 | 6.5 | 15.2 | 32.4 | 62.8 | 26.6 | |
| | Non-Sea State | 0.1 | 0.5 | 6.2 | 26.0 | 41.3 | 15.8 | -3.14** |
| | All | 0.4 | 4.2 | 14.0 | 31.4 | 55.9 | 23.5 | |
| 2000 | Sea State | 1.1 | 6.2 | 16.4 | 33.0 | 57.4 | 24.1 | |
| | Non-Sea State | 0 | 0.9 | 6.1 | 10.7 | 18.4 | 7.5 | -7.31** |
| | All | 0 | 3.0 | 10.4 | 24.5 | 40.9 | 17.9 | |

*Significant at the 10% level of significance
**Significant beyond the 1% level of significance

Turning our attention to the distributions of the initial Sea State participating and non-participating vessels, we note that the distributions of bycatch rates across the two groups seem quite similar in the early and mid-1990s. There is no evidence of an improvement of the non-participating group's bycatch rates relative to the participating group in the period following Sea State. Indeed, the upward trend in bycatch rates in the late 1990s, while noticeable for the non-Sea State vessels, is not nearly as dramatic as that observed for the Sea State group. This is noteworthy given that we would expect participants' bycatch rates to reflect improvement relative to those that did not participate in the post-1995 period. To more precisely compare the annual distributions of the two groups we utilize a nonparametric test for comparing the central tendency of empirical distributions known as the Wilcoxon rank-sum test (Lehmann and D'Abrera, 1998).[142] This statistic, which for the special case of two comparison groups is also known as the Mann-Whitney U test, works by sorting the observed bycatch rates in both groups and then comparing the sum of the rankings in each group. In large samples the distribution of the difference of these sums can be well approximated by a normal distribution, and it is the z statistic of this difference that we report in Table 6.1. The base category in this case is the group of initial non-participants and so negative test statistics are evidence of a rightward location shift of the non-Sea State bycatch rate distribution relative to the Sea State group. In the pre-Sea State years we find no significant evidence of any location differences between the two groups. However, there is mild evidence in 1996 and overwhelming evidence for 1998-2000 that the median bycatch rate of the initial non-participants was actually *lower* than that of the Sea State charter members. In other words, simple comparisons of summary statistics provide no evidence of an improvement in the bycatch rates of Sea State members relative to those that did not participate, despite their similar performance before the implementation of the program. The findings in 1998-2000 of relatively "dirty" fishing by Sea State "early adopters" is not necessarily

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[142] We forego the usual comparison of means via two-sample t tests for two reasons. First, the use of such tests is highly questionable with data as blatantly non-normal as ours. Secondly, the mean itself is highly susceptible to outliers, and we desire a test that is robust in this context.

evidence of a deleterious treatment effect of the program, however; we know from discussions with industry representatives that the holdout vessels joined the program around 1999 and so the differences across the two groups for these years are likely not interpretable as treatment effects.

### 6.1.2 Difference-in-Differences Estimation

The preceding analysis, while revealing in a number of ways, does not provide a convincing case for the success or failure of Sea State. To accomplish this, we draw upon tools from the policy evaluation literature – namely, the difference-in-differences (DID) estimator. This estimator analyzes the effect of a "treatment" variable on outcomes by utilizing data gathered before and after the treatment was implemented on a group that received the treatment and an otherwise indistinguishable control group that did not receive the treatment. By subtracting the average values of the "after" and "before" treatment outcomes for the treatment and control groups and then subtracting these differences from each other one is able to obtain an average "treatment effect" from the policy change. This differencing can be accomplished via a regression specification in dummy variables as follows:

$$y_{it} = \beta_0 + \beta_1 d_t + \beta_2 d_i + \beta_3 (d_t * d_i) + \varepsilon_{it}, \tag{6.1}$$

where $d_t = 1$ if the observation occurs in the post-treatment period, $d_i = 1$ if individual *i* is a member of the treatment group, and $(d_t * d_i)$ represents the interaction of these two variables. In this case $\beta_3$ is the effect of the treatment. Note that both pre-treatment differences in the two groups and shared time trends in the dependent variable are controlled for via this specification.

Of course a number of assumptions are implied in the use of this simple estimator, and the integrity of the results is often quite fragile with respect to the violations of these assumptions (Besley and Case, 2000, Meyer, 1995). First, the composition of the treatment and control groups must be time-stable; otherwise, issues of sample selection bias arise if individuals selected themselves into (or out of) the sample based on the policy treatment (Blundell and MaCurdy, 1999). Secondly, control groups must be as comparable to the treatment group as possible. In other words, factors that vary between the pre and post-treatment periods should impact the two groups equally or, failing this, be effectively controlled for by time-varying exogenous variables. Failure to achieve this comparability may lead to the confounding of the treatment effect with other time-varying factors. Finally, the treatment should be exogenous; in other words, the application of the treatment must not be correlated with unobserved drivers of the outcome in question.

The treatment in our case is inclusion in the Sea State program. The control group is therefore the handful of vessels from a single company that were not part of Sea State at its inception. In terms of stability of the two groups our "quasi-experiment" is valid by design since the sample includes only those vessels which were active in the fishery before and after Sea State and we only attempt to draw direct inferences for this sample. There are, of course, weeks in which some vessels do not fish, thus causing our panel to be unbalanced and irregularly spaced. This is not a problem, however, as long as the decision to fish in the Bering Sea is not itself influenced by the anticipated bycatch rate in that week.[143] In terms of comparability our treatment and control groups are well suited to our purpose. Within the seasonal and geographical constraints of our data (i.e. excluding Aleutian Islands fishing and the winter fisheries) the two groups pursue similar targeting strategies, produce similar products, face the same regulatory restrictions and utilize similar vessel capital and gear in fishing. Furthermore, the comparison of the empirical distributions of bycatch rates in Table 6.1 and the Wilcoxon rank-sum tests suggest that pre-treatment bycatch rates are indistinguishable across the two groups, not only in terms of central tendency, but in other quantiles as well. Compared to many well-reputed DID studies where the authors must often exert great creativity to find a comparable pairing of treatment and control groups and where the resulting groups often lie across geographic

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[143] Given the common property incentives in place, this would seem unlikely; rather, we would expect entry/exit decisions to be driven based on expected returns across fisheries.

and political borders (e.g. Card and Krueger (1994)), the comparison of the treatment and control groups seems quite natural in our case.

The third criterion, that the treatment be exogenous with respect to the outcome variable, presents a challenge. Unlike many DID studies where random chance or the vagaries of state and national policymaking control who receives the treatment, the decision to join Sea State was clearly a choice for vessel owners, and the factors that influence this choice, both observed and unobserved, may play a role in determining weekly bycatch rates. For instance, if the skippers of a particular company possess unusually great skill in locating and avoiding halibut bycatch and target catch (i.e. they are "highliners"), then the owner of the company may discern that the benefits of information sharing are relatively small compared to the potential losses of revealing recent fishing patterns to competitors and thus elect not to join (and vice versa for companies with low-skilled captains). This skill differential is partially controlled for by $d_i$ in the DID specification, but this control is likely imperfect and will fail to adequately capture the firm and vessel-specific impacts of skill on bycatch rates. As a result we might expect an upward bias in the estimate of the Sea State treatment effect due to the fact that the pooling of information embodied in the program likely affords a greater marginal benefit to a fisherman of low skill than to a highliner.

Alternatively, it may be that due to existing patterns of reciprocity and trust that certain vessels and companies are more disposed to cooperative behavior and information sharing than others. Accordingly, it may be that fishermen with already lower than average bycatch rates may select themselves into the Sea State program. As a result, the marginal benefit of the program on bycatch outcomes may be small and the potential impact of the program understated.[144] Given the bundled nature of the Sea State program as both an information service (which is intrinsically

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[144] Alternatively, it could be that the selection into the program of those with cooperative norms actually *overstates* the impact of the program by increasing the returns to the pooled information by providing a catalytic framework for bycatch avoidance and self-policing that may have been lacking or considerably compromised in the absence of selection along the lines of "cooperators" and "noncooperators".

neutral by nature and could be used to facilitate either "clean" or "dirty" fishing) and a framework for coordination and cooperative behavior, it is difficult to envision *a priori* the directional effects of possible selection bias on the estimated treatment effect.

Obtaining correct standard errors in DID models is of paramount importance to conducting valid inference. Bertrand et al. (2004) determined that many prior DID studies possessed standard errors that are too small due to failure to account for serial correlation in the error term. Given the close temporal spacing of our dataset, these concerns are likely of great relevance. We therefore specify an error structure that allows for vessel-specific heteroskedasticity, contemporaneous correlation across vessels as well as AR(1) correlation within panels and estimate this error structure for Models 1-3 in Table 6.2 using Prais-Winsten linear regression estimator modified for panel data (Greene, 2003). This procedure produces asymptotically unbiased estimates as long as the conditional mean is correctly specified and is also asymptotically efficient if the specified covariance structure is correct.[145]

Three different DID estimates of the effects of Sea State are presented in Table 6.2. Model 1 is closest in form to (6.1) although the presence of multiple years of data both before and after the advent of Sea State has allowed us to augment our model with yearly dummies as well as consider separate annual treatment effects. By doing this, we not only allow for time-varying treatment effects but also account for the uncertainty about precisely when the holdout vessels joined Sea State. Once this happens their group is no longer a valid control; by breaking the treatment effects down by year we prevent the estimates for treatment effects in years in which the treatment/control division is valid from being affected by the years in which it is not. We also account for an observed characteristic of vessels – the ratio of horsepower to vessel length – since

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[145] We have elected to specify the covariance structure over Bertrand et al.'s preferred solutions of the block bootstrap or panel-robust White standard errors for the reason that these estimators of the covariance matrix rely upon the number of cross sections going to infinity for consistency. Such a rationale does not seem reasonable for our sample of 18 vessels with panels that vary in length from 31 to 235 weeks (with an average length of 154). Conversely, the consistency of our standard errors relies on the number of observations in each panel going to infinity.

analysis from the previous chapter suggests that vessels that are relatively highly powered face lower implicit costs of travel between sites and thus may be more nimble in their responses to spatial gradients in bycatch rates.

A glance at the treatment variables (labeled Sea State*year) for Model 1 suggests that Sea State had no discernible impact on bycatch rates in the first three years of its inception. There do, however, appear to be strong effects from 1998 onward – suggesting that bycatch rates were far *higher* on average than those in Sea State than those without. This result is quite curious and we discuss it at length at a later point.

Notwithstanding these results, this estimator does not control for intra-seasonal variations in bycatch rate due to fluctuating biological conditions, recurring spatial closures and targeting patterns. Failing to account for such patterns could bias the estimation of the treatment effect if the treatment and control groups distribute their effort differently across the season. To account for such effects, we add monthly dummies to the previous model (with April being the omitted base category) to form Model 2. These estimates suggest that bycatch rates are lower, *ceteris paribus*, in the summer and fall than in the spring. Nonetheless, estimates of the treatment effects from Sea State are practically unchanged.

Table 6.2: Difference-in-Differences Regressions of Halibut Bycatch Rate

| | Model 1 | Model 2 | Model 3 | Model 4 | Model 5 |
|---|---|---|---|---|---|
| Year=1993 | 2.32 | 1.93 | 2.02 | 1.65 | 1.65 |
| | (0.70) | (0.67) | (0.71) | (0.73) | (1.28) |
| Year=1994 | 5.45 | 5.36 | 5.19 | 4.32 | 4.32 |
| | (1.62) | (1.81)* | (1.78)* | (1.83)* | (2.31)** |
| Year=1995 | 3.91 | 4.81 | 4.03 | 3.39 | 3.39 |
| | (0.81) | (1.04) | (0.88) | (0.87) | (1.09) |
| Year=1996 | 2.04 | 3.22 | 2.07 | 1.80 | 1.80 |
| | (0.44) | (0.74) | (0.46) | (0.47) | (0.61) |
| Year=1997 | 2.68 | 2.38 | 1.14 | 0.54 | 0.54 |
| | (0.69) | (0.65) | (0.30) | (0.17) | (0.20) |
| Year=1998 | 0.01 | -0.84 | -1.98 | -2.14 | -2.14 |
| | (0.00) | (-0.23) | (-0.51) | (-0.67) | (-0.76) |
| Year=1999 | 9.84 | 7.80 | 6.26 | 4.12 | 4.12 |
| | (2.15)** | (1.75)* | (1.32) | (1.00) | (1.34) |
| Year=2000 | -0.58 | -1.59 | -2.98 | -2.99 | -2.99 |
| | (-0.14) | (-0.41) | (-0.69) | (-0.83) | (-1.15) |
| Sea State (=1 if initial member) | -3.84 | -3.82 | | | |
| | (-1.64) | (-1.73)* | | | |
| Horsepower/vessel length | -0.16 | -0.13 | -0.86 | -0.78 | -0.78 |
| | (-1.57) | (-1.40) | (-1.26) | (-1.46) | (-0.96) |
| Month=May | | -3.21 | -3.59 | -5.59 | -5.59 |
| | | (-1.27) | (-1.43) | (-2.49)** | (-1.33) |
| Month=June | | -3.40 | -4.24 | -5.32 | -5.32 |
| | | (-1.16) | (-1.45) | (-2.09)** | (-1.01) |
| Month=July | | -6.92 | -7.15 | -7.79 | -7.79 |
| | | (-2.44)** | (-2.54)** | (-3.21)*** | (-1.44) |
| Month=August | | -12.28 | -12.34 | -12.97 | -12.97 |
| | | (-5.01)*** | (-5.08)*** | (-6.25)*** | (-2.70)** |
| Month=September | | -14.40 | -14.39 | -15.58 | -15.58 |
| | | (-5.90)*** | (-5.94)*** | (-7.53)*** | (-3.79)*** |
| Month=October | | -9.48 | -9.65 | -10.40 | -10.40 |
| | | (-3.70)*** | (-3.80)*** | (-4.78)*** | (-2.38)** |
| Month=November | | -5.10 | -5.44 | -5.99 | -5.99 |
| | | (-1.64) | (-1.76)* | (-2.23)** | (-1.70) |
| Sea State*1995 | 4.72 | 4.11 | 5.04 | 4.35 | 4.35 |
| | (0.91) | (0.84) | (1.03) | (1.03) | (1.08) |
| Sea State*1996 | 5.70 | 5.69 | 6.80 | 6.39 | 6.39 |
| | (1.08) | (1.14) | (1.32) | (1.47) | (1.63) |
| Sea State*1997 | 2.73 | 3.09 | 4.21 | 4.44 | 4.44 |
| | (0.65) | (0.79) | (1.01) | (1.27) | (1.63) |
| Sea State*1998 | 17.12 | 18.27 | 18.49 | 16.95 | 16.95 |
| | (3.86)*** | (4.40)*** | (4.22)*** | (4.69)*** | (4.14)*** |
| Sea State*1999 | 13.30 | 14.86 | 16.40 | 17.33 | 17.33 |
| | (2.60)*** | (3.02)*** | (3.10)*** | (3.81)*** | (2.79)** |
| Sea State*2000 | 20.61 | 21.47 | 22.83 | 22.10 | 22.10 |
| | (4.54)*** | (5.04)*** | (4.77)*** | (5.51)*** | (4.54)*** |
| Constant | 10.77 | 17.92 | 30.45 | 30.16 | 30.16 |
| | (3.03)*** | (4.72)*** | (2.92)*** | (3.68)*** | (2.18)** |
| Observations | 2784 | 2784 | 2784 | 2784 | 2784 |
| R-squared | 0.06 | 0.09 | 0.1 | 0.13 | 0.13 |
| Estimated rho | 0.33 | 0.283 | 0.266 | n/a | n/a |

z-statistics in brackets (See text for details of calculation.)

* significant at 10%; ** significant at 5%; *** significant at 1%

Model 3 addresses the concerns of endogeneity for the Sea State treatment by including vessel-specific fixed effects in place of the indicator for the control group of vessels.[146] In doing so, any time-invariant vessel or firm-specific factors that may be lurking in the error term of the DID specification, including those that are potentially correlated with the Sea State treatment, are absorbed into the fixed effects and can no longer bias our estimates. A reasonable case can be made for time-invariant effects as the most likely potential sources of endogeneity. First, the initial membership of Sea State broke down along longstanding and fairly inflexible bonds of cooperation and information sharing; indeed, Sea State can be viewed as just one of many efforts by the core members of the head and gut fleet at this point in time to organize themselves under the auspices of the Groundfish Forum for the purposes of research, public relations, and (perhaps most importantly) representation of their interests, as opposed to those of the politically influential pollock fleet and environmental NGOs, at Council meetings. In such a context, joining Sea State may have served as an external validation of being "part of the group" – the effect of which, if related to bycatch outcomes at all, is arguably time invariant. Secondly, we observe no reversals of the decision to participate in Sea State. Although far from conclusive, we would likely expect some defection from the program (especially given its positive cost and apparently marginal performance) if the decision to participate was critically tied to seasonally varying factors.

Model 3 presents the least squares dummy variable (LSDV) estimates of the fixed effects model with the estimates of the fixed effects suppressed. Interestingly, accounting for time-invariant endogeneity seems to have little impact on any of the estimated coefficients or their significance levels. This suggests that whatever time-invariant factors are involved in the decision to retain Sea State's services, they do not figure significantly in the decisions that

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[146] Note that the presence of vessel specific fixed effects effectively encompasses much of the variation in the ratio of horsepower to vessel length since most of this variation is between vessels. We nevertheless retain the variable in the fixed effects specification to capture the effects of the (admittedly small) variation in this variable within panels.

influence weekly bycatch rates.

Models 4 and 5 are identical to model 3 except for their calculation of the standard errors. To consider the sensitivity of our inferences to alternative covariance estimators, we estimate model 4 under an assumed parameteric covariance matrix that is identical to model 3 except for it presumes independence of the errors over time and use "panel robust" White standard errors for model 5. Model 5's standard errors are robust to heteroskedasticity, cross-correlation and serial correlation of a general form, although the assumptions necessary for its consistency are arguably lacking here. Model 4 confirms the findings of Bertrand, et al. (2004) in that t statistics that fail to account for serial correlation are a bit larger than those that do (although the distortion is far from large). No clear pattern emerges in the comparison of models 3 and 5; however, both models generate identical inferences. The inferences on the mean effects of Sea State are remarkably consistent across multiple specifications and estimates of the standard errors.

Up to this point, we have restricted our modeling to specifications in the conditional mean; however, there are several reasons why such an analysis may be inadequate on its own. First, the unconditional means in Table 6.1, with their considerable mass at zero and long upper tails suggest that the conditional mean may not be particularly informative as a summary of central tendency or "typical" bycatch behavior. Secondly, mean regression techniques are quite sensitive to outliers, and so our estimates may be highly leveraged by a relatively small number of extreme data points. Thirdly, there is no *a priori* reason to suspect that the treatment effect of Sea State would operate on the distribution of bycatch rates by a pure location shift. It could just as easily function through alterations in the variance (i.e. heteroskedasticity) or other higher moments as well. Failure to acknowledge these higher-order effects can yield partial or, worse yet, deceptive results (Bitler, et al., 2006).

To address these issues we employ a semiparametric estimator known as quantile regression (Buchinsky, 1998, Cade and Noon, 2003, Koenker and Bassett, 1978, Koenker and Hallock, 2001). Rather than specify the structure of the conditional mean, we instead specify the conditional quantiles of the dependent variable so that the interpretation of the regression coefficients is the marginal predicted change in the inverse cumulative distribution of the dependent variable evaluated at a particular quantile for a small change in one of the regressors. These regressions are typically estimated by minimizing the weighted absolute sum of residuals (where the weights depend upon the desired quantile) and are optimized using linear programming techniques. Quantile regression has a number of desirable properties. First, as a semiparametric estimator, the assumptions underlying its consistency as an estimation method are quite limited. Secondly, since it is estimated by minimizing the absolute sum of residuals, rather than the sum of squared residuals as in the case of the conditional mean, it is relatively robust to the influence of outliers. Thirdly, multiple quantile regressions can be estimated for a variety of quantiles to trace out the effects of regressors on the entire distribution of outcomes.

Before reviewing our estimated quantiles, we must first speak to the large quantity of zeros bycatch rates present in our data. This lump of probability mass at zero calls into question the suitability of a purely linear specification of the conditional quantiles and may result in a downward bias in estimates of the regression coefficients (Wooldridge, 2002). We chose to ignore this issue in our estimates of the conditional mean for the simple reason that the default parametric solution in this case, the censored Tobit model, is extremely fragile to deviations from the assumed normal and homoskedastic distribution of the errors. However, in the case of quantile regressions there is an appealing alternative known as censored quantile regression (Powell, 1986, Powell, 1984).[147] Let the dependent variable be governed by the following rule (which is the same as for the censored Tobit):

$$y_{it} = \max\{0,\ x_{it}'\beta + \varepsilon_{it}\}. \tag{6.2}$$

If the conditional quantile of the error term is zero (which occurs by default when a constant term

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[147] Chay and Powell (2001) and Buchinsky (1998) are good introductions to this technique from an applied perspective.

is included in the specification of the $\theta th$ quantile) then the quantile of the dependent variable can be expressed as follows:

$$Q_\theta(y_{it} \mid x_{it}) = \max\left\{0,\, Q_\theta(x'_{it}\beta_\theta + \varepsilon_{it}^{\theta} \mid x_{it})\right\} = \max\left\{0,\, x'_{it}\beta_\theta\right\}.^{148} \tag{6.3}$$

The parameters of this expression are estimated by iteratively minimizing the sum of the absolute residuals (i.e. estimating the uncensored model) for only those observations for which $x'_{it}\hat{\beta}_\theta > 0$ until the same observations are excluded on repeated iterations. The resulting estimates are robust to departures from normality and heteroskedasticity. Applications of censored quantile regression have grown substantially in recent years with uses ranging from analyses of historic census wealth data (Conley and Galenson, 1998) to estimation of demand functions for vegetable consumption (Gustavsen and Rickertsen, 2006).

Table 6.3 presents our estimates of the full model with fixed effects (Model 3 in the conditional mean specification) for a range of quantiles of the bycatch rate distribution.[149] We only estimate the model from the fourth decile up as the iterative estimation technique of dropping observations tends to disproportionately affect certain time periods, making the estimation of the associated dummy variables quite unstable (if not impossible) for the lower quantiles.

A comparison of the marginal effects of the regressors across quantiles reveals that there is a great deal of agreement in sign and significance across the quantiles meaning that the variables often exert uniform directional impacts or are comparable in their seeming lack of any impact.[150] There is little evidence of upward trend in the bycatch rate distribution for the central (4th and 5th) deciles relative to the base year of 1992, although there does appear to be some evidence of higher bycatch rates in the upper quartiles for the 60th-90th percentiles for the late

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[148] The notation we use is borrowed from Gustavsen and Rickertsen (2006).

[149] The z statistics are calculated in the traditional way from the bootstrapped standard error (calculated over 200 iterations).

[150] Technically speaking, these estimates are only the predicted marginal effects when the estimated fitted value is positive; otherwise, the effect of a marginal change in a regressor on the location of a quantile is zero.

1990s and 2000. The monthly dummies indicate that the high bycatch rates of the base month of April are lowered in successive months to a much greater degree in the upper quantiles than in the lower ones – indicating a tightening of the bycatch rate distribution, *ceteris paribus*, in the later parts of the season. A comparison of the estimates for the median to those for the conditional mean of Model 3 suggests that as measurements of central tendency or "typical" behavior, the coefficients of the conditional mean are somewhat inadequate in that they are clearly heavily influenced by the upper quartiles and often bear close resemblance to the quantile regression estimates for the 60th and 70th percentiles.

A glance at the estimates of the treatment effects for 1995 through 1997 reveals little consistent proof of any detectable effect, notwithstanding some evidence that the Sea State vessels had higher bycatch rates around and just below the median of the distribution in 1996 relative to their non-Sea State colleagues. For the sake of thoroughness, we also report estimates of a probit model in Table 6.3 with the same regressor set where we model the probability of a week with a bycatch rate of zero. Again, there is no evidence of a higher proportion of halibut-free weeks by Sea State members relative to the control group in the immediate aftermath of the program. These results confirm the findings of the models in the conditional mean. The added value of the quantile regression and probit approach is that we can now draw the same inference for the *entire distribution* of outcomes.[151]

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[151] We should note that the standard errors utilized for the quantile and probit regressions are subject to the critique of Bertrand, et al. (2004) in that they fail to account for serial correlation. We avoid addressing this issue due to the substantial difficulties involved for these estimation techniques (in particular, we are not aware of techniques to account for serial correlation in censored quantile standard errors). However, our standard errors and z statistics exhibit an upward bias in the presence of positive serial correlation, so that failing to account for this possible correlation actually strengthens our findings in that even under conditions most amenable to finding a treatment effect from 1995-1997 we are unable to do so.

Table 6.3: Probit and Censored Quantile Estimates of DID Model

| | Probit Halibut/wk=0 | Q40 | Q50 | Q60 | Q70 | Q80 | Q90 |
|---|---|---|---|---|---|---|---|
| Year=1993 | -0.09 | 1.42 | 1.14 | 1.59 | 2.28 | 3.27 | 1.19 |
| | (-0.83) | (1.01) | (1.04) | (1.50) | (1.74)* | (1.73)* | (0.44) |
| Year=1994 | 0.22 | 2.55 | 1.04 | 1.01 | 2.71 | 2.64 | 3.07 |
| | (2.06)** | (1.80)* | (0.88) | (0.95) | (2.12)** | (1.59) | (1.00) |
| Year=1995 | 0.25 | 0.07 | 2.43 | 2.38 | 3.25 | 9.80 | 12.47 |
| | (1.42) | (0.02) | (0.87) | (0.89) | (0.86) | (1.88)* | (1.30) |
| Year=1996 | -0.14 | -1.72 | 0.31 | 3.62 | 4.46 | 7.08 | 9.62 |
| | (-0.71) | (-0.66) | (0.13) | (1.53) | (1.42) | (1.96)** | (1.18) |
| Year=1997 | -0.42 | 1.82 | 2.34 | 2.57 | 3.38 | 3.03 | 2.26 |
| | (-2.41)** | (0.98) | (1.57) | (1.52) | (1.87)* | (1.25) | (0.43) |
| Year=1998 | -0.30 | 0.30 | 2.83 | 2.90 | 3.83 | 1.91 | -0.99 |
| | (-1.69)* | (0.11) | (1.30) | (1.80)* | (2.07)** | (0.78) | (-0.23) |
| Year=1999 | -1.12 | -1.00 | 2.30 | 15.38 | 18.51 | 22.06 | 22.54 |
| | (-4.13)*** | (-0.24) | (0.31) | (2.21)** | (3.37)*** | (4.45)*** | (3.02)*** |
| Year=2000 | -0.30 | 1.53 | 4.99 | 3.81 | 3.89 | 2.05 | -0.22 |
| | (-1.58) | (0.63) | (2.51)** | (2.28)** | (1.80)* | (0.83) | (-0.05) |
| Horsepower/vessel length | -0.04 | 0.00 | 0.26 | 0.10 | 0.17 | -1.14 | -1.37 |
| | (-0.69) | (0.00) | (0.44) | (0.17) | (0.26) | (-1.33) | (-1.10) |
| Month=May | -0.27 | -0.62 | -1.95 | -4.68 | -8.10 | -12.57 | -22.51 |
| | (-2.23)** | (-0.41) | (-1.14) | (-2.03)** | (-3.10)*** | (-3.53)*** | (-4.83)*** |
| Month=June | -0.82 | 3.47 | 2.08 | 0.37 | -3.33 | -7.83 | -15.64 |
| | (-5.40)*** | (2.09)** | (1.21) | (0.16) | (-1.22) | (-1.91)* | (-3.36)*** |
| Month=July | -0.38 | -0.78 | -1.05 | -3.38 | -7.62 | -11.20 | -20.72 |
| | (-2.61)*** | (-0.27) | (-0.60) | (-1.56) | (-3.10)*** | (-2.77)*** | (-4.18)*** |
| Month=August | 0.14 | -6.24 | -5.04 | -7.97 | -13.89 | -20.19 | -31.47 |
| | (1.33) | (-1.87)* | (-2.41)** | (-3.62)*** | (-5.76)*** | (-5.99)*** | (-8.03)*** |
| Month=September | 0.61 | -5.92 | -7.04 | -9.84 | -16.50 | -24.83 | -37.03 |
| | (5.76)*** | (-2.21)** | (-3.93)*** | (-4.69)*** | (-6.47)*** | (-7.69)*** | (-9.77)*** |
| Month=October | 0.04 | -4.16 | -3.86 | -6.78 | -12.67 | -19.85 | -29.86 |
| | (0.35) | (-1.59) | (-2.37)** | (-3.15)*** | (-5.32)*** | (-5.89)*** | (-7.11)*** |
| Month=November | -0.74 | 1.94 | -0.30 | -2.13 | -6.83 | -12.97 | -21.54 |
| | (-4.67)*** | (1.19) | (-0.17) | (-0.92) | (-2.58)*** | (-3.33)*** | (-5.22)*** |
| Sea State*1995 | -0.36 | 5.64 | -0.76 | 0.34 | 1.66 | -2.82 | -6.16 |
| | (-1.76)* | (1.12) | (-0.25) | (0.11) | (0.40) | (-0.54) | (-0.59) |
| Sea State*1996 | -0.24 | 7.26 | 6.05 | 3.70 | 5.47 | 4.96 | 3.76 |
| | (-1.05) | (2.01)** | (2.06)** | (1.29) | (1.50) | (1.11) | (0.41) |
| Sea State*1997 | -0.01 | 3.77 | 1.10 | 0.50 | 1.53 | 3.02 | 0.23 |
| | (-0.04) | (1.66)* | (0.65) | (0.29) | (0.73) | (1.02) | (0.04) |
| Sea State*1998 | -1.17 | 13.78 | 8.17 | 9.35 | 11.60 | 14.35 | 18.54 |
| | (-4.46)*** | (3.12)*** | (3.12)*** | (4.72)*** | (5.35)*** | (4.32)*** | (3.23)*** |
| Sea State*1999 | -0.29 | 14.45 | 10.68 | 0.71 | 3.16 | 8.57 | 15.56 |
| | (-0.84) | (2.61)*** | (1.40) | (0.10) | (0.52) | (1.30) | (1.49) |
| Sea State*2000 | -0.89 | 13.40 | 9.38 | 16.33 | 18.97 | 26.68 | 32.58 |
| | (-3.57)*** | (2.92)*** | (2.67)*** | (6.33)*** | (6.22)*** | (6.37)*** | (5.15)*** |
| Constant | 0.05 | 0.98 | 0.95 | 7.47 | 14.12 | 46.46 | 74.36 |
| | (0.06) | (0.10) | (0.11) | (0.86) | (1.41) | (3.66)*** | (3.95)*** |
| Sample Size | 2784 | 2784 | 2784 | 2784 | 2784 | 2784 | 2784 |
| Final Sample Size | n/a | 1809 | 2436 | 2621 | 2662 | 2717 | 2782 |
| Pseudo R-squared | 0.178 | 0.080 | 0.089 | 0.113 | 0.134 | 0.157 | 0.186 |

z-statistics in parentheses

* significant at 10%; ** significant at 5%; *** significant at 1%

As robust as the findings concerning Sea State are in the period immediately following its inception, so also are the somewhat puzzling findings for 1998-2000 that early participants actually exhibited substantially *higher* bycatch rates relative to the control group. What explains this strange pattern? First of all, we know that the holdout group joined Sea State in or around 1999. Accordingly, they have no real validity as a control group beyond this date. Allowing for some uncertainty for their date of participation, it is conceivable then that this worsening in the relative bycatch performance of charter Sea State members is explainable by a disproportionate positive effect of the program on the bycatch outcomes of new membership. However, a comparison of the statistics for the two groups in Table 6.1 and examination of the annual dummies against the "treated" year dummies in Table 6.2 and Table 6.3 indicates that the gap in relative performance was not caused by a drastic improvement in the bycatch rates of the initial non-participants – rather, it was driven by a rapid increase in the bycatch rates of original Sea State members.

A substantial portion of this increase in bycatch rates can be laid on a marked change of targeting strategy by the initial Sea State participants in the period from 1998 forward. Table 6.4 shows the percentage shares of species composition sampled hauls for each major groundfish target allocation. Note that these shares, although calculated from only a percentage of total hauls should provide unbiased estimates due to 100% observer coverage and the random sampling of hauls for species breakdown. Looking at the 1998-2000 period relative to beforehand, one observes a clear movement away from the targeting of yellowfin sole by "early adopters" with an increased focus instead on flathead sole and arrowtooth flounder.[152] The primary motivator in this decision was likely the depressed price of yellowfin sole products in this time period. The NMFS estimated price for head and gut yellowfin sole fell 30% between 1997 and 1998 from $0.27/lb (real-weight equivalent) to $0.19/lb and whole fish and kirimi products experienced

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[152] Arrowtooth flounder was not the real target of much of this effort as this species has a very limited market and a low value. It is, however, closely associated with flathead sole and other commercially valuable species.

similar declines. As a result, this group of fishermen devoted more of their effort to the catch of more valuable flatfish species. Unfortunately, the catchability of halibut associated with these alternative targets has been estimated at 3.5 to 5 times greater than in the yellowfin sole fishery (Spencer, et al., 2002); our data shows that arrowtooth flounder and flathead sole targeted hauls exhibit median halibut bycatch rates of 30 and 18 kg/mt respectively while yellowfin and rock sole have much lower rates of 3 and 6 kg/mt. Much of this greater catchability is spatially determined; flathead sole and arrowtooth flounder are typically found in deeper waters than yellowfin sole and these waters also hold relatively large concentrations of large halibut relative to the shallows (Adlerstein and Trumble, 1998, Adlerstein and Trumble, 1998). By way of contrast, the holdout company's vessels did not dramatically alter their targeting behavior away from yellowfin sole after 1998, thus explaining the relative stability of their bycatch rates.

Table 6.4: Shares of Species Composition Sampled Hauls Devoted to Target Categories

| | 1992-1997 | | 1998-2000 | | Δ in share | |
|---|---|---|---|---|---|---|
| Target Designation | Non-Sea State | Sea State | Non-Sea State | Sea State | Non-Sea State | Sea State |
| Arrowtooth Flounder | 0.7% | 1.8% | 0.0% | 8.2% | -0.7% | 6.4% |
| Bottom Pollock | 7.4% | 6.5% | 5.4% | 10.3% | -2.0% | 3.8% |
| Flathead Sole | 0.2% | 3.6% | 1.0% | 14.9% | 0.8% | 11.3% |
| Other Flat | 5.2% | 16.0% | 10.3% | 10.9% | 5.1% | -5.0% |
| Pacific Cod | 0.7% | 3.4% | 2.5% | 6.1% | 1.8% | 2.7% |
| Rock Sole | 20.3% | 12.2% | 17.7% | 9.7% | -2.6% | -2.5% |
| Rockfish | 1.5% | 2.8% | 0.5% | 1.2% | -1.0% | -1.6% |
| Turbot | 0.9% | 2.8% | 0.5% | 3.0% | -0.4% | 0.3% |
| Yellowfin Sole | 63.1% | 50.9% | 62.1% | 35.6% | -1.0% | -15.3% |

A consideration of the comparative "revenue inefficiencies" of the two sub-fleets, as shown in Figure 6.1, is telling. Our measure of inefficiency in this case is the ratio of weekly observed halibut bycatch to weekly observed revenues from species composition hauls (where revenues are calculated as described in Appendix B with actual as opposed to expected catch). The median quantity of halibut bycatch required to generate $1000 in pre-discard revenue hovered between 1.4 and 4 kg prior to 1995 with little difference between the two fleet groups; however, after 1995 the median inefficiency of both fleets grew steadily – possibly spurred on by an increase in halibut biomass over this horizon. Nonetheless, the increase in halibut per unit revenue exhibited by the Sea State cohort far outpaced that of their competitors who, as demonstrated previously, did not substantially alter their targeting patterns over this interval. This relative pattern parallels our findings concerning the movements of bycatch rates across the two groups, thus indicating that while the changes in targeting behavior by original Sea State vessels were motivated by a desire to increase the economic returns to fishing, this strategy did not sufficiently increase the value per unit of groundfish catch so as to overcome the increase in the bycatch rate.[153]

Our reduced form characterization of bycatch outcomes is highly suggestive and apparently quite robust. However, before passing the final verdict on Sea State we pause briefly to examine what the structural model of fishing location choice from Chapter 5 can add to our understanding.

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[153] Of course this measure of the relative bycatch efficiency of the fleets does not account for the difference in variable costs associated with different target strategies; we lack any direct data on costs, so we are not able to derive the (arguably more appropriate) ratio of bycatch of halibut per unit of variable rents.

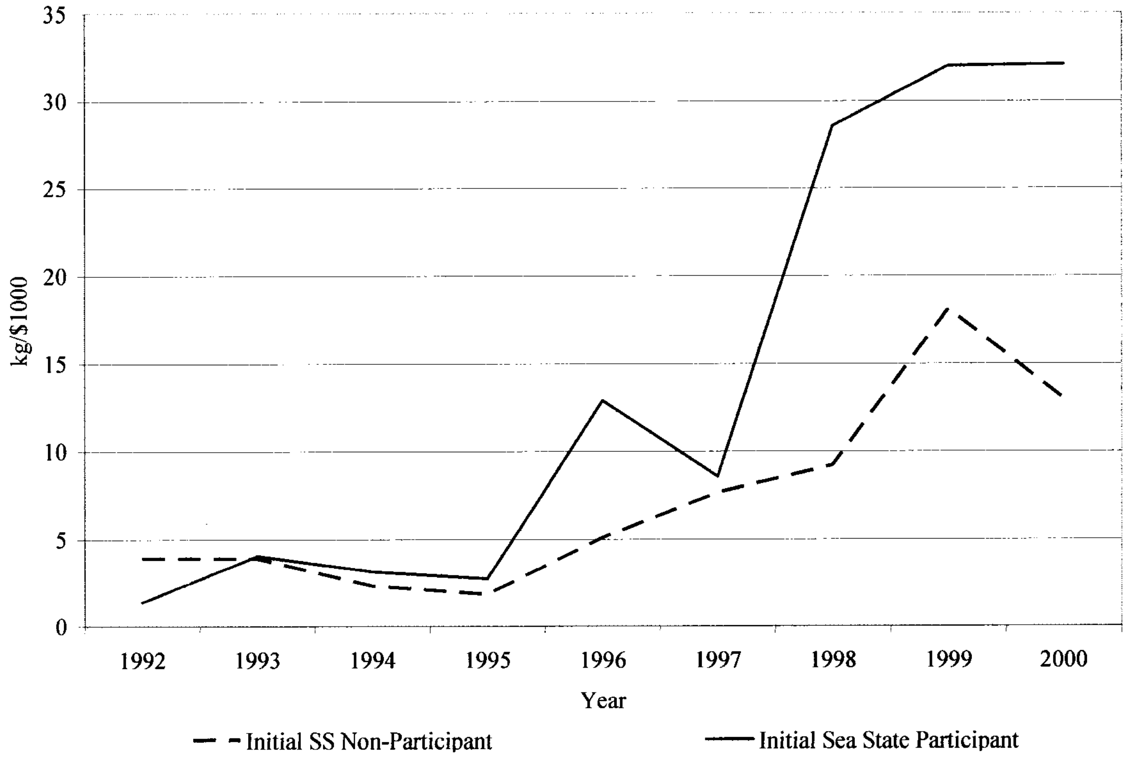

Figure 6.1: Median Annual Halibut Bycatch per $1000 Revenue

## 6.2 Did Sea State Improve Incentives for Bycatch Avoidance?

The reduced form models of the previous section are inherently limited in that they are best adapted to analyzing the joint product of fishermen's preferences (as represented by their indirect utility functions) and the biological, economic and regulatory constraints that interface with these preferences. This limitation is dangerous in that it is quite easy to confuse "demand" with "supply" in certain contexts – potentially attributing changes in outcomes to alterations in the underlying incentives (demand) when an alteration in the constraints (supply) is the most likely culprit. For instance a naïve analysis of bycatch rates may attribute an increase in bycatch rates over time to a weakening of incentives for bycatch avoidance when, in fact, this trend may be driven by disadvantageous biological, regulatory or economic shocks.

The availability of high resolution panel data and an untreated group of vessels allows us to control for these factors somewhat in our DID specifications; nevertheless, it is difficult to judge with any certainty whether an important variable has been omitted or whether some other subtle form of endogeneity lurking in the error term may bias our conclusions. In the absence of clear knowledge in this regard (and a suitable instrument!) it is necessary to place further structure on the modeling approach.

For this purpose we utilize the model of fishing location choice developed in Chapter 5 to investigate whether vessels in Sea State exhibited any tendency toward increased avoidance in their preferences after the program's inception. This model is very well suited to this purpose for a number of reasons. First, the choices in this model are demarcated over spatial alternatives, which is the primary realm of decision making that Sea State is aimed at influencing. Secondly, the temporal resolution of the model is quite fine and thus matches nicely with the flow of information from Sea State. Thirdly, we have already accounted for the informational asymmetries existing between Sea State participants and non-participants in our model of expectations formation. Finally, a number of the "supply" factors previously described (such as changes in relative prices, spatial closures or trends in the abundance and distribution of species) are painstakingly accounted for in the development of the model so that we can be reasonably sure that an estimated "treatment effect" is exactly that.

To ascertain the effects of Sea State, if any, on the relative tradeoffs between short-run economic returns and halibut bycatch, we focus, as in Chapter 5 on the specification of the marginal disutility of expected halibut bycatch. We hypothesize that Sea State membership exerted a consistent relative effect regardless of the levels of the other variables that play a role in influencing the avoidance of bycatch. In other words, its effect is manifested entirely though displacement in the intercept term of the marginal disutility. We begin with the specification utilized in Chapter 5 and expand upon it as follows:

$$\begin{aligned}\lambda_{it} &= \gamma_0 + \gamma_1 SeaState_i + \gamma_2 AfterSS_t + \gamma_3 After1998_t + \ldots \\ &+ \gamma_4 (AfterSS_t * SeaState_i) + \gamma_5 (After1998_t * SeaState_i) + Z_{it}'\delta,\end{aligned} \tag{6.4}$$

where $SeaState_i = 1$ to indicate vessels that were originally in the Sea State "treatment" and $AfterSS_t$ and $After1998_t = 1$ to indicate the periods from 1995 forward and 1998 forward respectively. $Z_{it}$ represents all the previously included variables indicated in Table 5.1. The division of the post-treatment time horizon into two periods mimics the use of yearly dummies for temporal and treatment effects in the reduced form DID models, allowing us to investigate the presence of treatment effects in the years immediately preceding the introduction of Sea State without fear of contamination from later years when both groups were effectively rolled into the same group. Also, by establishing a break at 1998 we are able to more closely investigate the apparent break evidenced in the reduced form models to see if the gap in bycatch outcomes between the two groups is associated with a contemporaneous diversion in their underlying tradeoffs.[154]

Table 6.5 shows selected results of this estimation. We present the median, minimum and maximum estimates of the shadow cost associated with each element of (6.4), where these shadow costs and their standard errors are calculated exactly as in the previous chapter. For simplicity of presentation, we do not present estimates of the other parameters; however, the qualitative predictions of the previous chapter are unchanged from this alteration in the specification.

The estimates on the interaction term for 1995 onward are not significantly different from zero at any conventional level of significance. It therefore appears that our structural modeling approach has confirmed the findings of the reduced form models that Sea State membership had no measurable impact on preferences during the period from 1995 to 1997. The results for 1998

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[154] We should note that, in keeping with our argument in the previous chapter that the cost term should include the same variables that figure in the implicit cost of halibut, we have opted to include these extra variables in the marginal disutility of distance term as well. However, the group dummies are expunged due to the use of vessel-specific terms in the marginal cost of distance.

onward are quite revealing. The strongly positive and significant coefficient on the dummy for the 1998-2000 period indicates that baseline halibut avoidance (as measured by the implicit cost of halibut to the cohort of holdout vessels) actually increased in this period; however, the interaction term for this period is negative and statistically significant, indicating that the treated vessels (the orginal Sea State members) avoided halibut considerably less than their untreated comrades. However, the absolute magnitude of this interaction term is only slightly greater (but not significantly so) than the post-1998 dummy, indicating that preferences for avoidance of halibut for initial participants were actually roughly stable between 1995 and 2000.[155]

Table 6.5: Selected Results from DID-Augmented RUM Model

| | Median | Minimum | Maximum | Standard Deviation |
|---|---|---|---|---|
| Constant | \$70.34 | \$34.71 | \$120.51 | \$27.27 |
| | (1.98)** | (1.99)** | (2.07)** | |
| Sea State | \$9.44 | \$4.66 | \$16.17 | \$3.66 |
| | (1.18) | (1.18) | (1.19) | |
| AfterSS | \$9.40 | \$4.64 | \$16.10 | \$3.64 |
| | (0.85) | (0.85) | (0.86) | |
| After1998 | \$20.47 | \$10.10 | \$35.06 | \$7.93 |
| | (2.59)*** | (2.64)*** | (2.71)*** | |
| AfterSS*Sea State | \$1.53 | \$0.76 | \$2.62 | \$0.59 |
| | (0.18) | (0.18) | (0.18) | |
| After1998*Sea State | -\$23.30 | -\$39.92 | -\$11.50 | \$9.03 |
| | (-3.74)*** | (-4.03)*** | (-3.81)*** | |
| $N$ | 45,200 | | | |
| Number of Estimated Parameters | 139 | | | |
| Log-likelihood | -20,005 | | | |
| Pseudo $R^2$ | 0.7846 | | | |
| Predictive $R^2$ | 0.8480 | | | |

Z Statistics are included in parentheses and are all derived using standard errors calculated by the delta method.
** significant at 5%; *** significant at 1%

The implication of these results is somewhat provocative and alters the interpretation of the reduced form estimates. Analysis of bycatch rates and our measures of revenue inefficiency

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[155] Recall from the previous chapter that heterogeneity in the marginal cost of halibut is completely attributable to heterogeneity in the marginal utility of revenues, which is a constant divisor in all the shadow cost terms in Table 6.5. The implication is that the estimated impacts on the marginal cost of halibut for all 18 vessels maintain the relative magnitudes presented in the median case but are simply scaled up or down by a vessel-specific factor.

seemed to suggest that the initial non-participants exhibited relative stability in their bycatch avoidance compared to the participating group in the late 1990s – managing to hold bycatch rates stable or on a relatively shallow upward trend (depending upon whether annual dummies from the conditional mean, median or upper quantile DID specifications are examined). The initial Sea State vessels, by comparison, seem profligate in their usage of bycatch. However, the results of our structural DID model suggest exactly the opposite. In spite of the acceleration of their bycatch rates and their rapidly declining revenue per unit of bycatch, these vessels actually exhibited a fairly stable marginal tradeoff between bycatch and monetary rewards. In other words, the marked increase in bycatch rates observed between 1998 and 2000 on the part of Sea State charter members is overwhelmingly driven by "supply side" factors, and the relatively mild increases exhibited by the remaining cohort of vessels were only achieved at considerable extra effort.

There are two possible "supply side" candidates to explain this erosion of bycatch outcomes. The first is the implementation of the IR/IU regulations in 1998 requiring the full retention of all pollock and cod bycatch in the groundfish fisheries (see footnote 104). It is possible that this regulation induced extra avoidance of pollock across the groups, possibly causing an indirect increase in halibut bycatch rates due to interactions in the spatial locations of the two species. There are two problems with this theory, however. First, simple DID regressions like those employed in the previous section with the catch rate of pollock as the dependent variable find no evidence of an increase in such avoidance. Secondly, the catchability of halibut in the bottom pollock target fishery is actually quite high compared to many of the other targets pursued by the head and gut fleet (Spencer, et al., 2002), and so increased avoidance of pollock would likely have been coincident with *lower* halibut bycatch rates, not higher rates.

A far more likely suspect is an increase in the biomass of halibut or, more precisely, an increase in the strength of age cohorts for which groundfish trawl gear has limited selectivity. This has been vehemently maintained by fishermen who assert that only the (very few) vessels that utilize halibut excluder devices have been able to hold bycatch rates steady relative to their rates from unaltered gear in previous years (Hezel, 2006).[156] Estimates of halibut biomass in the Bering Sea by the IPHC have failed to support such an increase; however, these estimates are highly suspect in this region since the IPHC typically extrapolates biomass estimates from management areas in the Gulf of Alaska due to the minor importance of the commercial halibut fishery in the Bering Sea. Also, IPHC longline surveys are designed to accurately estimate the abundance of commercially exploitable halibut, which are typically far larger than those caught in the groundfish fisheries. The precipitous climb in bycatch rates evidenced in the late 1990s by Sea State charter members paired with their apparently stable preferences for bycatch avoidance over this same period is strongly indicative of a harmful shift in the production possibilities frontier of fishermen, a shift most easily explained by an increase in the abundance of Bering Sea halibut biomass.

## 6.3 Conclusion

The verdict of both the reduced form and structural models is clear: participating in Sea State did not provide any detectable change in halibut bycatch outcomes or preferences for bycatch avoidance relative to those that did not join. Of course, given these findings, the natural question is "why?". A variety of hypotheses have been suggested, and we consider them here.

Holland and Ginter (2001) suggest that weak prices for yellowfin sole may have led to fishermen supplementing their yellowfin harvest with other, more valuable species (such as flathead sole or cod). These species are often more highly associated with concentrations of halibut and could therefore undermine efforts at halibut avoidance. We have already documented this behavior for early Sea State participants. Nevertheless, there are two problems with attributing the apparent failure of Sea State to this change. First, the weakening of yellowfin

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[156] We lack information on which vessels used excluders at particular points in time, so we are unable to test this claim.

prices did not begin in earnest until 1998 and therefore fails to account for the first three years of lackluster halibut avoidance by Sea State members. Secondly, the shift in targeting behavior in the late 1990s, while yielding higher average bycatch rates, did not markedly affect the relative *marginal* tradeoffs between revenues and halibut bycatch by initial Sea State participants. In other words, there doesn't appear to be a significant weakening of spatial avoidance behavior linked with declines in yellowfin sole prices.

The alleged increase of halibut biomass in the Bering Sea has also been blamed for eroding the success of Sea State. This claim seems unequivocally true if one's metric for success is the maintenance of bycatch rates at or below their pre-1995 levels. However, such a view avoids the crux of the issue – namely, why didn't Sea State vessels exhibit an improvement in the *incentives* to forego short-run gains in the interest of halibut avoidance? It is entirely possible that the increase in halibut over the years raised the total costs of bycatch avoidance and made competition more difficult to sustain, but this does not explain why the Sea State program failed to show any results in the implicit tradeoffs of fishermen or their bycatch rates in the first couple of years of the program when the outlook for halibut avoidance could not have been that much more bleak than in 1994.

The most common explanation for Sea State's lack of success in halibut bycatch avoidance has been that noncooperative and predatory behavior on the part of non-participants destroyed the within-Sea State incentive for cooperative behavior (Gauvin, et al., 1995, Gauvin and Rose, 2000). It is alleged that these vessels enter the fishery with their large vessels and heavy gear and fish in a way that exhibits disregard for preserving the season through avoidance of halibut hot spots. The problem with this hypothesis is that we simply find no substantial evidence to support it. Holdout vessels compare favorably to Sea State member vessels from 1995 to 1997 in terms of their bycatch rates and their latent preferences for halibut avoidance. Furthermore, from 1998 to 2000, initial non-participants well outpaced their competition in bycatch avoidance. Given the public availability of vessel bycatch rates through the VIP program, it seems unlikely that misperceptions about the actual performance of one's competitors could persist and meaningfully influence behavior.[157]

One possibility is that the holdout vessels, in spite of their relatively low bycatch rates, contribute disproportionately to the quantity of halibut bycatch due to the high volume of their hauls. Indeed, they do catch larger average quantities of groundfish per hour than do other head and gut vessels. If we take differentials in total weekly *observed* halibut catch as representative measures of the differentials in actual catch, then it does appear that vessels from this group landed greater quantities of halibut per week in 1995 and 1997.[158] The observed differential is around 1mt per week which when scaled upward by a factor of 2 to account for an average observer sampling rate of roughly 50% equals about 2mt. Such a difference is substantial and could conceivably spur the remaining vessels toward noncooperative behavior. However, as a simple test of whether the presence or absence of vessels from this one "disruptive" company influences behavior we regressed the weekly bycatch rates of all other vessels from 1995 onward on the number of vessels from the holdout company active in the fishery for that week along with monthly and annual control variables (not shown). We found no statistical evidence of any change in bycatch rates (and thus the strength or weakness of cooperative bycatch avoidance) associated with the participation of these vessels. This calls into question whether the high volume fishing of this group really influences cooperative incentives for the rest of the fleet.[159] Furthermore, the observed bycatch differential reverses in the favor of the late joiners of Sea State from 1998 onward, which is reflective of their substantially better performance in terms of bycatch rates over this horizon. This should have neutralized them as an outside threat to the

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[157] Of course we assume here that the observer data we employ (and the observer data used for computation in the VIP) are trustworthy. There have been a small number of documented cases of data fouling by head and gut crews; however, these reports include both Sea State and non-Sea State vessels so that there does not appear to be a case for any *a priori* bias in the data.

[158] There are problems in working with weekly observed catch differentials. In particular, this measure is susceptible to variations in the percentage of hauls sampled across vessels.

[159] Of course, it could be that skippers anticipate the entry of the non-participatory fleet and rationally backward induct that bycatch avoidance does not pay, even in a week where "cooperators" have the fishery to themselves.

remaining vessels – if anything there behavior was more "cooperative" than that of long-term Sea State members. Furthermore, they actually joined the program themselves around this time, and yet we still fail to observe any improvement in the incentives of the remaining fleet for bycatch avoidance. Altogether, the argument that predatory behavior by outsiders substantially undercut cooperation within Sea State seems rather weak.

A more likely culprit for the neutral effect of Sea State on incentives lies in the simple common property story of Chapter 3. The somewhat vague cooperative structure of Sea State – the formal institutions of information sharing had no analog in the institutions of decision making and collective enforcement – was simply not up to the task of curbing the powerful individual incentives toward excessive bycatch. These incentives were at work across the entire fleet, both within Sea State and without, and the blame for the lack of any real cooperation cannot be placed on the shoulders of any one cluster of "renegade" vessels.

It is important to remember, nonetheless, that the introduction of Sea State has engendered considerable success for this same fleet (although usually sans the vessels from the non-participating company, at least in our time period) when it comes to the avoidance of red king crab in the rock sole roe fishery. The successes of Sea State in this fishery are well documented and described in Chapter 2.[160] It is nevertheless useful to recount the characteristics of this fishery that make it amenable to an informal system of bycatch information sharing and avoidance.

First of all, the rock sole roe fishery (as shown in Figure 2.4) is spatially concentrated to the north of the Alaska Peninsula and Unimak Island due to the seasonal distribution of the target species. This places the fishermen within close proximity of one another so that monitoring and enforcement is facilitated. Second, the horizon over which cooperation must be sustained is quite short. At its longest, the fishery extends from January 20 to the first couple of days in March

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[160] Future research will focus on the precise spatial mechanisms through which bycatch was reduced in this fishery. We also plan to assess how much of the observed improvement in bycatch outcomes is attributable to contemporaneous spatial closures rather than the impact of the Sea State program.

when the fish have finished spawning. This brief season facilitates cooperative behavior since it only requires that fragile cooperative norms be maintained for a period of a few weeks. Third, the benefits of cooperation in bycatch avoidance are quite high. Roe-in head and gut products command prices that are 3-4 times that of other head and gut products for rock sole and well beyond the value of any alternative targets available at this time of year. This high value, while potentially a lure for selfish opportunistic behavior, may also increase the lure of cooperation since even relatively small and low-cost actions can generate substantial personal benefits, even when divided over the whole fleet.

Finally, the relative distributions of rock sole and red king crab populations (and their movements through time) facilitate avoidance and cooperation at a variety of levels. Red king crab frequently overlap with rock sole due to the overlapping of their mating migrations. Crab in the southern Bering Sea/Bristol Bay typically move in large "waves" of sexually segregated individuals from deep waters to shallow and often move quite quickly – covering up to a mile per day (Blau, 1997). As a result, king crab bycatch often exhibits highly spatially concentrated and relatively short-lived patterns over space. In such a context, bycatch can often be dramatically curtailed by relatively small movements away from well-defined "hot spots". The costs of such movements (both in terms of foregone catch and fuel costs) are probably small, and it is likely relatively simple to identify vessels who are fishing noncooperatively given the defined nature of hotspots, the rapid updates from Sea State and the clustering of fishing effort in the grounds.

Contrast these characteristics with those of the yellowfin sole fishery. Unlike the rock sole fishery, the fisheries in the summer and fall are highly dispersed over hundreds of kilometers of the ocean, thus hampering identification of cooperative and noncooperative behavior and limiting distant fishermen's ability to exert pressure on their competitors to avoid bycatch. The horizon for cooperation in halibut avoidance is essentially the entire season as it is encountered in varying levels for a range of target species. The creation of sub-seasonal allocations of halibut across the season breaks the horizon up somewhat but the fact that underages or overages are "paid forward" to the next sub-season essentially maintains the continuity of the season. This places great strain on cooperative behavior. Furthermore, the benefits from cooperation in bycatch avoidance, although substantial, are not remotely as great as for the rock sole roe fishery, further dampening incentives for cooperation.

Finally, and perhaps most importantly, the spatiotemporal distribution of halibut frustrates bycatch avoidance. Compared to red king crab, halibut are distributed far more evenly across the Bering Sea, albeit with clear seasonal tendencies pertaining to the varying migratory patterns of particular age and size classes (Adlerstein and Trumble, 1998, Adlerstein and Trumble, 1998). These seasonal patterns, although useful, are often too coarse to facilitate avoidance. In addition, attempts to seek micro-scale regularities in halibut abundance may be frustrated by natural variability. Our own model of expected halibut bycatch, which operates by placing weights on data at multiple spatial and temporal scales in a manner that best explains the data, placed an unusually high weight on so-called "broad seasonal patterns" relative to more temporally and spatially precise information; however, there remained substantial unexplained variation about the conditional mean relative to the models for other species. Although more research is warranted in this area, this suggests that the spatiotemporal distribution of halibut is governed by broad seasonal regularities but with precious little replicability at the scales needed for decision making. The data pooling and expert analysis provided by Sea State can help in this regard, but it cannot create regularities that are not there. It is indicative of the intrinsic problems of halibut avoidance that participants in the much-vaunted rock sole roe fishery have failed to recreate their successes with king crab with halibut. Indeed, halibut bycatch has increased considerably in the wake of Sea State (partially as a result of avoidance of high crab-bycatch areas) (Gauvin, et al., 1995, Gilman, et al., 2006). One might suspect that the success of cooperation in avoiding crab bycatch might yield external benefits in halibut avoidance, but such an effect has not been forthcoming.

In summary, the failure of Sea State in altering incentives for bycatch avoidance for halibut lies in the intersection of common property incentives and the spatiotemporal association of the targeted and bycatch species. Cooperation in bycatch avoidance seems to have a fighting chance under a common property system of management when nature provides a helping hand but can scarcely be expected to outpace the "race for bycatch" when nature is less benevolent.

# Chapter 7

# Conclusion

The bycatch and discard of marine species is the complex joint product of economic, technological, biological and regulatory factors, and, like so many other aspects of fishing behavior, it is responsive to economic incentives embedded in the institutional structure of fisheries management. In light of the history of the Eastern Bering Sea head and gut fishery, such a statement may seem self-evident. However, as discussed in Chapter 1, much of the economic and policy literature on the subject has ignored the nexus of regulatory institutions and the production possibilities of fishermen. Many studies have treated fishing gear and the way it is used as fixed and exogenous. Such characterizations, while often convenient for the isolated discussion of incentives for discard behavior (Anderson, 1994, Arnason, 1994, Vestergaard, 1996), leave no room for incentives to work at the most basic level of the production process.

This implicit view, although intended as a mere artifice to facilitate analytical results, closely mimics the predominant philosophy of bycatch management in regulated fisheries which may be characterized as "technology based". In this mindset, a fisherman utilizing a particular gear is thought to catch some proportion of the bycatch species present at a location. The logical role of a regulator under such a paradigm is to: 1) exclude gears with low bycatch selectivity from bycatch-rich fishing grounds, 2) mandate the adoption of more "efficient" gears, and, if these measures prove insufficient, to 3) establish caps on the catch (or landings) of bycatch species. Such an approach may be successful in achieving biologically determined regulatory goals, but it operates at the considerable cost of economic rents, and, more importantly, fails to address the institutional shortcomings that preclude the voluntary adoption of such spatial and technological restrictions by the fishermen themselves.

Other economic studies of bycatch have utilized the tools of production theory to investigate the implicit substitution possibilities between species for particular gear types with a goal of determining the responsiveness of fishermen toward incentive-based measures such as ITQs on bycatch and/or target species (Squires and Kirkley, 1996, Squires and Kirkley, 1991). Unfortunately, this approach, while highly flexible, is intrinsically limited in the range of substitution possibilities that may be uncovered by the underlying incentives inherent in the management system and the narrow range of scenarios present in the data. Furthermore, it ignores potential strategic interactions between fishermen and smoothes over the fundamental nature of fishing as perhaps the world's only example of commercialized hunting on a grand scale.[161]

In an attempt to develop analytical and empirical models of fishery behavior that recognize the links between the incentives embedded in regulation and the tradeoffs made by fishermen as well as incorporate the structural details of spatial and strategic behavior that characterizes fisheries, we anchored our research around the case study of the head and gut groundfish trawl fisheries of the Eastern Bering Sea. Chapter 2 describes this fishery at length, characterizing the biological, technological and regulatory constraints that determine the seasonal distribution of fishing effort over a vast and diverse continental shelf. The chapter also provides the details of a common form of management that is analyzed in detail in the following chapters – the common property quota system. Under this system, fishermen compete with one another for shares of the allowable take of both bycatch and targeted species. When either target or bycatch quotas are determined to be near to binding, the retention of targeted species is immediately curtailed by regulatory action. We close the chapter by describing the long history of premature closures in these fisheries due to halibut and crab bycatch and discuss possible causes of these

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[161] The implications (and validity) of applying production theoretic models to fisheries, which differ in a marked fashion from the agricultural and industrial applications for which these techniques were developed, have never been addressed.

closures, including a "race for bycatch" spurred on by insecure property rights for an indispensable joint product of groundfish production.

Chapter 3 presents a stylized static model of the head and gut fishery in which a relatively small number of vessel captains attempt to maximize their individual profits over a season. There are two species, the target species and bycatch, and fishing technology is such that greater avoidance of bycatch is only achievable at the increasing expense of daily harvest of the target species. Daily profits are linearly increasing in the target species and linearly decreasing in the take of the bycatch species (due to the direct economic cost of sorting and discarding bycatch). A regulator is charged with the task of enforcing exogenously determined catch quotas on both species and achieves this control by terminating the season when either target or bycatch quota binds. We characterize the static, quota-constrained optimum in this setting and determine that fishery rents are maximized when the season is as long as possible since fishermen can harvest at a low intensity and therefore face reduced costs of discard throughout the season. Furthermore, the rate of harvest and the coinciding bycatch rate should *decrease* in the number of vessels in the fishery. We also find that it is appropriate in certain situations for the bycatch quota to bind and to therefore leave target quota unused, but only when industry capitalization is quite low relative to the amount of available target species quota.

The Nash equilibrium to the game between fishermen is, by comparison, much more complex and subtle; however, the crux of the individual fishermen's decision problem is to attempt to equilibrate the marginal benefits of an extra unit of harvest (the extra daily revenue net of the increased marginal costs of discard from bycatch) with his *personal* marginal costs, taking into account his impact of their actions on the equilibrium season length. These costs include the losses to oneself from a shorter equilibrium season, but do not include the external costs of one's decision on the *N-1* competitors. Indeed, the personal share of the full marginal cost decreases with the number of competitors such that Nash equilibrium harvest and bycatch rates actually increase with greater fleet capitalization rather than decrease as prescribed by the optimal solution.

The result, even for parameterizations that are stacked in favor bycatch avoidance, is an escalation of discard costs, greatly shortened seasons and rapid degeneration of rents with increased entry relative to the optimal solution. At some threshold level of competition, fishermen are forced to their maximum capacity rate of harvest such that they behave like pure competitors (i.e. they act as if their behavior has *no* effect on the equilibrium harvest) and implicitly place zero value on an extra unit of bycatch quota.

The model also predicts that adoption of bycatch saving technologies under common property quotas will not be forthcoming, even with little or no associated loss of target catch. This result arises because bycatch saving technologies actually reduce the marginal personal cost of a unit of harvest (due to the reduction in marginal discard costs), thus driving equilibrium harvest rates up across the fleet and dissipating potential increases in rents from the new technology. Rational, forward-looking fishermen foresee this result and therefore cling to the status quo – thus thwarting mutually-beneficial innovation. Finally, we determine the implicit tax on bycatch that must be borne by fishermen to bring private incentives in line with the social optimum and come to the startling conclusion that this penalty must *increase* with improvements in the "cleanness" of harvesting technologies.

Chapter 4 begins the empirical portion of the research with a thorough description of the datasets utilized in our analysis. We draw upon a wide range of data in our work; however, the data that makes the fine temporal and spatial analysis of the successive chapters possible derives from onboard observers who randomly sample hauls for species composition. This data, although limited in its use due to confidentiality concerns, is a treasure trove for empirical analysis given its fine breakdown of information over space and time, the level of recorded detail on catch composition, and the generally integrous nature of the data – particularly when compared to the logbook data and other datasets frequently utilized by fisheries researchers.

We use this data in Chapter 5 to estimate a random utility model of spatial location choice over 165 potential locations in the Eastern Bering Sea at an unusually fine temporal scale

– the individual haul of the net. The decision of where to fish is not only motivated by expected revenues and costs but also by the expected concentration of halibut bycatch in an area.

To specify this model in a realistic fashion, we develop a unique approach to predicting expected revenues and bycatch at a site by utilizing nine years of catch data to calibrate individual species models that assimilate own and shared information across multiple spatial and temporal scales in a manner that is consistent with rational information processing. This approach allows fishermen to possess heterogeneous expectations at a site due to their unique histories and information sharing networks – an important feature for explaining divergent behavior at a high level of spatiotemporal detail. It also allows us to generate predictions of expected revenues that are more reflective of the species and location-specific regulations employed by fisheries managers than the simple approaches previously utilized in the literature.

We specify the marginal disutility of halibut as a function of bycatch quota scarcity, recent competition within the fishery and vessel-specific future participation within the current sub-season. We find that fishermen respond in a manner consistent with noncooperative behavior by exhibiting less avoidance of halibut when there is more intense competition within the fishery. Likewise, fishermen with longer participation horizons typically place a higher implicit cost on halibut bycatch as well. The implicit cost of halibut fluctuates substantially over a season with little or no apparent avoidance early in the season but considerable avoidance late in the season. This last minute "good behavior" appears to be driven in large part by the increased scarcity of common-pool bycatch quota – an effect that is also reinforced by the lack of viable outside fishing opportunities at this stage of the season. Although consistent in many ways with the game theoretic model of Chapter 3, these observed behaviors are quite subtle and are indicative of a complex and varied pattern of halibut avoidance on the part of fishermen. Nevertheless, even when the personal implicit cost of halibut is at its highest, it is still well below its value as a complement of production for the fleet as a whole.

In a common property setting, a vessel's cost of travel not only includes the direct economic costs of fuel – it also includes the value of lost bycatch taken by one's competitor in the interim (assuming bycatch quota is anticipated by fishermen to bind before target quota). We therefore specify costs as functions of the same variables that influence the value of halibut and find that a substantial portion of the estimated variation in per-kilometer costs is explained by movements in halibut quota scarcity – far more than is explainable by observed or unobserved vessel heterogeneity. These findings have considerable methodological implications for the characterization of costs in fishing location models and may help in explaining the disturbingly large estimates of the variable cost of distance in many studies.

The effect of the common quota system is to increase spatial inertia within the fleet. This is a symptom of common property management that has not, to our knowledge, been discussed or empirically verified in the literature. The implications of this inertia for fisheries management may be far reaching, leading to reduced sensitivity to spatial gradients in bycatch rates and revenues while potentially fostering localized depletion and habitat destruction through excessive clustering of successive hauls.

Chapter 6 utilizes multiple empirical approaches to assess the success or failure of a cooperative program of bycatch avoidance for Pacific halibut. In 1995 a portion of the head and gut fleet retained Sea State Inc. to pool and analyze observer information on the spatial distribution of bycatch rates across the Bering Sea and relay this information to participating vessels on a daily basis. This information could then be used to help form perceptions on the spatial distribution of bycatch and hopefully aid fishermen in making decisions to avoid bycatch hotspots, monitoring the performance of other vessels and using this information to foster mutual cooperation in bycatch avoidance.

Fortunately, the availability of data before and after the advent of Sea State as well as the existence of both a participating and non-participating cohort of vessels allows us consider the counterfactual of whether the Sea State vessels performed better in terms of their bycatch outcomes than they would have in the absence of the program. We employ difference-in-differences (DID) estimation (taking care to account for seasonal factors and time-invariant sources of endogeneity) on weekly bycatch rate data and find no evidence of a significant treatment effect of Sea State on mean bycatch rates. To assess the robustness of our results, we estimate censored quantile regressions and probit models for the same DID specification and find that the determination of no significant treatment effect is valid across the entire distribution of outcomes. We also find from 1998 onward that the original group of Sea State members (who were joined in Sea State around this time by the holdout group of nonparticipating vessels) actually exhibit *worse* bycatch rates relative to their competitors. We trace these changes in bycatch rates to alterations in the targeting behavior by the charter Sea State group away from yellowfin sole and toward deeper-dwelling flatfish species. These changes were driven by depressed prices for yellowfin sole and drove some fishermen into areas with relatively high bycatch of halibut.

We supplement these reduced form results by utilizing the structural model of fishing site choice in Chapter 5. We augment the specification of the marginal disutility of halibut in our model with a DID structure to account for differences between the Sea State participants and non-participants both before and after the introduction of the program in 1995. Given the evidence of a widening gap in relative bycatch performance from the reduced form models, we also allow for differential strength of avoidance across the two groups in the period from 1998-2000. This structural approach allows us to consider the evolution of indirect preferences for bycatch avoidance in isolation from "supply side" changes in the biological, economic or regulatory context that may confound analyses based solely on analyzing observed bycatch rates. Somewhat surprisingly, we find that incentives for bycatch avoidance remained fairly stable for charter Sea State participants from 1995-2000 while the willingness to pay for bycatch avoidance for the cohort that originally opted out of Sea State increased dramatically in the late 1990s. The fact that bycatch rates increased for both groups over this time period (although at a substantially greater rate for the original Sea State group) provides compelling evidence to support the assertions of fishermen that halibut biomass has increased to a substantial degree over the last decade.

Finally, we confirm the ineffectiveness of Sea State in improving cooperation in bycatch avoidance and address the merits of several hypotheses for why the program did not yield better results. We combine our prior empirical analysis with a systematic comparison of the characteristics of the failed Sea State implementation for the yellowfin sole fishery to its apparently successful performance for the avoidance of red king crab bycatch in the rock sole fishery. Ultimately, we conclude that the combination of negative incentives due to the common property quota system and specific aspects of the spatiotemporal distribution of halibut that make its avoidance a great deal more costly and prone to uncertainty than for red king crab ultimately doomed the performance of the program in fostering cooperative bycatch avoidance. These results suggest that the success or failure of cooperation in bycatch avoidance depends only in part upon the compatibility of the overarching system of property rights. Poor incentives can be compensated for somewhat if the physical characteristics of the fishery and the distribution of bycatch species help reduce the costs of avoiding bycatch and sustaining cooperation among fishermen; nonetheless, common property incentives may seriously curtail the number of fisheries for which such cooperation is sustainable.

## 7.1 The Future of Incentives for Bycatch Avoidance

This thesis has highlighted the importance of considering the incentive effects of management measures designed to curtail bycatch in marine fisheries by both analytically and empirically demonstrating the tendency of fishermen to engage in destructive strategic behavior that results in the dissipation of economic rents and often thwarts conservation goals. We have also shown how cooperation in the commons, while possible under favorable biophysical conditions, cannot be counted upon to foster sufficient bycatch avoidance as it is far too easily crowded out by regulatory institutions that are fundamentally inconsistent with such cooperation.

With the disadvantages of this system of management now evident, the next issue is what can be done to provide proper incentives for bycatch avoidance? We derived the basic conditions that needed to be satisfied in such a solution in Chapter 3 but intentionally left the door wide open for a range of potential policy instruments. This decision was motivated by the fact that the relative efficacy of various proposals will likely depend upon a number of highly context-dependent factors such as the number of active vessels, their heterogeneity in terms of capital and the skill of the crew, the costs and efficacy of monitoring and enforcement and other less tangible factors such as the cohesiveness of fishermen in acting cooperatively on the grounds and the underlying legal and political biases for or against certain classes of policies. The answers to these and other questions are of paramount importance for the wise design of bycatch policies, and it may be that the best solution is not necessarily one derived in the rarified atmosphere of an academic's office but a "second best" solution that can actually work in an atmosphere of positive transactions costs and where many competing and powerful interests have a voice.

The good news is that successful implementations of incentive-based policies for bycatch management do exist and are beginning to gain the attention of both fishermen and managers alike. The two dominant paradigms appear to be the extension of individual tradable quota markets to encompass bycatch species and the internal allocation of access privileges to both bycatch and target species through fishing cooperatives. In terms of the use of tradable quotas, two systems have emerged at the forefront: the New Zealand quota management system (QMS) and the individual bycatch quota (IBQ) system in the British Columbia groundfish trawl fishery.

New Zealand began managing its fisheries under individual transferable quotas in 1986 with initial allocations for 17 inshore and 9 offshore fisheries. This system has grown over time such that as of 2004 there were 93 species included under the program with the eventual goal of expanding it to cover all living marine resources (including invertebrates and some species of seaweed) that are either economically valuable or for which sustainability concerns may be an issue due to fishing (Sanchirico, et al., 2006).[162] Fishermen under this system must reconcile their catch of a wide range of target and bycatch species by purchasing or leasing quota (where the total amount of available quota is generally limited by the annual TAC) or else by utilizing one of several alternative measures that help to build flexibility into the catch/quota balancing mechanism.[163] Discards are expressly prohibited for all but a few species with high survivability and enforcement is accomplished through a dual reporting system involving both fish processors and fishers and through the limited use of vessel monitoring systems and onboard observers. By requiring fishermen to consider their quota holdings for the entire portfolio of species they catch, the New Zealand system helps to internalize the value of bycatch species into fishermen's decisions. Although there are some concerns, especially concerning the extent of unobserved discards and the ability of the QMS to provide sufficient flexibility to fishermen in terms of the reconciliation of catch vs. quota holdings while simultaneously preventing overfishing, the New Zealand QMS is highly regarded as an effective application of market-based thinking to a complex multispecies fishery that has generated both economic and ecological benefits (Newell, et al., 2005, Sanchirico, et al., 2006).

The groundfish trawl fisheries of British Columbia, which includes a variety of target species such as hake, rockfish, cod and flatfish, has been administered under a complete system of ITQs since 1997 but have had individual bycatch quotas (IBQs) for the catch of halibut since 1996. Under this system, fishermen face an aggregate restriction on how much halibut bycatch is allowed in particular areas, but are free to trade amongst themselves for the right to this bycatch. Much as in Alaska, the retention of Pacific halibut bycatch is prohibited, and prior to the introduction of IBQs was administered under a common quota system quite similar to that in

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[162] New Zealand's QMS is quite elaborate and our description is necessarily brief. For more detail consult Annala (1996), Dewees (1998), Newell, et al. (2005) and Sanchirico, et al. (2006).

[163] The measures include rollover or rollback provisions that allow fishermen to borrow against past or future quota and the payment of a "deemed value" for overharvests relative to one's quota holdings.

place in the Bering Sea with predictably similar results. With the introduction of IBQs in 1996, total halibut bycatch declined from 681mt in the previous year to 140mt, and subsequent years have maintained or improved upon this substantial initial reduction. Furthermore, by internalizing the full cost of bycatch in fishermen's decision making the IBQ system has fostered a wide range of innovations in bycatch avoidance that were previously unthinkable (Grafton, et al., 2004). For instance, fishermen often use short "test tows" to check the composition of species at a site before beginning fishing at a new site. They also frequently share information with other fleet members and have made substantial investments in technology to increase the selectivity of their fishing practices.[164] Finally, and perhaps most importantly, the use of IBQs coupled with tradable quotas for target species have generated substantial additional rents due to the avoidance of premature fishery closures, increases in the value of landed product and numerous cost savings (Grafton, et al., 2004).

The use of fishermen's cooperatives as a management tool has gained some momentum in recent years, particularly in the United States. Rather than establish a formal market for catch and bycatch species, fisheries managers instead precisely define a group of vessels with rights to a particular quantity or share of the annual TAC. These vessels are then given the right to develop rules and procedures for the allocation and internal trading of target and bycatch TAC across vessels and other measures to avoid the "race for fish". They are also frequently allowed to develop internal systems of monitoring and enforcement for the avoidance of bycatch. Due to the external legitimization of the cooperative structure, these internal policies are binding upon participants in a way that would not be possible otherwise.

One particularly well-known fishing cooperative is that for the BSAI offshore catcher processor pollock fleet. This group of 19 vessels receives an annual share of pollock which they parse amongst themselves. The successes of this cooperative are well documented with rents

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[164] Some of these technologies include devices that let the skipper vary the configuration of the net opening while trawling and sensors that transmit updates on the quantity and composition of catch to the bridge while fishing is ongoing (Grafton, et al., 2004).

springing from a number of sources including direct reductions in operating costs due to less intensive fishing, improved coordination between the processing deck and the skipper, increases in the utilization of caught fish, improvements in product quality and the development and marketing of new products (Wilen, 2005). In addition, pollock fishermen have engaged Sea State to provide near real-time information on the location of bycatch hot spots for salmon. However, unlike the head and gut fleet's use of Sea State which has relied on fairly ad hoc voluntary agreements with little enforceability, the pollock fleet has developed automatic rules for the closure of areas with high salmon bycatch. These rules have "teeth" because of the strong legal basis underlying the cooperative – a legal basis that has moved the rights to catch and bycatch out of the common domain and into the hands of a small number of cooperating vessels.

At the moment of our writing, legislation that would allow the formation of a cooperative among the head and gut groundfish fleet is being considered by the North Pacific Fishery Management Council. The details are currently under debate, but it now appears that a substantial portion of the fleet will be included within this cooperative and will be able to internally allocate individual shares of both catch and bycatch species. If the results of rationalization of the pollock fleet and the analogous British Columbia groundfish fleet are any indication, there is substantial cause for optimism.

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# Appendix A:

# Necessary and Sufficient Conditions for Nash Equilibria

To establish the necessity of the conditions for Nash equilibria, we posit particular solutions and then develop conditions under which 1) the beliefs (about the identity of the binding quota) are consistent with those obtained under the solution, 2) where the implied harvest rate and season length honor the constraints of the model, and 3) where there is no incentive to marginally deviate from the solution. In order to establish sufficiency of these conditions, we provide arguments that show that the necessary conditions not only protect against marginal (quota preserving) individual deviations but also prevent non-marginal (non quota preserving) deviations as well. We rely on intuitive arguments rather than algebraic proofs where possible since the mathematics is generally more tedious than instructive. Solutions from these analytical conditions were numerically tested over numerous parameterizations using a program written in MATLAB such that we are confident of their correctness.[165]

## A.1: Necessary Conditions

**Case 1:** $Q_B/Q_X \leq h_B(h_{\max})/h_{\max}$

A. $Q_X$ Binding – Interior Solution

$$\hat{h}_X = \left(\frac{p}{cb}\cdot\frac{(1-1/N)}{(\alpha-1/N)}\right)^{\frac{1}{\alpha-1}}, \qquad \hat{T} = \frac{Q_X}{N\hat{h}_X}$$

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[165] All MATLAB code is available upon request from the authors.

(N1) $$N \le \frac{1-\left(cQ_B/pQ_X\right)}{1-\alpha\left(cQ_B/pQ_X\right)}$$

(N2) $$\bar{T} \ge \hat{T} \longrightarrow N \ge f(p,c,b,\alpha,Q_X,\bar{T})$$

The equilibrium harvest rate is easily obtained via equation (5). Condition (N1) ensures that the equilibrium harvest rate falls below the threshold level at which the bycatch quota begins to bind. (N2) keeps the harvest rate from dropping to a point where the season length constraint is no longer honored. No condition is needed to ensure that $\hat{h}_X \le h_{\max}$ given (N1) and the assumptions underlying Case 1. Given the interiority of this solution there is obviously no marginal incentive to deviate.

B. $Q_X$ Binding – Corner Solution

$$\hat{h}_X = \frac{Q_X}{N\bar{T}}, \qquad \hat{T} = \bar{T}$$

(N1) $$N \le \frac{1-\left(cQ_B/pQ_X\right)}{1-\alpha\left(cQ_B/pQ_X\right)}$$

(N2) $$\bar{T} \le \hat{T}_{\text{int}} \longrightarrow N \le f(p,c,b,\alpha,Q_X,\bar{T})$$

(N3) $$N \ge \frac{1}{\bar{T}}\left(\frac{bQ_X^{\alpha}}{Q_B}\right)^{\frac{1}{\alpha-1}}$$

Condition (N1) is the same as in the previous equilibrium; an internal $Q_X$ equilibrium is supported under this criteria. However, unlike before, this harvest rate leads to an equilibrium season length that exceeds the season limit (N2). In order to avoid leaving excess target species at the end of the season, every fisherman has an incentive to increase his harvest rate until $Q_X$ binds at $\bar{T}$ . (N3) ensures that the resulting season length still falls below the upper threshold for $Q_X$ to bind.

There is no marginal pressure to deviate upward from this solution, since doing so would only drive the agent further from the internal "peak" they would prefer to achieve given a longer season. Downward deviations in the harvest rate are trivially eliminated.

C. $Q_B$ Binding – Interior Solution

$$\hat{h}_X = \left( \frac{p}{cb} \cdot \frac{(1-\alpha/N)}{(\alpha-\alpha/N)} \right)^{\frac{1}{\alpha-1}}, \qquad \hat{T} = \frac{Q_B}{Nb\hat{h}_X^{\alpha}}$$

(N1) $$N \ge \frac{\alpha\left(1-\left(cQ_B/pQ_X\right)\right)}{1-\alpha\left(cQ_B/pQ_X\right)}$$

(N2) $$\bar{T} \ge \hat{T} \longrightarrow N \ge g(p,c,b,\alpha,Q_B,\bar{T})$$

(N3) $$N \le \frac{\alpha(p-cbh_{\max}^{\alpha-1})}{p-\alpha cbh_{\max}^{\alpha-1}}$$

The solution in this case is analogous to the interior equilibrium for $Q_X$ and (N1) and (N2) have very similar interpretations. Condition (N3) is needed to bound the equilibrium harvest rate below $h_{max}$. This condition is only needed when $\bar{h} \le h_{\pi\max}$; otherwise, the right hand side of this inequality goes to infinity and the condition becomes redundant. Given the interiority of this equilibrium, there are clearly no reasons for any participant to marginally deviate from this solution.

D. $Q_B$ Binding – Corner Solution (Season Length Binding)

$$\hat{h}_X = \left( \frac{Q_B}{bN\bar{T}} \right)^{\frac{1}{\alpha}}, \qquad \hat{T} = \bar{T}$$

(N1a) $$N \le \frac{\alpha\left(1-\left(cQ_B/pQ_X\right)\right)}{1-\alpha\left(cQ_B/pQ_X\right)}$$

(N2a) $N \leq \frac{1}{\overline{T}}\left(\frac{bQ_X^{\alpha}}{Q_B}\right)^{\frac{1}{\alpha-1}}$

*or*

(N1b) $N \geq \frac{\alpha\left(1-\left({cQ_B}/{pQ_X}\right)\right)}{1-\alpha\left({cQ_B}/{pQ_X}\right)}$

(N2b) $\overline{T} \leq \hat{T}_{\text{int}} \longrightarrow N \leq g(p,c,b,\alpha,Q_B,\overline{T})$

(N1a) is the converse of (N1) in the interior case, indicating a situation in which the interior equilibrium harvest rate would fall below the value for which it is technologically possible for $Q_B$ to bind. Fishermen's beliefs fail to be self-consistent and they have left both bycatch and target species behind. An agent's profits can be improved by fishing a bit less efficiently up until the point where the season limit engages just as the bycatch quota binds. At this point there is no marginal incentive to decrease one's harvest rate since doing so would merely lower daily profits with no gain in season length. It is also possible to prove via a trivial albeit tedious bit of algebra that there is no incentive to marginally increase one's harvest. (N2a) ensures that $N$ is sufficiently small to draw a harvest level over the threshold such that $Q_B$ can bind.

(N1b) is the same as (N1) representing a case in which the interior solution does fall above the threshold for which bycatch can bind. However, (N2b) shows that this rate of harvest is too small to exhaust the quota by season's end. The incentive then is to incrementally raise one's effort until all available bycatch is exhausted just as $\overline{T}$ is reached. There is obviously no incentive to fish "cleaner" at this point since the season can be no longer. It is also trivial to show that there is no marginal incentive to further increase one's effort – the increases in daily profits are outweighed by the associated losses from a shorter season.

### E. $Q_B$ and $Q_X$ Binding

$$\hat{h}_X = \left(\frac{Q_B}{Q_X b}\right)^{\frac{1}{\alpha-1}} = h_{trans},\ \hat{T} = \frac{Q_B}{Nb\hat{h}_X^{\alpha}}$$

$$\text{(N1)} \quad N \leq \frac{\alpha\left(1-\left({cQ_B}/{pQ_X}\right)\right)}{1-\alpha\left({cQ_B}/{pQ_X}\right)}$$

$$\text{(N2)} \quad N \geq \frac{1}{\overline{T}}\left(\frac{bQ_X^{\alpha}}{Q_B}\right)^{\frac{1}{\alpha-1}}$$

$$\text{(N3)} \quad N \geq \frac{1-\left({cQ_B}/{pQ_X}\right)}{1-\alpha\left({cQ_B}/{pQ_X}\right)}$$

Condition (N1) has the same basis as (N1a) of the previous case – fishermen individually face incentives to employ as low a harvest rate as is consistent with their belief that $Q_B$ binds. (N2) is the converse of (N2a) indicating a situation in which $N$ is too large to support the previous corner solution since the associated harvest level will cause the target species to bind at $\overline{T}$ rather than the bycatch species. As a result, ever fisherman employs the minimal amount of effort consistent with their belief that bycatch binds, causing the season length to decline below it maximum level. It is a trivial exercise in algebra to rule out upward deviations in the harvest rate. Downward movements are problematic, however, since even the slightest deviation changes the binding quota to $Q_X$. To rule out profitable downward deviations we require that the derivative of the objective function (4) with respect to one's harvest rate evaluated at $h_{trans}$ (where $Q_X$ binds) be positive. (N3) is the condition that results. Note that this condition is the converse of (N1) for both cases in which $Q_X$ binds; it is necessary that no "target" equilibria be possible for this equilibrium to hold.

### F. $Q_B$ Binding – Corner Solution ($h_{max}$ binding)

$$\hat{h}_X = h_{\max}, \qquad \hat{T} = \frac{Q_B}{Nb\hat{h}_{\max}^{\alpha}}$$

(N1) $N \geq \dfrac{\alpha(p - cbh_{\max}^{\alpha-1})}{p - \alpha cbh_{\max}^{\alpha-1}}$

Note that (N1) is the converse of (N3) in the interior equilibrium case. In this case $N$ is simply too large for an interior equilibrium to be possible. As a result, agents simply harvest as quickly as possible. Assumption 3.2 ensures that $Q_B$ binds, so no further conditions are needed. There is no marginal incentive to deviate since (N1) rules out the profitability of downward deviations in harvest and there is no capacity for further expansion.

**Case 2:** $Q_B/Q_X > h_B(h_{\max})/h_{\max}$

G. $Q_X$ Binding – Interior Solution

$$\hat{h}_X = \left(\frac{p}{cb}\cdot\frac{(1-1/N)}{(\alpha-1/N)}\right)^{\frac{1}{\alpha-1}}, \qquad \hat{T} = \frac{Q_X}{N\hat{h}_X}$$

*If* $h_{max} = \bar{h}$,

(N1a) $\bar{T} \geq \hat{T} \longrightarrow N \geq f(p,c,b,\alpha,Q_X,\bar{T})$

(N2a) $N \leq \dfrac{p - cbh_{\max}^{\alpha-1}}{p - \alpha cbh_{\max}^{\alpha-1}}$

*If* $h_{max} = h_{\pi\max}$,

(N1b) $\bar{T} \geq \hat{T} \longrightarrow N \geq f(p,c,b,\alpha,Q_X,\bar{T})$

Since $Q_B$ can no longer bind, there is no longer any need for a condition analogous to (N1) from the interior "$Q_X$ binding" case. However, (N2a) is needed here to ensure that the harvest rate falls below the maximum allowable level. This condition is not needed when the argmax of the daily profit function falls below $\bar{h}$. In this case it is never individually optimal to operate at the peak of the daily profit function and so the right hand side of (N2a) grows infinitely large. (N1a) and (N1b) are needed in either case to ensure that the season length constraint is honored. Parallel arguments to this same equilibrium type for Case 1 establish that there is no incentive for deviation from this solution.

H. $Q_X$ Binding – Corner Solution

$$\hat{h}_X = \frac{Q_X}{N\overline{T}}, \qquad \hat{T} = \overline{T}$$

(N1) $\overline{T} < \hat{T}_{\text{int}} \longrightarrow N < f(p,c,b,\alpha,Q_X,\overline{T})$

This solution is analogous to its namesake for Case 1. However, (N1) in that case is no longer necessary since Case 2 precludes $Q_B$ ever binding. (N3) is now guaranteed by the combination of the mathematical condition for Case 2 and Assumption 2. The same logic employed for Case 1 rules out the possibility of profitable marginal deviations in this case.

I. $Q_X$ Binding – Corner Solution ($h_{max}$ binding)

$$\hat{h}_X = h_{\max}, \qquad \hat{T} = \frac{Q_X}{Nh_{\max}}$$

*If* $h_{max} = \overline{h}$,

(N1) $\overline{T} \geq \hat{T}_{\text{int}} \longrightarrow N \geq f(p,c,b,\alpha,Q_X,\overline{T})$

(N2) $N \geq \dfrac{p - cbh_{\max}^{\alpha-1}}{p - \alpha cbh_{\max}^{\alpha-1}}$

This solution is the counterpart to the first part of the interior solution for this case and is similar in spirit to the "$Q_B$ Binding – Corner Solution ($h_{max}$ binding)" solution for Case 1. (N1) and (N2) show that one would like to reach an interior solution but this solution lies beyond the maximum harvest rate that is technologically possible. As a result, agents harvest at this maximum level. Notice that hits solution never holds when $h_{max} = h_{\pi\max}$. Parallel arguments to those used for the "$Q_B$ Binding – Corner Solution ($h_{max}$ binding)" solution establish that there are no profitable marginal deviations from this solution.

## A.2 Sufficiency Arguments

We now need to establish conditions under which the equilibria described above are not only impervious to marginal deviations in harvest but are also devious to individual deviations in the harvest rate that could lead to a change in the binding quota. The following lemma is helpful in this regard:

*Lemma A.1: No rational, noncooperative agent will prefer to deviate from one of the candidate equilibria described above to cause a situation in which* $\bar{T}$ *binds alone.*

The proof of this fact is simple and easily expressed in words. By deviating, individuals place themselves in a situation where the marginal profitability of an extra unit of harvest $\bar{T}\pi'(h_X)$ is always positive. As a result, an agent will desire to increase their harvest until one of the quotas "bites". With this fact in hand, we only need to consider those deviations that involve switching from one binding quota to another.

Equilibrium D is certainly robust to any downward deviations in harvest, since the season length is already maximized. It is also the case that there are no profitable increases in harvest since such increases would result in a situation in which bycatch quota still binds and it has already been shown that quota-preserving deviations do not pay off. Therefore, the necessary conditions for D are also sufficient to establish it as a symmetric, pure-strategy Nash equilibrium.

Upward deviations in harvest for candidate equilibria C, E, and F are likewise eliminated due to the fact that they are all quota-preserving and thus subject to the same reasoning employed for D. Downward deviations in harvest are more difficult to eliminate, but the following lemma proves very helpful:

*Lemma A.2: If* $N \geq \dfrac{1-\left({cQ_B}/{pQ_X}\right)}{1-\alpha\left({cQ_B}/{pQ_X}\right)}$*, there is no incentive to deviate from any candidate solution in which* $Q_B$ *binds.*

It is intuitive although tedious to prove that an individual's objective function (4) evaluated at a particular binding quota cannot possess an interior minimum. Therefore, if the first derivative of the profit function with $Q_X$ binding is positive at the threshold harvest rate between the two quotas ($h_{trans}$) then we can rest assured it is positive at all lower values as well and so Lemma A.2 provides a strong condition under which it never pays to deviate in a downward direction from a "bycatch binding equilibrium". It is clear upon immediate inspection, however, that the necessary conditions already assure that this condition holds for all $Q_B$ equilibria. *We can now state with confidence that the necessary conditions for C, D, E, and F are also sufficient to guarantee their status as Nash equilibria.*

The reasoning to establish the sufficiency of the necessary conditions for the Case 1 $Q_X$ equilibria is analogous. One way to eliminate a profitable upward deviation in this case is to find under what conditions the first derivative of the objective function (4) with $Q_B$ binding is negative at $h_{trans}$. In this case, the marginal returns to increased harvest must be negative for all larger values of daily harvest as well. A condition that ensures this is given by the following lemma:

*Lemma A.3: If* $N \le \dfrac{\alpha\left(1-\left({cQ_B}/{pQ_X}\right)\right)}{1-\alpha\left({cQ_B}/{pQ_X}\right)}$, *there is no incentive to deviate from any candidate solution in which* $Q_X$ *binds.*

Again, this inequality is assured by the necessary conditions for both A and B. *We can now say that the necessary conditions for A and B are also sufficient to characterize them as Nash equilibria.*

The necessary conditions for candidate equilibria in Case 2 are sufficient by definition since agents are not able in this case to cause $Q_B$ to bind.

A careful look at the full set of necessary and sufficient conditions reveals that they embrace all positive values of $N$ and none of the equilibria are found to overlap with one another in $N$-space. We have therefore succeeded in finding a symmetric, pure strategy Nash equilibrium for any combination of parameter values or number of participants.[166]

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[166] We do not argue for the uniqueness of these solutions in the class of pure strategy, symmetric equilibria although this seems likely.

# Appendix B:

# Specification and Estimation of Expectations Models

This appendix describes the construction of the predictions for expected revenues and expected bycatch utilized in the models of fishing location choice presented in Chapter 5 and Chapter 6. The basic rationale for our expectations modeling strategy is presented in Chapter 5, so we do not dwell on the underlying motivation here. The process used in generating our predictions can be neatly divided into a series of 4 steps: 1) normalization of observed species catch rates, 2) selection of appropriate explanatory variables and functional form, 3) estimation of the expectations relationship, and 4) prediction of regulation-reflective expected catch and revenue variables.

## B.1 Normalization of Catch Rates

As described in Chapter 5, our expectations modeling approach works by balancing one's own information on the predicted rate of catch at a site against the information possessed on the catch rates of one's competitors. To facilitate the estimation of this weighting rule we have presumed that the relative weights for each information source are invariant across the fleet. However, given the presence of heterogeneous vessel capital, it stands to reason that the actual weight ascribed to the information of competitors may differ according to known differentials in the efficiency of catch between vessels (e.g. the captain of a relatively small, low-horsepower vessel may down weight information from his competitors for the simple reason that they possess the technical ability to accrue a higher rate of catch per hour). To overcome this issue, we use a production function approach to normalize the catch efficiency of vessels to a common basis. This then allows us to treat all catch rates as comparable across vessels and thus subject to the same weights in the expectations model.[167]

To estimate our production function, we utilize observer data with species composition detail for our sample of 19 vessels over the same seasonal time period as our RUM model (April 15th – December) for the years 1992-2000. The choice of the appropriate basis for the normalization of vessel "effort" – in other words, the dependent variable in our production function – is somewhat up for grabs. One could use measures such as revenues per hour or, alternatively, estimate individual production functions for each species. However, these methods are likely prone to potential biases due to potential vessel-specific propensities for high revenue hauls and differences of species targeting strategies within the fleet. Developing a primal specification that is robust to these sorts of endogeneities is difficult; nevertheless, we ultimately chose to use the sum of the hourly rates of catch for the seven commercially valuable groundfish species we track in our modeling (these being yellowfin, rock and flathead sole, cod, pollock, Pacific ocean perch and Greenland turbot).[168]

We model the hourly catch of the sum of these seven species using a flexible translog functional form where the regressors are composed of four characteristics for each vessel that we observe on an annual basis from the federal and state permit files – these being vessel length, horsepower, age and hold capacity. The translog functional form is specified entirely in the natural logarithms of these dependent variables and includes the squares of the log terms for each variable as well as all their unique cross-products. In addition to these vessel characteristics we also linearly enter annual, monthly and spatial dummies (where the spatial dummies are defined

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[167] Such an approach is commonplace within the fisheries economics literature. See, for example, Holland and Sutinen (1999).

[168] This choice has its own limitations. Indeed, one difficulty with any specification that aggregates the catch of multiple species into a single dependent variable is that the resulting scaling of effort across vessels applies equally to the catch rates of all species, whereas it may be the case that the combination of physical and intellectual capital onboard a vessel may allow for differential species selectivities across vessels *at the same time and location.*

over NPFMC management areas) into our specification to account for temporal and spatial factors that may influence the average catch rate.[169]

Table B.1 reports the OLS estimation results for our production function, suppressing for the sake of parsimony the estimates of the spatial and temporal "shifter" variables (despite the fact that many of these variables are themselves highly significant). We find that many of the observed vessel characteristics figure significantly in explaining the combined catch rates of the seven commercially harvested species, often both in their "pure" form and in their interactions with other vessel characteristics. The R-squared of 0.14 suggests that a substantial portion of the variation in the catch rate remains unexplained by our model; however, there are two factors that nevertheless support the validity of our approach. First, we estimated this model using data from individual hauls (as opposed to a temporal aggregation of catch per hour). As a result, we should surmise that the role of random noise in catch rates would increase relative to a more aggregated model and so R-squared should be correspondingly smaller. Second, if we treat the translog production function as a flexible approximation to a linear Schaefer production function (where the catchability term is a function of all the observed vessel characteristics) then the temporal and spatial "shifter" variables serve as proxies for the abundance and distribution of the portfolio of targeted species. Clearly these proxies are limited in their ability to capture the pattern of abundance and so we would expect a fair bit of unexplained variation to remain in our model. However, if we believe that the catchability coefficient is not affected by unaccounted-for variations in spatiotemporal patterns of abundance, then the estimated relative harvest efficiency of vessels is not harmed by the crudeness of our proxy.[170]

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[169] By entering these factors linearly (as opposed to interacting them with vessel characteristics) we assume that these spatial and temporal fluctuations merely act to proportionally shift catch productivity for all vessels. This allows us to calculate normalization factors for effort that are time invariant (except to the degree that vessel characteristics vary through time).

[170] Previous research (Squires and Kirkley, 1999) has suggested that the skill of captains and other unobserved vessel-specific effects may play a significant role in explaining relative performance. We tested this approach by estimating vessel-specific intercepts in our production function. However, despite the substantial number of observations per vessel, the estimates for these intercepts were often highly

Table B.1: Selected Results from OLS Estimation of Translog Production Function

| Variable | Estimate | t-statistic |
|---|---|---|
| ln(length) | 14.62 | 4.39*** |
| ln(age) | 0.52 | 0.79 |
| ln(hp) | 2.46 | 2.62*** |
| ln(hold) | 1.40 | 2.00** |
| ln(length)^2 | 0.32 | 0.91 |
| ln(age)^2 | -0.10 | -1.8* |
| ln(hp)^2 | 0.23 | 4.51*** |
| ln(hold)^2 | -0.05 | -3.37*** |
| ln(age)*ln(hp) | -0.38 | -4.20*** |
| ln(age)*ln(vlength) | 0.62 | 3.35*** |
| ln(hp)*ln(length) | -1.70 | -7.21*** |
| ln(age)*ln(hold) | -0.02 | -0.33 |
| ln(length)*ln(hold) | -0.60 | -2.94*** |
| ln(hp)*ln(hold) | 0.36 | 6.11*** |
| Constant | -47.88 | -5.75*** |
| Observations | 36,350 | |
| R-squared | 0.14 | |

* significant at 10%; ** significant at 5%; *** significant at 1%

To calculate the effort standardization factors, we simply calculate the log catch rate implied by the vessel characteristics in our sample and then exponentiate this value. We then perform the same operation for an arbitrary (but fixed) baseline vessel in a particular year of our sample and then divide the former value by this number. This value represents the average proportion of the baseline vessel's hourly catch achieved by the vessel in question. The average

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imprecise. This caused the effort normalization factors to vary to an unrealistic degree in our sample. We therefore abandoned this panel data approach in favor of our cross-sectional model.

value in our sample was approximately 1 with a standard deviation of 0.098. This suggests a relatively small degree of variation in the relative catch efficiencies in our sample. The maximum and minimum values of these factors were 0.76 and 1.26 respectively so that the most efficient vessel accumulated catch at a rate 65% faster than the least efficient vessel. Having obtained these factors, it is then a simple matter to divide the catch rates of the seven commercial species (and halibut) by these factors and to thus normalize them to the efficiency level represented by the baseline vessel.

## B.2 Selection of Variables and Functional Form

As described in Chapter 5, our approach to modeling the expected catch rate of a particular species at site *i* at haul *t* can be analytically characterized as follows:

$$E(CATCH_{it} / HR \mid d(i,t)_1 I_1,\ldots,d(i,t)_J I_J) = \exp\begin{pmatrix} \psi_0 + \psi_1(d(i,t)_1,\ldots,d(i,t)_J) * I_1 \\ + \ldots + \psi_J(d(i,t)_1,\ldots,d(i,t)_J) * I_J \end{pmatrix} \qquad \text{(B.1)}$$

where the $I_j$ ($j$=1,…$J$) represent particular classes of information that fishermen potentially draw upon and the $d(i,t)_j$ are indicator (0,1) variables of whether a particular piece of information is available to a fisherman at a moment in time. The weights, $\psi_j$, although fixed across individuals and over time, are allowed to vary depending upon the informational content available to a particular fisherman. Certain information may be lacking at moments in time, necessitating a reshuffling of the priority placed on the information that is available.

This specification, being highly flexible, requires a number of decisions to make it estimable. First of all, we must decide upon the appropriate regressors. A fully flexible estimation of the weights in (B.1) (i.e. one that allows the weights to freely vary for all observed information scenarios) leads to a rapid expansion of the dimensionality of the estimation problem as variables are added to the specification. To limit the curse of dimensionality in our model, we limit ourselves to the following five variables, where it is understood that all catch rate variables are in their normalized form:

1. Recent fine grained information (the average of today's and previous day's catch rate observations at a site)
2. Older fine grained information (the average catch rate for the period spanning the day before yesterday and back another week at a site)
3. Oldest fine grained information (the average catch rate at a site for the period beginning where number 2 ends and extending a week further back)
4. "Logbook" data (a moving symmetric 2-week average from last year's catch rate record at a site)
5. "Coarse grained" info (a site's expected catch rate, common to all vessels, based on a more aggregated spatial and seasonal scale).

This typology of information is loosely based upon the categories discussed by Wilson (1990) and conforms in many ways to the patterns of information processing discussed in anthropological studies (Gatewood, 1984).

A number of comments on our specification are needed. Firstly, with the exception of variable 5, there is no indication in the descriptions of the variables of exactly *whose* information is incorporated into the variables. We have left these descriptions intentionally vague to incorporate varying degrees of information sharing in our specification. Ultimately, of the three fine grained information sources, only the "older" and "oldest" information (variables 2 and 3) are allowed to contain information from sources other than the vessel itself. Variable 1 is specifically meant to include very recent data that is not likely to be shared extensively across information networks due to its high (but ephemeral) personal value.[171] As described in 5.3.3, we

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[171] Although there is a strong economic logic to preclude the sharing of recent information by skippers, much of our decision to enforce this restriction in our model is motivated by the fact that the ordinal nature of haul data within a day prevents us from establishing the relative timing of hauls between vessels to accurately track such a rapid-fire exchange of information.

entertain six different hypotheses about the degree of information sharing as it varies across groups of vessels and changes over time. The complex sharing scenarios embodied in Table 5.2 can ultimately be constructed by estimating (B.1) for each species under four different sharing scenarios for variables 2 and 3 – full sharing across the sample, no sharing, sharing only among initial Sea State non-participants, and sharing only among charter Sea State vessels – and then selectively combining the predictions from each of these models to reflect the specifics of the particular informational scenario.

Secondly, we must better define the precise meaning of coarse grained information in our model. It is meant to include information at a sufficiently aggregated level of spatial and temporal variation so as to be common knowledge to all fishermen for all areas at all points in time; it may include well-known factors such as the broad trends of seasonal migration as well as information on species abundance relayed to the industry from annual surveys by fisheries scientists.[172] Unlike the other four variables in our expectations model which are simple averages over a time horizon, we actually utilize the normalized data in our sample to estimate models of species-specific catch rates over a broad scale and to produce predictions at this low level of resolution.

Specifically, for the 6 species in our model that primarily frequent the continental shelf (this being every species except for Pacific ocean perch and turbot), we aggregate our 165 zones into 7 larger areas based on their dominant bathymetry (loosely coinciding with the divisions between inner, middle and outer shelf) and a division between northerly and southerly sites (see Figure B.1). These divisions are designed to coincide as nearly as possible with the zones utilized by NMFS in its annual groundfish surveys, albeit with some necessary concessions due to the expediency of designing our zones to coincide with the bounds of our grid structure. In order to provide more spatially disaggregated predictions for the two species that are primarily linked with

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[172] The Alaska Science Center provides an annual "report to the fishing industry" to spatially summarize the catch results of the annual continental shelf survey. A similar report was created from 2002 onward for the continental slope region (depths below 200m).

the deeper waters of the continental shelf we define a set of 6 zones for the sites that span the 200m shelf break – again closely coinciding with the habitat divisions employed by NMFS in its trawl surveys (see Figure B.2). We then aggregate each season into three sub-seasons: the spring (April-June), summer (July and August) and fall (September-December). By interacting the relevant shelf/slope zone indicators with the seasonal dummies and then adding annual dummies to the specification, we are able to estimate the expected catch rates associated with the broad, recurrent movements of each species while simultaneously accounting for annual trends in their overall abundance.[173] We then place this full set of indicator variables within an exponential link function to ensure positive catch rate predictions and then estimate the model on our sample using quasi-likelihood procedures (described in more detail below) with the normalized catch rate as the dependent variable. The fitted values from this nonlinear regression provide the values for the fifth variable in our expectations specification.

Thirdly, each of these information types, excepting the "coarse grained" information contained in the fifth variable, is potentially unavailable to a particular fishermen at a point in time due to his visitation patterns and that of vessels in his information network, therefore implying that we must somehow account for this lack in our specification of the weighting functions. We use a very flexible dummy variable approach whereby the influence ascribed to a piece of information is allowed to vary with each combination of available data and is determined entirely by the catch data itself – implying a sort of "rational expectations" in information processing on the part of fishermen achieved by long experience with the system.

Note that the 4 variables that are potentially missing at a point in time are calculated with respect to species composition sampled hauls, which constitutes a subset of total effort by the vessel. The implication is that a "missing" piece of information in our estimation of (B.1) may in fact be known to a fisherman; however, since the purpose of our estimation is merely to use catch data to

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[173] We also allow for a special seasonal effect around the Pribilof Islands by creating a indicator for 3 sites around this island group and interacting it with the seasonal dummies as well.

determine the appropriate weights under particular informational scenarios, it is perfectly valid to estimate the model *as if* the observed scenarios and the actual scenarios are one and the same. Given the random yet closely-spaced nature of species composition sampling, it is reasonable to treat the calculations of variables 1-4 as unbiased measures of the information actually possessed by fishermen on a prospective fishing site – the only difference being that the quantity of information held by the skipper is weakly greater than that available to us as analysts. We numerically catalog the 16 potential combinations of informational variables in Table B.2.

Fourthly, in order to retain observations in the estimation for which one or more of the variables is missing while simultaneously ascribing zero weight to these variables, we replace the missing values with zero. When interacted with the dummy variables that indicate the absence of an observation for a variable, this transformation creates a column vector of zeros for the variable(s) that is missing under the particular informational scenario. These variables are then harmlessly dropped in order to avoid perfect collinearity within the estimation process.

As a final point, we should note that although we have henceforth described our specification as being an exponential function in the levels of our 5 variables, we in fact estimate the model as an exponential function of the linear combination of their natural logarithms – the reason for this being that the log transformation stabilizes predictions at the upper end of the covariates and provides a substantially better overall fit to the data than the specification in levels. In the instances when one of the variables has a value of zero, we merely impute a substitute value of 0.0001 before taking the logarithm.

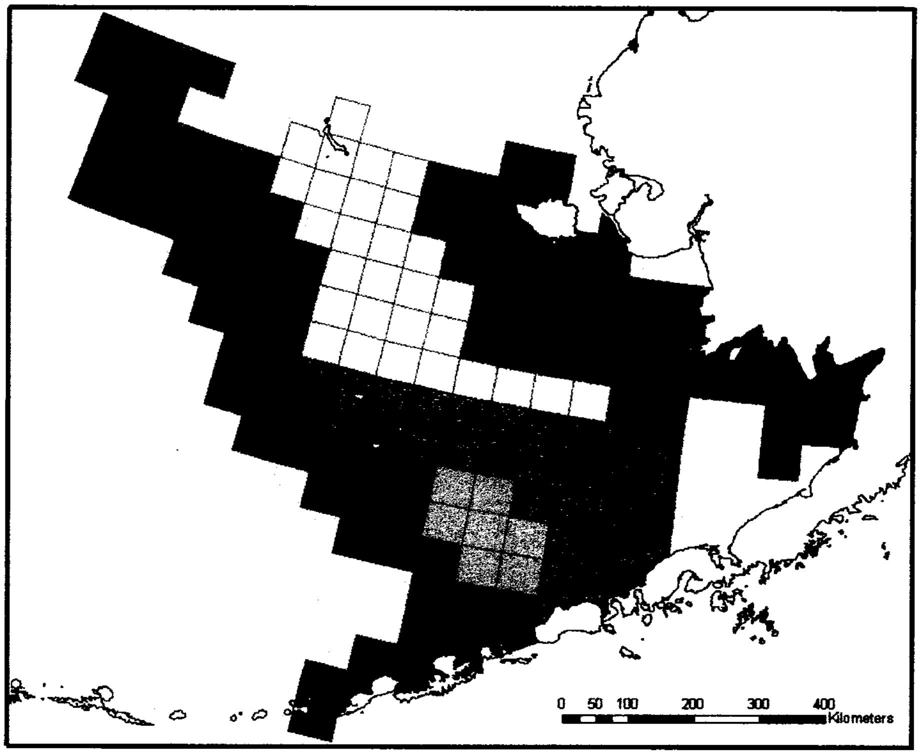

Figure B.1: Seven Shelf/Slope Zones for Coarse Grained Expectations Model

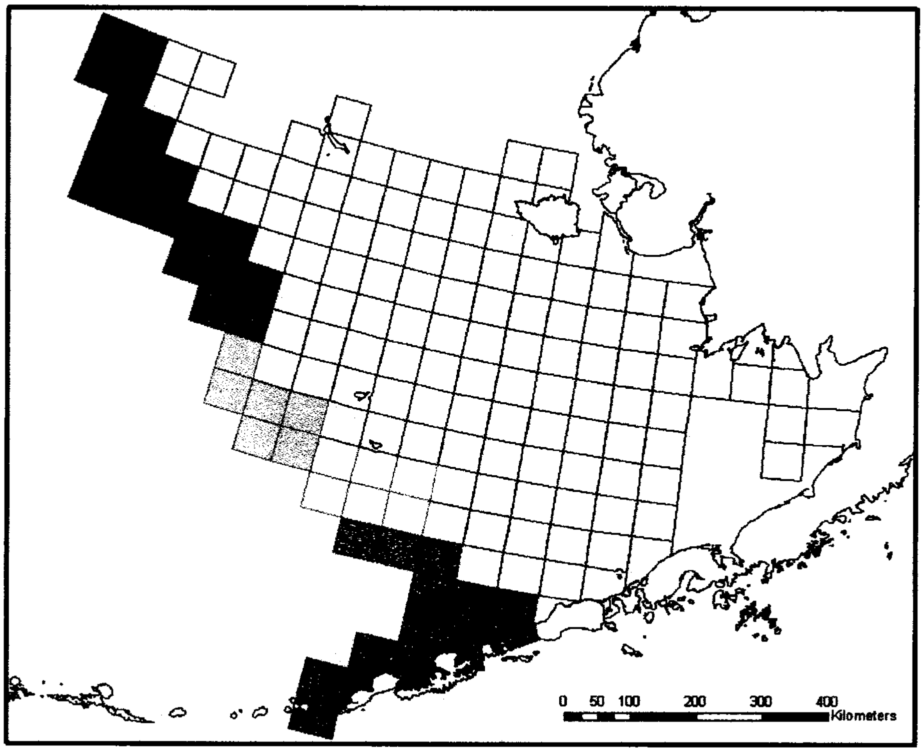

Figure B.2: Six Continental Slope Zones for Coarse Grained Expectations Model

Table B.2: Information Scenarios Present in Observer Data

| | =1 if variable missing | | | |
|---|---|---|---|---|
| Information Scenario | Variable 1 (recent fg info) | Variable 2 (older fg info) | Variable 3 (oldest fg info) | Variable 4 (logbook info) |
| 0 | 0 | 0 | 0 | 0 |
| 1 | 1 | 0 | 0 | 0 |
| 2 | 0 | 1 | 0 | 0 |
| 3 | 0 | 0 | 1 | 0 |
| 4 | 0 | 0 | 0 | 1 |
| 5 | 1 | 1 | 0 | 0 |
| 6 | 1 | 0 | 1 | 0 |
| 7 | 1 | 0 | 0 | 1 |
| 8 | 0 | 1 | 1 | 0 |
| 9 | 0 | 1 | 0 | 1 |
| 10 | 0 | 0 | 1 | 1 |
| 11 | 1 | 1 | 1 | 0 |
| 12 | 1 | 1 | 0 | 1 |
| 13 | 1 | 0 | 1 | 1 |
| 14 | 0 | 1 | 1 | 1 |
| 15 | 1 | 1 | 1 | 1 |

## B.3 Model Estimation and Results

There are a number of pathways by which to approach the estimation of our expectations specification. However, we ultimately chose to characterize the rate of catch as a Poisson process with a conditional mean as shown in (B.1) and estimate the parameters via quasi-maximum likelihood (QML) procedures (Gourieroux, et al., 1984, Gourieroux, et al., 1984). The Poisson QML estimate has the advantage of being both computationally tractable (the likelihood is globally concave) and possessing desirable robustness properties. Specifically, our estimates of the informational weights remain consistent even if the Poisson density is the wrong choice for our model – the only stipulation being that our expression for the conditional mean is correct.[174] To conduct inference that is robust with respect to the distribution of catch rates, we simply replace the usual ML estimates of the standard errors (which are inconsistent if the density is misspecified) with the robust QML variance estimate (Cameron and Trivedi, 2005).

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[174] This result arises because the Poisson is a member of a small class of densities known as the linear exponential family for which this property holds generally (Nelder and Wedderburn, 1972).

Presentation of the estimation results is complicated by the fact that no one set of estimated equations forms the basis of the final expectations hypotheses that we compare via the BIC in Table 5.2. Indeed, our "winning" informational hypothesis is constructed by the synthesis of predictions from each of four different models with different assumptions on the degree of sharing across vessels. Rather than present results for each of these models (which are quite similar to one another anyway), we instead show the estimates for one particular informational assumption – that users pool their own information on variable types 2 and 3 with information from Sea State charter participants. In light of the "best" information structure we arrived at in Chapter 5, the estimates in Table B.3 can be looked upon as the "priority weights" the data says Sea State vessels should place on various sorts of information on targeted species for the entire period and for halibut bycatch for the period from 1995 to 1999 when only a subset of vessels in our sample are assumed to pool information on halibut bycatch.

Assessing the fit of these nonlinear regressions is somewhat problematic – the usual measures of $R^2$ lose their desirable properties outside of a linear regression context. For our purposes, we employ two separate alternative measures of $R^2$. The first is the squared sample correlation coefficient between the observed catch rate and the predicted values from our model. This definition coincides with one of the properties of the $R^2$ in a linear context and has the desirable characteristic of falling between 0 and 1 but the undesirable property of sometimes decreasing with the addition of extra variables (Cameron and Windmeijer, 1996). The second measure of $R^2$, developed by Cameron and Windmeijer (1997), is based upon the Kullback-Leibler divergence and measures the percentage of potentially recoverable information (i.e. the percentage of the gap in the log likelihoods between the perfectly-fitting model and one with only a constant term) that is recovered by the regressors. This measure has a wealth of desirable properties when the likelihood is properly specified, and maintains two desirable properties (that the measure be bounded between 0 and 1 and that $R^2$ be non-decreasing with the addition of variables) even when the stochastic specification is in doubt (Cameron and Windmeijer, 1996).[175] A glance at the measures of fit for each of the species suggests that our model does a fairly nice job of explaining the variations of catch rates in the data – especially when considered in light of the high degree of natural variability in catch data at this level of disaggregation. Some species, such as flathead sole, yellowfin sole and Greenland turbot, are especially predictable on the basis of the information contained in our model, while the spatial abundance of others, such as halibut are comparatively difficult to explain.

A word of explanation is warranted about the smaller number of observations employed in the estimation of the models for POP and Greenland turbot. Since these species are only present in a small sub-area of the fishing grounds, we only estimate the model in areas for which the data suggests a reasonable chance of positive abundance. For POP this limits the estimation to hauls in the 6 slope zones defined above, whereas for turbot we expand beyond the slope to include all hauls that occur in grids where the mid-depth (the average of the maximum and minimum depths found within a zone) is greater than or equal to 100 meters. In other words, turbot are allowed to have positive catch rates over both the slope and outer shelf regions. Later, when we generate predictions for the catch rates of these two species, we impute zero values of POP and turbot for zones outside of the geographic domain of the estimation sample.

The base scenario for the estimation results in Table B.3 is one in which all information is available to the agent, and the estimates can be interpreted as the percentage change in the predicted catch rate at a site for a one percent change in the relevant variable. There does not appear to be a consistent relative weighting between one's own recent information (variable 1) and the older but pooled information of one's competitors (variable 2). For instance it appears

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[175] We do not show the results of tests for the appropriateness of the Poisson assumption as the validity of our QML estimates is not dependent upon the proposed distribution of catch rates; however, we easily rejected the Poisson distribution for all species using a number of accepted tests. Alternative nonlinear models and estimators (such as the negative binomial, zero-inflated Poisson and tobit) yielded little or no improvement in in-sample goodness of fit (as measured by the mean squared error of predictions) and lack the robustness to misspecification of the Poisson QMLE.

that an increase in the expected catch of cod indicated by shared information of up to a week old has a much larger effect on catch expectations than an equivalent increase in one's own recent catch at a site, whereas the relative magnitudes of these estimated effects are comparable for the three sole species. This result may be indicative of a lesser degree of short-term site fidelity on the part of relatively mobile cod as compared to the more sedentary flatfish. Interestingly, the oldest fine grained information receives little or no consideration when there is more recent information to draw upon. Similarly, year-old logbook data generally seems to have little explanatory influence when more recent spatially-precise data on expected catch are available. Spatially and temporally coarse background information seems to carry some weight even when there is plenty of recent and spatially precise information to guide decision making, although the influence of this information is often less than that of one or the other of the two most recent fine grained variables.

Of course, these observations do not apply equally to each species. Indeed, two species are conspicuous for their divergent pattern of estimates. POP is unusual in that the oldest fine grained information (variable 3) has a very large and significant influence on current catch expectations whereas more recent information has a statistically insignificant influence and the most recent catch has a significant but relatively small impact compared to that seen for other species. This pattern is a challenge to explain but may have something to do with the unusually fixed and clustered nature of POP populations due to their highly-specific habitat preferences (Brodeur, 2001). This pattern may make substantial proportions of the POP biomass in a grid "sitting ducks" to knowledgeable fishermen in the near term, causing temporary scattering of schools so that information obtained from just a few days back is of little use. However, the high site fidelity of POP brings them back to their previous haunts in a relatively short period as evidenced by the large and significant influence of older fine grained information.

Table B.3: Expectations Model Estimates with Pooling of Information by Sea State Vessels

| | cod/hr | flathead sole/hr | rock sole/hr | yellowfin sole/hr | pollock/hr | halibut/hr | POP/hr | Greenland turbot/hr |
|---|---|---|---|---|---|---|---|---|
| Var 1: New fg info | 0.09 | 0.35 | 0.37 | 0.41 | 0.38 | 0.06 | 0.07 | 0.07 |
| | (2.85)*** | (10.79)*** | (3.25)*** | (14.02)*** | (12.95)*** | (7.44)*** | (2.49)** | (2.45)** |
| Var1*Scenario 2 | 0.43 | 0.10 | -0.21 | 0.01 | -0.03 | 0.01 | -12.06 | 0.23 |
| | (3.13)*** | (1.23) | (-1.28) | (0.05) | (-0.14) | (0.40) | (-8.36)*** | (1.83)* |
| Var1*Scenario 3 | 0.14 | 0.08 | -0.35 | 0.13 | 0.01 | 0.04 | 0.07 | 0.21 |
| | (2.18)** | (1.26) | (-2.17)** | (2.20)** | (0.18) | (1.25) | (1.05) | (1.43) |
| Var1*Scenario 4 | 0.10 | 0.08 | 0.09 | 0.01 | -0.06 | 0.00 | 0.21 | 0.38 |
| | (2.28)** | (1.75)* | (0.76) | (0.09) | (-1.70)* | (0.29) | (2.18)** | (4.07)*** |
| Var1*Scenario 8 | 0.25 | 0.44 | -0.38 | 0.10 | 0.36 | 0.09 | 0.26 | 0.70 |
| | (2.62)*** | (4.57)*** | (-2.40)** | (0.89] | (2.92)*** | (2.75)*** | (1.02] | (5.28)*** |
| Var1*Scenario 9 | 0.05 | 0.26 | 0.35 | 0.13 | -0.13 | -0.04 | 0.20 | 0.33 |
| | (0.24) | (2.05)** | (1.87)* | (0.80) | (-0.65) | (-1.01) | (0.88) | (1.91)* |
| Var1*Scenario 10 | 0.23 | 0.00 | 0.17 | 0.25 | -0.15 | 0.04 | -0.15 | 0.42 |
| | (3.36)*** | (0.03) | (1.31) | (2.21)** | (-3.17)*** | (2.830*** | (-2.27)** | (4.97)*** |
| Var1*Scenario 14 | 0.29 | 0.23 | 0.37 | 0.32 | 0.14 | 0.08 | 0.04 | 0.17 |
| | (3.02)*** | (4.09)*** | (3.06)*** | (2.37)** | (1.23) | (2.85)*** | (0.60) | (3.14)*** |
| Var 2: Older fg info | 0.50 | 0.41 | 0.59 | 0.38 | 0.28 | 0.09 | 0.18 | 0.26 |
| | (14.10)*** | (9.20)*** | (3.19)*** | (8.59)*** | (6.07)*** | (4.01)*** | (1.13) | (2.65)*** |
| Var 2*Scenario 1 | -0.46 | 0.00 | -0.29 | 0.06 | 0.05 | -0.01 | 0.00 | -0.26 |
| | (-5.80)*** | (0.03) | (-1.51) | (0.85) | (0.69) | (-0.28) | (0.02) | (-2.52)** |
| Var 2*Scenario 3 | -0.24 | -0.04 | 0.22 | -0.18 | -0.10 | -0.05 | 0.09 | 0.01 |
| | (-3.35)*** | (-0.52) | (0.77) | (-1.70)* | (-1.47) | (-0.81) | (0.48) | (0.06) |
| Var 2*Scenario 4 | -0.05 | -0.08 | -0.24 | -0.07 | 0.11 | 0.01 | -0.17 | -0.34 |
| | (-1.02) | (-1.44) | (-1.30) | (-0.89) | (1.95)* | (0.40) | (-1.06) | (-2.44)** |
| Var 2*Scenario 6 | -0.26 | -0.08 | -0.25 | -0.09 | 0.07 | 0.00 | -0.12 | 0.18 |
| | (-3.04)*** | (-0.66) | (-1.25) | (-0.73) | (0.78) | (0.07) | (-0.49) | (0.82) |
| Var 2*Scenario 7 | -0.26 | 0.00 | -0.12 | 0.19 | -0.02 | 0.03 | 0.37 | -0.24 |
| | (-2.47)** | (0.07) | (-0.62) | (2.88)*** | (-0.17) | (1.10) | (1.16) | (-2.28)** |
| Var 2*Scenario 10 | -0.30 | -0.06 | -0.38 | -0.27 | 0.17 | -0.04 | -0.01 | -0.28 |
| | (-3.79)*** | (-0.79) | (-1.89)* | (-1.95)* | (2.10)** | (-1.47) | (-0.06) | (-2.73)*** |
| Var 2*Scenario 13 | -0.27 | -0.11 | -0.27 | 0.08 | -0.05 | -0.02 | -0.14 | -0.11 |
| | (-4.62)*** | (-1.41) | (-1.34) | (0.75) | (-0.64) | (-0.88) | (-0.87) | (-1.05) |
| Var 3: Oldest fg info | -0.01 | 0.05 | 0.00 | 0.02 | 0.06 | 0.02 | 0.77 | 0.00 |
| | (-0.63) | (2.10)** | (0.03) | (0.81) | (2.33)** | (2.01)** | (2.86)*** | (0.00] |
| Var 3*Scenario 1 | 0.05 | 0.05 | 0.14 | 0.05 | 0.02 | 0.05 | -0.21 | 0.06 |
| | (0.99) | (0.75) | (1.64) | (1.30) | (0.35) | (2.40)** | (-0.63) | (1.15) |
| Var 3*Scenario 2 | -0.01 | -0.21 | 0.30 | 0.22 | 0.11 | -0.02 | 2.29 | -0.04 |
| | (-0.35) | (-2.17)** | (1.76)* | (2.19)** | (1.44) | (-0.87) | (4.71)*** | (-0.83) |
| Var 3*Scenario 4 | -0.01 | -0.03 | 0.02 | -0.03 | -0.07 | -0.01 | -0.80 | 0.02 |
| | (-0.61) | (-1.06) | (0.27) | (-1.12) | (-2.48)** | (-0.42) | (-2.92)*** | (0.36) |
| Var 3*Scenario 5 | 0.07 | 0.08 | 0.26 | 0.35 | 0.01 | 0.00 | -0.11 | -0.01 |
| | (3.26)*** | (0.69) | (2.73)*** | (3.31)*** | (0.32) | (0.11) | (-0.40) | (-0.20) |
| Var 3*Scenario 7 | 0.05 | 0.08 | 0.04 | -0.01 | 0.02 | -0.01 | -0.72 | 0.12 |
| | (1.95)* | (1.83)* | (0.61) | (-0.35) | (0.45) | (-0.69) | (-2.65)*** | (2.27)** |
| Var 3*Scenario 9 | 0.29 | -0.04 | 0.12 | 0.15 | -0.02 | -0.02 | -0.72 | -0.04 |
| | (2.26)** | (-0.86) | (1.21) | (1.90)* | (-0.69) | (-0.59) | (-2.56)** | (-0.65) |
| Var 3*Scenario 12 | 0.05 | 0.21 | 0.46 | 0.34 | 0.01 | 0.00 | -0.49 | -0.03 |
| | (1.65)* | (2.67)*** | (5.42)*** | (5.01)*** | (0.14) | (0.03) | (-1.14) | (-0.50) |
| Var 4: Logbook info | 0.01 | 0.02 | -0.04 | 0.02 | 0.02 | 0.03 | 0.02 | 0.09 |
| | (0.82) | (1.51) | (-1.16) | (0.78) | (1.01) | (4.94)*** | (0.32) | (1.82)* |
| Var 4*Scenario 1 | 0.06 | 0.10 | 0.10 | 0.06 | 0.04 | -0.02 | 0.15 | 0.01 |
| | (2.52)** | (2.11)** | (1.80)* | (1.38) | (0.97) | (-0.90) | (1.54) | (0.22) |
| Var 4*Scenario 2 | -0.05 | 0.14 | 0.05 | 0.16 | 0.00 | 0.01 | 10.69 | -0.47 |
| | (-1.58) | (1.50) | (1.02) | (1.35) | (0.00) | (0.15) | (8.72)*** | (-2.73)*** |
| Var 4*Scenario 3 | 0.02 | 0.04 | 0.01 | -0.03 | 0.02 | -0.03 | 0.09 | -0.06 |
| | (0.77) | (1.41) | (0.31) | (-0.57) | (0.70) | (-1.71)* | (1.10) | (-1.06) |
| Var 4*Scenario 5 | 0.00 | 0.27 | 0.14 | 0.22 | 0.07 | 0.04 | 0.53 | 1.16 |
| | (0.14) | (1.55) | (2.21)** | (1.84)* | (1.28) | (1.21) | (2.66)*** | (3.68)*** |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Var 4*Scenario 6 | 0.03 | 0.06 | 0.06 | 0.10 | 0.08 | -0.01 | 0.54 | -0.02 |
| | (1.21) | (0.79) | (1.29) | (1.24) | (1.83)* | (-0.48) | (1.01) | (-0.27) |
| Var 4*Scenario 8 | -0.06 | 0.12 | 0.11 | 0.12 | -0.16 | -0.04 | 0.02 | 0.01 |
| | (-2.46)** | (1.73)* | (0.56) | (1.74)* | (-2.59)*** | (-1.46) | (0.24) | (0.08) |
| Var 4*Scenario 11 | 0.10 | 0.17 | 0.32 | 0.24 | 0.20 | 0.02 | 0.32 | 0.01 |
| | (2.85)*** | (1.79)* | (4.70)*** | (4.38)*** | (2.97)*** | (0.82) | (1.95)* | (0.06) |
| Var 5: coarse grained info | 0.25 | 0.10 | 0.07 | 0.08 | 0.22 | 0.66 | -0.10 | 0.39 |
| | (5.86)*** | (3.37)*** | (0.58) | (2.18)** | (6.04)*** | (23.23)*** | (-0.27) | (3.95)*** |
| Var 5*Scenario 1 | 0.43 | 0.18 | 0.41 | 0.23 | 0.26 | 0.00 | 0.11 | 0.25 |
| | (3.96)*** | (2.28)** | (2.82)*** | (4.11)*** | (4.25)*** | (0.09) | (0.35) | (2.31)** |
| Var 5*Scenario 2 | 0.15 | 0.42 | 0.54 | 0.03 | 0.25 | 0.09 | -6.85 | 0.41 |
| | (1.05) | (3.53)*** | (2.21)** | (0.26) | (1.39) | (1.92)* | (-12.08)*** | (3.16)*** |
| Var 5*Scenario 3 | 0.08 | -0.03 | 0.11 | 0.10 | 0.13 | -0.03 | 0.50 | -0.16 |
| | (1.18) | (-0.53) | (0.62) | (0.99) | (2.25)** | (-0.63) | (1.74)* | (-1.29) |
| Var 5*Scenario 4 | -0.02 | 0.05 | 0.10 | 0.12 | 0.04 | 0.02 | 0.79 | 0.00 |
| | (-0.35) | (1.43) | (0.71) | (2.83)*** | (0.95) | (0.81) | (2.85)*** | (0.03) |
| Var 5*Scenario 5 | 0.52 | 0.46 | 0.58 | 0.21 | 0.53 | 0.10 | -0.28 | -0.78 |
| | (10.75)*** | (2.96)*** | (3.68)*** | (2.54)** | (9.00)*** | (2.24)** | (-0.83) | (-2.49)** |
| Var 5*Scenario 6 | 0.30 | 0.41 | 0.53 | 0.43 | 0.28 | 0.04 | 0.24 | -0.14 |
| | (3.64)*** | (4.08)*** | (3.44)*** | (6.00)*** | (3.45)*** | (1.29) | (0.50) | (-0.65) |
| Var 5*Scenario 7 | 0.30 | 0.27 | 0.41 | 0.24 | 0.39 | 0.01 | 0.43 | 0.25 |
| | (3.26)*** | (5.45)*** | (2.53)** | (4.48)*** | (3.50)*** | (0.44) | (1.11) | (2.43)** |
| Var 5*Scenario 8 | 0.32 | -0.08 | 0.87 | 0.19 | 0.14 | 0.05 | 0.68 | -0.48 |
| | (3.04)*** | (-0.83) | (4.68)*** | (1.66)* | (1.20) | (1.13) | (1.78)* | (-2.71)*** |
| Var 5*Scenario 9 | 0.23 | 0.26 | 0.09 | 0.14 | 0.48 | 0.08 | 0.37 | 0.00 |
| | (1.17) | (1.89)* | (0.48) | (0.93) | (2.56)** | (1.55) | (1.14) | (0.03) |
| Var 5*Scenario 10 | 0.09 | 0.13 | 0.16 | 0.07 | 0.05 | 0.04 | 0.95 | -0.04 |
| | (1.53) | (3.40)*** | (1.17) | (1.27) | (0.89) | (1.72)* | (3.67)*** | (-0.32) |
| Var 5*Scenario 11 | 0.47 | 0.66 | 0.64 | 0.54 | 0.53 | 0.07 | 0.74 | 0.30 |
| | (9.66)*** | (6.74)*** | (4.30)*** | (9.58)*** | (7.64)*** | (2.00)** | (2.52)** | (2.63)*** |
| Var 5*Scenario 12 | 0.53 | 0.59 | 0.46 | 0.47 | 0.67 | 0.08 | 0.59 | 0.33 |
| | (11.73)*** | (7.59)*** | (3.10)*** | (7.53)*** | (13.34)*** | (2.33)** | (1.43) | (3.23)*** |
| Var 5*Scenario 13 | 0.36 | 0.52 | 0.57 | 0.37 | 0.50 | 0.11 | 0.95 | 0.25 |
| | (6.35)*** | (7.61)*** | (3.70)*** | (3.86)*** | (7.76)*** | (4.20)*** | (3.52)*** | (2.55)** |
| Var 5*Scenario 14 | 0.26 | 0.28 | 0.18 | 0.13 | 0.28 | 0.08 | 0.93 | 0.19 |
| | (2.68)*** | (5.05)*** | (1.28) | (1.00) | (2.58)*** | (2.47)** | (3.34)*** | (1.84)* |
| Var 5*Scenario 15 | 0.56 | 0.79 | 0.87 | 0.79 | 0.74 | 0.12 | 0.98 | 0.28 |
| | (14.98)*** | (26.96)*** | (6.31)*** | (28.09)*** | (21.79)*** | (4.90)*** | (3.56)*** | (2.91)*** |
| Constant | 0.99 | 0.52 | 0.18 | 0.76 | 0.47 | 1.06 | 0.82 | 1.61 |
| | (7.00)*** | (9.42)*** | (1.83)* | (3.48)*** | (3.13)*** | (12.27)*** | (0.55) | (7.41)*** |
| Observations | 36,354 | 36,354 | 36,354 | 36,354 | 36,354 | 36,354 | 3,506 | 5,015 |
| R-squared | .228 | .505 | .238 | .344 | .281 | .13 | .199 | .474 |
| R-squared† | .244 | .594 | .536 | .43 | .331 | .243 | .539 | .614 |

QML robust z-statistics in parentheses
* significant at 10%; ** significant at 5%; *** significant at 1%
† Cameron & Windmeijer (1996)

The estimates for halibut are also very interesting in their divergence from the patterns evidenced for other species. When all information is available to fishermen, the influence of the most recent information, much as for cod, is quite small. However, unlike cod, the "expectations elasticities" for the two other fine grained information categories are both quite small. More than any other species in our sample, halibut expectations (if rationally formed) are responsive to commonly-held coarse grained information to the relative exclusion of other sources of information. This seems to be indicative of a pattern of abundance that, while somewhat predictable on a broad seasonal scale, is highly noisy at a spatial and temporal resolution. This conjecture is supported by the relatively low explanatory fit of the halibut regression in terms of its $R^2$. The small influence of pooled fine grained information in our estimates may call into question the merit of information-pooling programs such as Sea State in terms of the value of their services in helping to predict halibut "hot spots" – notwithstanding the additional difficulties of incentive problems cited in Chapter 6.

The multiplicative interactions between each variable type in Tale B.3 should be interpreted as the change in the weighting of the variable compared to the base case of full information. There obviously many possibilities to explore in these estimates; however, we only note a few generalities here. First of all, the absence of one or more pieces of fine grained information seems, in most scenarios, to have a marked impact upon the additional responsiveness of expectations to coarse grained information. This effect is especially noticeable for scenarios in which the most recent fine grained information is unavailable (compare scenarios 5, 6, 7, 11, 12 and 13 against 2, 3, 4, 8, 9 and 10). Furthermore, older types of shared fine grained information appear to have little value as informational substitutes for recent own-information. This can be seen by looking at the changes to the relative weightings in scenario 1 in which only the most recent information (variable 1) is unavailable. In these cases, the best use of the remaining information appears to be to leave the weights on other fine grained information unchanged (or, in the case of cod to dramatically down-weight it) while making expectations much more responsive to coarse grained information. Except for a few scattered exceptions, the estimates seem to indicate that it is best to pay logbook data little heed – the only notable caveat being that it does appear sensible to consider logbook data when one lacks any other information besides coarse grained data (scenario 11).[176]

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[176] Despite the generally sensible nature of our estimates, it is difficult to explain a few of the specific results. In particular, the estimates for POP reveal a worrisome degree of sensitivity of the relative weights

## B.4 Prediction of Expected Catch and Revenues

The final step of predicting expected catch of halibut and expected revenues of commercial species for use in our RUM model is itself a three-part process. First, for each of the four elemental assumptions on information sharing we predict the expected catch of all 8 species. Secondly, we filter these raw predictions through the contemporaneous species-specific closures and retention restrictions to generate the regulation-reflective expected catch rates. Thirdly, we calculate the relevant unit price for each species (accounting for the product allocation of the vessel) and then apply these prices to the regulation-reflective expected catch rates to achieve, at long last, the expected revenues per standardized hour of fishing.

The prediction of expected catch rates from our model is quite simple. We simply calculate the five variables from the full set of observer species composition data on our 19 vessels (allowing for variables 2 and 3 to vary in the extent of sharing in the four aforementioned ways) and then calculate the predicted values from our model estimates. A brief caveat is warranted, however. Our predictions are conditional upon *observed* catch history which, given the lack of full species composition sampling of all hauls, is only a partial record of the catch history at a site.[177] As a result, even if our estimated models coincide exactly with the expectations rules utilized by fishermen, we cannot claim that we are able to obtain the *actual* expectations of fishermen because we only possess a portion (roughly 50% on average) of the information possessed by captains. Nevertheless, given that fishermen typically fish a site for a few hauls before moving on and observers rarely go for more than a couple of hauls without sampling for species composition, we typically have at least one (but usually several) species-composed sample point over the horizon needed to calculate variables 1-4. The essential

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to the informational scenario. It may be that the high degree of habitat fidelity and other aspects of POP biology make it ill-suited to our particular discretization of the Bering Sea slope. However, given the reasonable explanatory power of our model and the relatively minor importance of POP as a target species, we elect to leave our specification unchanged.

[177] We do have a record of every haul made by the vessels, but the hauls without species composition sampling only report the total catch of all species.

conclusion is that misclassification of the informational scenario due to partial sampling is a fairly rare event and is most likely to occur for variable 1 since it is calculated over a short time horizon and is not pooled over multiple vessels. It seems reasonable then to suppose that our predictions provide a reasonable proxy for the predictions that would have been made if we were privy to the entire catch history of vessels. At the very least, they are the best predictions given our particular modeling strategy and the information available to us.

To transform these raw catch predictions into something resembling the amount actually retainable for processing by vessels, we must incorporate numerous regulatory restrictions on the retention of species. These restrictions can be broadly classed into two categories: 1) complete prohibitions on retention and 2) restrictions where only a small amount of "bycatch" can be retained. The first sort of restriction is easily handled by modifying the raw catch rate prediction to zero to reflect the mandatory discard of the species in a particular area; the second is a bit more involved. When a species is put on "bycatch" status, the quantity that can be retained is an additive function of set proportions of the retained quantities of other so called "basis" species. (A basis species is essentially any commonly harvested groundfish species – except arrowtooth flounder in recent years – for which a closure or retention restriction is not currently in place.) For example, suppose that yellowfin sole is on bycatch status but cod and rock sole are not. Then if these are the only three species that are retained, the crew can retain an amount of yellowfin sole not to exceed the sum of 20% of the cod and 35% of the rock sole kept onboard for processing. By keeping track of closures and prohibitions for each of our species we can therefore identify the *maximum* amount of each that can be retained conditional upon the expected catch and regulatory status of the other target species. If the raw predicted catch exceeds this quantity, then we downgrade our predicted expected catch rate to reflect this maximum retainable bycatch level.[178]

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[178] We apply this approach to each individual haul; in other words, we assume fishermen comply in a very simple (and possibly unrealistic) fashion by forgetting about their backlog of retained catch of various

A brief note is warranted on how we calculate predictions of retainable catch for a particular zone when only a portion of a zone is impacted. Whenever possible, we designed our configuration of zones to minimize the incidence of such cases. However, in a few cases (particularly for the zones shown in Figure 2.8) a closure, prohibition or retention restriction divides a spatial alternative. In the case of a blanket closure (i.e. no fishing allowed), we simply redefine the zone as the area not contained within the closure and modify the surface area variable in our RUM model to reflect the new, smaller zone. In the case of prohibitions or restrictions on the catch of a particular species, the correct approach is not immediately apparent. Ultimately, however, we elected to stay consistent with the implicit assumption of our discrete spatial RUM model that implicitly posits that the distribution of all species is completely homogeneous within a particular cell at a moment in time. Under these conditions, a fisherman would never fish in an area of a zone that is under more restrictive regulation than the least restrictive part of that zone, as his catch rate would be the same but his retention possibilities would suffer. Therefore, the expected catch for a zone is the maximum retainable catch in the part of the zone that least curtails the retention of the species. This is only one of several possible approaches, but it has the benefit of internal consistency with the underlying structure of our RUM model.

Upon obtaining our predictions of expected, regulation-reflective catch rates, we are finally ready to combine these with data on market prices and weekly production patterns to generate predictions of expected revenue rates. As detailed in Chapter 4, our data on prices are production-weighted averages for particular product and species combinations for the at-sea fleet while our production data is much more specific, with weekly breakdowns by vessel of the quantity of each product made. To begin, we convert our prices (which are in $/kg. of finished

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species and applying the retention formulas in a myopic fashion to each haul. We do this because of our inability to track the quantity of retained catch over the course of a cruise. Of course, in reality fishermen may build up a bank of retention overcompliance on certain species which may allow them to substantially exceed retention limits on a haul-by-haul basis for a period of time in the future. Despite the obvious shortcomings of our approach, it nevertheless provides a reasonable picture of the *average* impact of species retention limits on expected retainable catch rates.

product) into real weight equivalent prices per kilogram. To do this we simply divide each price by the accepted product recovery rate for that species and product type to account for the loss of catch weight from processing. To achieve vessel-specific measures of species prices we treat the observed product mix as predetermined from the viewpoint of the captain and accordingly calculate the weekly price for each species as a weighted average of the real weight equivalent prices for each product, where the weights are the vessel shares of retained catch of the species devoted to each product. Since our RUM model forces fishermen at all times to consider the revenue implications of seven major commercial species, we must provide a weekly vessel-specific price for each species, even in weeks for which there is no production of a particular species. To impute a price in these instances, we merely substitute the calculated price from the nearest week. Finally, if a vessel never engages in production for a particular species within our sample, then the imputed price for that species is zero.

With these prices established, it is now a simple matter to combine them with our predictions of regulation-reflective expected catch rates and, at long last, obtain predictions of expected revenues per standardized hour of towing for each spatial alternative within our RUM model. A simple regression of "actual" regulated revenue rates (a quantity obtained by using the same prices and retention calculations as above but with the actual catch rates in the data) on our predictions yields an $R^2$ of 0.41 with a slope on the regression line of 1.02 – suggesting that our modeling approach does a very good job of predicting revenues. All that remains before substitution of our measures into the RUM model is to undue the normalization of the duration of fishing in our predictions of revenue rates and halibut catch rates. This is done in order to avoid the creation of faux heterogeneity for the coefficients of these variables due to absorption of differences in the efficiency of harvest across vessels.

# Appendix C:

# An Explanation of Sampling From Alternatives

In this appendix we outline the sampling from alternatives procedure that is utilized for the estimation of the conditional logit models in Chapter 5 and Chapter 6. Throughout we employ the conditional logit specification of the choice probabilities; it should be noted, nonetheless, that a similar procedure could be devised for any GEV model (e.g. nested logit but not multinomial probit or mixed logit) and is thus fairly general in its application (Bierlaire, et al., 2003).

It is easily demonstrated, see Train (2003), that the probability of agent *i* choosing site *n*, conditional on the analyst's selection of the set of alternatives *X* from the full choice set *B*, is:

$$P_i(n \mid X) = \frac{\exp(V_{in}) q(X \mid n)}{\sum_{j \in B} \exp(V_{ij}) q(X \mid j)} = \frac{\exp(V_{in}) q(X \mid n)}{\sum_{j \in X} \exp(V_{ij}) q(X \mid j)}, \tag{C.1}$$

where $q(X \mid j)$ is the probability of the analyst drawing choice set *X* conditional on alternative *j's* inclusion. With a slight bit of rearranging, (C.1) can be written as:

$$P_i(n \mid X) = \frac{\exp(V_{in} + \ln q(X \mid n))}{\sum_{j \in X} \exp(V_{ij} + \ln q(X \mid j))}. \tag{C.2}$$

Insofar as $q(X \mid j)$ satisfies a condition known as the *positive conditioning property*, that $q(X \mid n) > 0$ implies that $q(X \mid j) > 0$ for every $j \in X$ (i.e. that the choice set *X* could have been drawn with any of its elements as the observed choice), then McFadden (1978) and Bierlaire et al. (2003) show that maximum likelihood estimation where the conditional probabilities in (C.2) replace the usual probabilities in the log likelihood provides consistent estimates of the parameters. Indeed, this estimator is easily implemented by entering the logarithm of the $q(X \mid j)$'s as a regressor in the observed utility function with a coefficient constrained to one.

Our specification of the conditional choice set probabilities is grounded in the notion that individual vessels' full choice sets may differ due to physical characteristics of the vessel that allow greater or lesser ranges of motion, skipper experience, or various other factors. We define the full choice set for each vessel as the totality of sites that are visited over the entire 1992-2000 period *by that vessel*, including the two years of data that predate our sample to account for the possibility that some sites were actually considered in the early years of our sample that were visited in 1992-1993 but not thereafter. We then utilize the individual sample visitation frequencies for each site to draw *without replacement* from a multinomial distribution where the probabilities of the distribution are re-conditioned after each draw on the previous draws. We perform this operation five times for each choice occasion, yielding a sampled choice set of six alternatives including the chosen one.

The joint probability of these draws from a choice set, conditional on one known draw, $q(X \mid j)$, is governed by a well-defined but rather obscure distribution known as the Wallenius' noncentral hypergeometric (Chesson, 1976, Fog, 2004, Wallenius, 1963). This distribution characterizes the probability of a particular outcome in an urn experiment where the balls (which are drawn without replacement) are not only of various colors but also of different sizes so that some balls are more likely to be drawn than others. The same logic governs the sequential construction of our choice sets where each site in an agent's full choice set is a "color" and the sizes of the balls are analogous to the sample probabilities of a site being drawn conditional on a particular site's already having been selected into the choice set.

In this particular case $q(X \mid j)$ can be represented as follows (suppressing, in the interest of notational clarity, individual subscripts with the understanding that all probabilities are individual specific):

$$q(X \mid j) = \int_0^1 \prod_{i \in X,\, i \neq j} \left(1 - z^{P(i|j)/d(j)}\right) dz, \qquad \text{(C.3)}$$

$$d(j) = \sum_{i=1}^{165} P(i \mid j) * \left(1 - I_X(i)\right), \tag{C.4}$$

where $P(i \mid j)$ is the probability of drawing site *i* into the sample given that *j* has already been selected. ( $P(j \mid j) = 0$ since sampling is conducted without replacement.)

We numerically approximate the integrand in (C.3) for each choice occasion and its sampled alternatives using an implementation of adaptive Simpson quadrature available in the MATLAB software package. The time required for the software to calculate over 271,000 integrals to an accuracy of $1 \times 10^{-6}$ was minimal.

# Appendix D:

# Full Estimation Output from Chapter 5 and a Discussion of Additional Results

The summary of results in Chapter 5 concentrates on the results concerning the marginal costs of halibut bycatch and distance. This appendix summarizes additional results from our model that, while interesting, did not merit inclusion in the chapter itself. These results can be roughly divided along the variables related to state dependence, herding and miscellaneous control variables. The full results of the maximum likelihood estimation of the RUM model from Chapter 5 are contained in Table D.1.

Glancing at the results for the continuous measures of state dependence in Table D.1 reveals that there are apparently positive and gradually diminishing returns to experience (hours spent fishing) at a site and these returns to experience are higher for recent experience than that accrued in the more distant past. Evaluated at the median estimate, an hour of experience at a site with no recent experience (i.e. no visitation in the last two days) has a marginal value of approximately \$139 while an extra hour of experience after 12 hours of recent experience has a value of \$102.[179] Conversely, the first hour of experience counts for only about \$16 when considered after a period of longer than a couple of days and the 12th hour has a value between \$14 and \$15. In other words, recent experience at a site necessitates that a premium in expected rents (or some other characteristic) exist at unfamiliar sites to induce fishermen to choose them. Nevertheless, experience is a rapidly depreciating asset. These findings seem to agree with

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[179] To obtain these estimates, divide the state dependence coefficient estimates by the median estimate of marginal utility of revenue productivity. Then divide the resulting quantities by 3 (the average duration of a tow) to obtain the shadow values in 1000s of dollars.

earlier results on state dependence in fisheries location choice (Holland and Sutinen, 2000, Smith, 2005).

Interestingly, the results on continuous measures of experience at a site are not mimicked in the estimates of the state dependence dummy variables.[180] Instead, we find widespread evidence that, *ceteris paribus*, vessels tend to *avoid* areas in which they just completed a haul. The strength of this preference varies widely over vessels – the implication of our estimates is that vessels require a premium in expected variable rents of between $28 and $1324 (with a median of $643) to "stay put" at a site.[181] This spatial "momentum" runs counter to previous studies that have consistently reported positive state dependence (i.e. inertia or habit persistence) (Bockstael and Opaluch, 1983, Holland and Sutinen, 2000, Smith, 2005). This divergence may be due to our bifurcation of state dependence into separate variables reflecting recent experience as well as a dummy variable reflecting the last fishing location. Many previous studies have ignored these experience effects in their specifications and are likely picking up the net effect of the two measures – an effect which may very well indicate positive state dependence on average. Alternatively, it may be that our relatively fine spatial and temporal scale leads to different results from previous studies which have often modeled decisions at a much coarser level. It seems reasonable that measures of spatial inertia or momentum could be highly sensitive to the spatial and temporal scales under consideration, although we are not aware of any studies that address this question.

It is tempting to ascribe a great deal of behavioral significance to the state dependence variables by characterizing them as reflecting the "returns to experience" or, in the case of our dummy variable, the "preference for variety" or "negative habit persistence". To do so, however,

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[180] Recall that these dummy variables indicate scenarios in which the alternative under consideration constitutes the last recorded location of the vessel.

[181] Of course, these estimates ignore the offsetting effects of experience discussed in the previous paragraph. A site that was recently visited is likely to reflect higher levels of recent experience than others in an agent's consideration set. Whether state dependence is positive or negative overall is both vessel and context dependent.

ignores the fact that state dependence as it is commonly operationalized in the econometric literature is largely a residual effect that arises as a result of our inability as analysts to fully characterize the heterogeneous information and preference of agents (Smith, 2005). We have gone to considerable pains to overcome these difficulties, but it remains uncertain how much of the state dependence we uncover is truly a matter of preferences and not merely an artifact of an incomplete specification. Indeed, it is quite possible that the state dependence variables are capturing serial correlation in the unobservable portion of utility due to the lack of such a feature in our stochastic specification.

The variables reflecting "herding" behavior show a tendency for fishermen to be attracted to sites that have experienced visitation by their competitors over the previous day. All other things being equal, skippers require a median premium in expected rents of around $95 per vessel to avoid choosing a site with a higher level of visitation. The cause of this behavior is not clear. It could be the effect of rational (i.e. Bayesian) information processing under conditions of uncertainty (Banerjee, 1992), a result of risk averse preferences, or it may arise as a result of preferences that have relatively little to do with the returns from fishing (such as minimizing physical risk at sea by staying close to other vessels or a simple desire to fish with others).[182]

The response to competitors' effort concentrations beyond the previous day indicates that fishermen tend to avoid these areas. This effect may be due to temporary localized depletion of sites over moderate intervals of time after a herding-induced effort spike or the residual effects of congestion over the previous days.[183] The coefficient on the 3-day effort lag seems to indicate that this effect weakens over time, however.

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[182] An earlier version of this model incorporated competitors' fishing locations directly into the model of expected revenues such that the herding variables in the RUM model should have been purged of revenue signal effects. The results on the three variables were qualitatively similar, although the coefficient on the previous day's participation was a bit smaller in magnitude. The implication seems to be that our herding effects seem to reflect something beyond the effects of rational, risk-neutral information processing.

[183] Fishermen often claim to avoid trawling over areas that have been recently fished by competitors, citing lower productivity as the reason. This tendency is especially true when the previous vessels utilize heavy gear that make substantial contact with the seafloor and leave little opportunity for escapement (Hezel, 2006).

The effects of distance from the primary port (Dutch Harbor) concur with our prior expectations. Everything else being equal, captains prefer to stay close to port when choosing where to fish. This tendency could arise as an outcome of a complex dynamic process in which fishermen select an expected trajectory of sites at each stage of the decision process – a process we have not attempted to model here. In such a case, it is clearly preferable to avoid substantial steam times back to port with a full hold and so a captain may work his way back to port over some portion of the trajectory. This conjecture of dynamic decision making subject to a hold capacity constraint seems to derive some credence from our estimates which reveal that vessels with smaller holds seem to be on a shorter "tether" than their larger competitors. Alternatively, it could be that vessels tend to stay close to port for safety reasons and that vessels with smaller holds, being smaller overall, tend to stay even closer due to their reduced seaworthiness in rough conditions. However, this effect seems less likely given the inclusion of a three-way interaction between distance from port, hold capacity and wind speed in an earlier version of our model. The effect was highly insignificant, indicating that smaller vessels do not seem to respond to weather conditions differently by seeking shelter more readily than their larger competitors.

The coefficient on the logarithm of area indicates that fishermen are attracted to larger sites more readily than smaller ones; however, the relative attraction grows at a slower rate than the area of the sites themselves – the hypothesis that the coefficient is equal to one is easily rejected. Proportional attraction is to be expected in models where the elemental alternatives (the latent choices considered by the agent) are aggregated for analysis and the aggregation has no effect on the analysis. Less-than-proportional attraction may indicate that our grouping of elemental spatial alternatives has favored the aggregation of sites in a way that the degree of aggregation is somehow correlated with deleterious (but unobserved) characteristics of the elemental alternatives. This is but one example of the "modifiable areal unit problem" that has received a great deal of attention in the spatial analysis literature, although with little in the way of robust solutions (Fotheringham, et al., 2000, Openshaw, 1983). Given the conflicting goals involved in selecting a spatial choice set and the lack of a general solution to the modifiable areal unit problem, we have elected to retain our spatial grid with the hopes that our inclusion of an area control variable helps minimize any possible biases.[184]

The coefficients on the expected catch rate of pollock suggest that fishermen do attempt to avoid this frequently discard species when deciding where to fish. Head and gut or whole pollock products face a fairly weak demand and are, as a result, quite low in value (perhaps to a degree that is not wholly reflected in our database of prices). Sorting and discarding large quantities of pollock bycatch may be fairly costly and net space occupied by pollock excludes the catch of more valuable species. The median implicit cost of pollock bycatch prior to 1998 was $1088 per metric ton.

The apparent reduced avoidance of pollock in the wake of the increased retention/improved utilization standards (IR/IU) of 1998 that required the retention and processing of all pollock bycatch is somewhat surprising. One would expect that reduced freedom of discard would have caused *increased* avoidance; instead, the median implicit cost of pollock bycatch fell to $640/mt. This study is not centered on pollock bycatch and discards and so we do not attempt an in-depth explanation here. It could be, however, that the anticipation of the standards (the fishermen were given a period of several years to prepare before the implementation of IR/IU) led fishermen to develop new processing capabilities and product markets for pollock bycatch that were lacking beforehand – the ultimate result being less of a tendency to avoid pollock catch in spite of more stringent retention and processing standards.

The final control variable we consider is the expected discards of target species due to regulatory strictures on retention. These can be loosely regarded as the minimum level of expected discards at a site – economic factors could lead to additional discards but we do not

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[184] The location choice literature in economics has said little about the modifiable areal unit problem. Most studies ignore aggregation completely or enter site area into the model (improperly) in levels rather than in log form. To the author's knowledge, no study in the fishing location choice literature has commented on the sensitivity of their model to the spatial aggregation employed. Clearly, further work is needed in this area.

consider economic discards in our model. The catch of species that must be discarded is clearly costly; there are direct costs of sorting and discarding as well as the opportunity cost of the time "wasted" in catching non-marketable species. Therefore, it should come as no surprise that fishermen do exhibit significant avoidance of regulatory discards in their location choice behavior. The estimated implicit cost of regulatory discards is between \$106 and \$346 per metric ton with a median value of \$208.

It seems apparent that the implicit value placed on expected regulatory discards in the North Pacific would be too low since avoidance decisions are solely based on own-costs whereas the catch of a non-marketable species, due to high discard mortality, robs society of the benefit of the discarded catch as well as any future reproductive potential from the discards.[185] Forgetting about the capital value of discards for a moment and operating in a completely static environment, the optimal implicit cost of a unit of discarded catch to fishermen should be the market value of that catch less the marginal cost of bringing it to market (i.e. price net of marginal processing, storage and transportation costs). We lack measures of marginal processing and transportation costs; however, we conjecture that they are quite small in magnitude relative to the unit price of discarded catch. Our estimates suggest that expected discards in our sample had a median ex-vessel value of approximately \$510 with an interquartile range between \$380 and \$763. In other words, the vessel with the median level of discard avoidance in our sample could face marginal costs of over 50% of ex-vessel value and nevertheless undervalue discards in the majority of cases. Considering the dynamic value of avoided discards in terms of their future contribution to the fishery only widens the gap between the optimal level of avoidance and that reflected in fishermen's spatial behavior.

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[185] There is also a problem in that fishermen are likely to place comparable implicit costs on discards, regardless of their species composition, whereas from a social welfare perspective, catch of certain species should be avoided over others due to their higher market or non-market values. Given the lack of a secure right to harvest avoided discards in the future and the likelihood that many species face very similar costs of sorting and discard per unit weight, our assumption of uniform avoidance of regulatory discards seems tenable.

Table D.1: Full Results from RUM Model of Chapter 5

| | Estimates | Standard Errors | Z Statistic |
|---|---|---|---|
| *Scale Parameters** | | | |
| Vessel 1 | 1 | n/a | n/a |
| Vessel 2 | 1.2926 | 0.1310 | 2.23 |
| Vessel 3 | 1.5342 | 0.2191 | 2.44 |
| Vessel 4 | 1.2794 | 0.0965 | 2.90 |
| Vessel 5 | 1.0892 | 0.0540 | 1.65 |
| Vessel 6 | 1.5367 | 0.1338 | 4.01 |
| Vessel 7 | 1.3705 | 0.1064 | 3.48 |
| Vessel 8 | 1.3797 | 0.0908 | 4.18 |
| Vessel 9 | 1.3611 | 0.2584 | 1.40 |
| Vessel 10 | 1.1530 | 0.0745 | 2.05 |
| Vessel 11 | 1.0899 | 0.0514 | 1.75 |
| Vessel 12 | 1.4759 | 0.1179 | 4.04 |
| Vessel 13 | 1.5411 | 0.1027 | 5.27 |
| Vessel 14 | 1.2947 | 0.1307 | 2.25 |
| Vessel 15 | 0.9724 | 0.0436 | -0.63 |
| Vessel 16 | 1.5416 | 0.1128 | 4.80 |
| Vessel 17 | 1.2604 | 0.0768 | 3.39 |
| Vessel 18 | 1.3305 | 0.0794 | 4.16 |
| Vessel 19 | 1.2366 | 0.0672 | 3.52 |
| | | | |
| *Marginal utility of revenue productivity ($1000s/hr)* | | | |
| Vessel 1 | 0.2724 | 0.0431 | 6.32 |
| Vessel 2 | 0.3855 | 0.1126 | 3.42 |
| Vessel 3 | 0.8919 | 0.1746 | 5.11 |
| Vessel 4 | 0.6624 | 0.0895 | 7.40 |
| Vessel 5 | 0.3385 | 0.0450 | 7.52 |
| Vessel 6 | 0.7906 | 0.1430 | 5.53 |
| Vessel 7 | 0.4091 | 0.0883 | 4.63 |
| Vessel 8 | 0.6659 | 0.0932 | 7.14 |
| Vessel 9 | 0.8800 | 0.2489 | 3.54 |
| Vessel 10 | 0.4478 | 0.0600 | 7.46 |
| Vessel 11 | 0.2844 | 0.0439 | 6.48 |
| Vessel 12 | 0.4538 | 0.0919 | 4.94 |
| Vessel 13 | 0.5861 | 0.0872 | 6.72 |
| Vessel 14 | 0.3896 | 0.0983 | 3.96 |
| Vessel 15 | 0.2975 | 0.0425 | 7.00 |
| Vessel 16 | 0.7308 | 0.1028 | 7.11 |
| Vessel 17 | 0.6535 | 0.0837 | 7.81 |
| Vessel 18 | 0.3683 | 0.0572 | 6.44 |
| Vessel 19 | 0.6592 | 0.0764 | 8.63 |
| | | | |
| *State dependence* | | | |
| Vessel 1 | -0.2485 | 0.1185 | -2.10 |
| Vessel 2 | -0.9993 | 0.3238 | -3.09 |
| Vessel 3 | -0.6979 | 0.3415 | -2.04 |
| Vessel 4 | -0.0570 | 0.1888 | -0.30 |

| | | | |
|---|---|---|---|
| Vessel 5 | -0.3645 | 0.1071 | -3.40 |
| Vessel 6 | -1.4135 | 0.2607 | -5.42 |
| Vessel 7 | -0.2643 | 0.2175 | -1.22 |
| Vessel 8 | -1.8227 | 0.2045 | -8.91 |
| Vessel 9 | -3.0282 | 0.8390 | -3.61 |
| Vessel 10 | -1.3783 | 0.1500 | -9.19 |
| Vessel 11 | -0.4036 | 0.1196 | -3.37 |
| Vessel 12 | -0.8768 | 0.1949 | -4.50 |
| Vessel 13 | -2.3293 | 0.2441 | -9.54 |
| Vessel 14 | -0.5542 | 0.2863 | -1.94 |
| Vessel 15 | -0.9444 | 0.1133 | -8.34 |
| Vessel 16 | -2.0135 | 0.2324 | -8.66 |
| Vessel 17 | -1.7455 | 0.1833 | -9.52 |
| Vessel 18 | -0.3214 | 0.1435 | -2.24 |
| Vessel 19 | -1.4860 | 0.1599 | -9.29 |
| # fishing hours at site -- today & yesterday | 0.1888 | 0.0064 | 29.50 |
| (# fishing hours at site -- today & yesterday) ^ 2 | -0.0041 | 0.0002 | -21.58 |
| # fishing hours at site -- 1 week prior to yesterday | 0.0217 | 0.0015 | 14.66 |
| (# fishing hours at site -- 1 week prior to yesterday) ^ 2 | -0.0001 | 0.0000 | -9.67 |
| | | | |
| *"Herding" Variables* | | | |
| Number of vessels in site -- 1 day previous | 0.1303 | 0.0097 | 13.43 |
| Number of vessels in site -- 2 days previous | -0.0495 | 0.0116 | -4.27 |
| Number of vessels in site -- 3 days previous | -0.0225 | 0.0095 | -2.37 |
| | | | |
| *Other Control variables* | | | |
| Distance from Dutch Harbor | -0.2199 | 0.0518 | -4.25 |
| Distance from Dutch Harbor*hold capacity | 0.0085 | 0.0021 | 4.05 |
| Natural logarithm of Area | 0.5129 | 0.1030 | 4.98 |
| Expected pollock catch | -0.4939 | 0.0605 | -8.16 |
| Expected pollock catch * dummy(=1 if year>=1998) | 0.2032 | 0.0704 | 2.89 |
| Expected regulatory discards | -0.0943 | 0.0187 | -5.04 |
| | | | |
| *Marginal disutility of distance* | | | |
| Vessel 1 | -1.1009 | 1.1579 | -0.95 |
| Vessel 2 | -0.0753 | 1.4108 | -0.05 |
| Vessel 3 | -2.6789 | 1.5474 | -1.73 |
| Vessel 4 | 0.4711 | 1.0172 | 0.46 |
| Vessel 5 | -0.2613 | 1.0887 | -0.24 |
| Vessel 6 | -0.9396 | 1.5836 | -0.59 |
| Vessel 7 | -0.7122 | 1.4155 | -0.50 |
| Vessel 8 | -1.0599 | 1.5438 | -0.69 |
| Vessel 9 | 3.9809 | 2.0061 | 1.98 |
| Vessel 10 | -1.7743 | 1.1602 | -1.53 |
| Vessel 11 | -0.4893 | 1.0813 | -0.45 |
| Vessel 12 | -1.5258 | 1.3847 | -1.10 |
| Vessel 13 | 0.7666 | 1.4107 | 0.54 |
| Vessel 14 | -0.5256 | 1.3488 | -0.39 |
| Vessel 15 | -1.4075 | 1.4482 | -0.97 |
| Vessel 16 | -0.9563 | 2.2642 | -0.42 |

| | | | |
|---|---|---|---|
| Vessel 17 | -1.5983 | 1.5248 | -1.05 |
| Vessel 18 | -0.2308 | 1.1687 | -0.20 |
| Vessel 19 | -1.6578 | 1.5177 | -1.09 |
| % utilization yfs halibut quota | 4.8550 | 1.1947 | 4.06 |
| % utilization rs/of halibut quota | 2.9502 | 0.7461 | 3.95 |
| % utilization yfs halibut quota * % utilization rs/of halibut quota | -3.8744 | 1.1083 | -3.50 |
| Future vessel participation within yfs season (weeks) | -0.0013 | 0.0153 | -0.08 |
| Halibut mortality from yfs in previous week (mt) | -0.0043 | 0.0014 | -3.07 |
| Halibut mortality from rs/of in previous week (mt) | -0.0007 | 0.0012 | -0.58 |
| Closure dummy: yfs | -0.6823 | 0.1279 | -5.33 |
| Closure dummy: rs/of | 0.0237 | 0.0964 | 0.25 |
| Horsepower (1000s) | -0.7052 | 0.4574 | -1.54 |
| Horsepower (1000s) * Vessel length (100s ft) | 0.6040 | 0.1580 | 3.82 |
| Average Wind Speed (mph) | 0.0131 | 0.0050 | 2.62 |
| Seasonal dummy: pre-96_season2 | -1.0523 | 0.3600 | -2.92 |
| Seasonal dummy: post-96_season2 | 0.1425 | 0.3541 | 0.40 |
| Seasonal dummy: post-96_season3 | 0.4330 | 0.2991 | 1.45 |
| Seasonal dummy: post-96_season4 | 0.6669 | 0.3572 | 1.87 |
| Annual trend | -0.5162 | 0.1682 | -3.07 |
| Annual trend^2 | 0.0511 | 0.0181 | 2.82 |
| Seasonal trend: # days remaining * pre-96_season1 | 0.0056 | 0.0041 | 1.37 |
| Seasonal trend: # days remaining * pre-96_season2 | 0.0104 | 0.0028 | 3.71 |
| Seasonal trend: # days remaining * post-96_season2 | 0.0379 | 0.0107 | 3.54 |
| Seasonal trend: # days remaining * post-96_season3 | -0.0039 | 0.0024 | -1.63 |
| Seasonal trend: # days remaining * post-96_season4 | -0.0002 | 0.0025 | -0.08 |
| | | | |
| *Marginal disutility of halibut bycatch* | | | |
| Constant | 24.6049 | 13.2001 | 1.86 |
| % utilization yfs halibut quota | -35.0291 | 17.7890 | -1.97 |
| % utilization rs/of halibut quota | -12.9155 | 10.7445 | -1.20 |
| % utilization yfs halibut quota * % utilization rs/of halibut quota | 40.1275 | 16.9285 | 2.37 |
| Future vessel participation within yfs season (weeks) | 0.5955 | 0.1915 | 3.11 |
| Halibut mortality from yfs in previous week (mt) | -0.0445 | 0.0182 | -2.45 |
| Halibut mortality from rs/of in previous week (mt) | 0.0054 | 0.0211 | 0.26 |
| Closure dummy: yfs | -8.8928 | 1.8668 | -4.76 |
| Closure dummy: rs/of | 0.9479 | 1.3048 | 0.73 |
| Seasonal dummy: pre-96_season2 | 33.1578 | 7.4485 | 4.45 |
| Seasonal dummy: post-96_season2 | -7.3759 | 5.5941 | -1.32 |
| Seasonal dummy: post-96_season3 | -8.7890 | 5.0449 | -1.74 |
| Seasonal dummy: post-96_season4 | -4.1323 | 5.8826 | -0.70 |
| Annual trend | -3.0032 | 2.4727 | -1.21 |
| Annual trend^2 | 0.2226 | 0.2583 | 0.86 |
| Seasonal trend: # days remaining * pre-96_season1 | -0.2086 | 0.0567 | -3.68 |
| Seasonal trend: # days remaining * pre-96_season2 | -0.3425 | 0.0537 | -6.38 |
| Seasonal trend: # days remaining * post-96_season2 | 0.0306 | 0.1195 | 0.26 |
| Seasonal trend: # days remaining * post-96_season3 | 0.0267 | 0.0370 | 0.72 |
| Seasonal trend: # days remaining * post-96_season4 | -0.0469 | 0.0342 | -1.37 |
| | | | |
| *Summary Stats* | | | |
| *N* | 45,200 | | |

| | |
|---|---|
| Log-likelihood | -20,027.29 |
| Pseudo $R^2$ | 0.7843 |
| Predictive $R^2$ | 0.8478 |
| *Likelihood Ratio Tests* | Chi-Square |
| H0: Homogeneous Scale Parameters (dof=18) | 189.04 |
| H0: Homogeneous MU of Revenue Productivity (dof=18) | 112.10 |
| H0: Homogeneous State Dependence Dummies (dof=18) | 283.24 |
| H0: Homogeneous Marginal Disutility of Distance (dof=18) | 101.84 |
| H0: No State Dependence Variables (dof=23) | 3854.04 |
| H0: No Herding Variables (dof=3) | 228.60 |
| H0: No Halibut (dof=20) | 185.84 |

*Z tests for scale parameters are conducted using a null hypothesis value of 1.