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**STRATEGIC JOINT PRODUCTION UNDER COMMON-POOL OUTPUT QUOTAS:
THE CASE OF FISHERIES BYCATCH**

by

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ABSTRACT

We develop a simple game-theoretic model to explain the production decisions of firms when the production of a marketed good is complementary with the output of an associated good for which no market is available and the output of both goods is regulated by exogenously determined common pool output quotas. This scenario matches that of many fisheries in which regulators attempt to simultaneously manage harvests of targeted species and bycatch of other species through common pool quotas and seasonal closures. Under a competitive equilibrium, individual fishermen fail to fully account for the external effects of their harvest decisions on the season length, leading to excessive discards, drastically shortened seasons, and large shares of un-harvested quota for all but the smallest of fishery sizes. These results are robust for even very efficient (low-bycatch) fishing gears. We examine the sensitivity of our predictions to changes in output prices, discard costs, quota allocations and differing degrees of spatial correlation of target and bycatch species. Finally, we derive the optimal bycatch penalty function and describe its significance in light of various policy alternatives available to regulators.

Keywords: fisheries, bycatch, multispecies management, common property, game theory

STRATEGIC JOINT PRODUCTION UNDER COMMON-POOL OUTPUT QUOTAS: THE CASE OF FISHERIES BYCATCH

“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

1. INTRODUCTION

The bycatch and discard of non-targeted species is ubiquitous in today's fisheries. A wide array of factors including the spatial coexistence of marine species, imperfectly selective gear, and incentive-distorting managerial policies ensure that a significant portion of catch diverges from the desired species, sex, or size. Some of this bycatch does find its way into (typically low-valued) markets, but the vast majority is returned to the sea, whether by choice or due to regulatory pressure, in the form of discards. One estimate places the volume of discards at 17.9 metric tons a year, approximately 25% of global landings (Alverson, 1994) although a reappraisal by Kelleher (2005) places this proportion at around 8%.²

The sheer volume of these discards, the charismatic nature of some bycatch species (e.g. sea turtles and dolphins), and the potential value of this harvest in targeted fisheries has led to a vigorous outcry from conservation organizations, industry groups, and the general public alike to reduce bycatch and its associated mortality. The upshot of these efforts, particularly in developed countries with entrenched traditions of command-and-control fisheries practices, has been a frenzy of new policies directed at curtailing various symptoms of the bycatch problem.³ Among the favored approaches are the mandated adoption of bycatch-averting gears and time and area closures to protect vulnerable aggregations of bycatch species. Some gear modifications have achieved marked reductions in bycatch; turtle excluder devices (TEDs) in the Gulf of Mexico shrimp fishery are a notable example. However, such

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

² A large proportion of this biomass is dead upon discard due to the physiological effects of decompression, the weight of fish in a net, or rough handling onboard the ship. This figure does not include non-fish bycatch or incidental catch that was retained for sale.

³ For instance, since the re-authorization of the Magnuson-Stevens Act in 1996 the United States' NOAA Fisheries has been under a Congressional mandate to minimize, “to the extent practicable”, bycatch and its associated mortality. This mandate was made all the more pressing when in 2002 an environmental NGO demanded that NOAA initiate rulemaking to “count, cap, and control bycatch in the nation's fisheries” (Oceana, 2002).

technological solutions are considerably less successful when the bycatch species are of similar size and shape – as is the case in many demersal trawl fisheries. In these instances, small reductions in the bycatch of one species are typically achieved only at the substantial expense of foregone targeted species (Gauvin, Haflinger and Nerini, 1995; Rose and Gauvin, 2000). Also, gear innovations designed to exclude one source of bycatch may do little to help screen out other species. This appears to be the case in the Gulf of Mexico shrimp fishery where the widespread use of TEDs has not curtailed the extremely high discard rate of finfish – it is estimated that approximately 4.5 pounds of fish are discarded for every pound of shrimp landed (Harrington, Myers and Rosenberg, 2005).

Spatial and temporal closures are similarly limited in that high-bycatch areas may also be desirable for targeted fishing due to habitat overlap or trophic interactions between species, so that closures may result in considerable economic losses to fishermen. Also, spatial heterogeneity in the distributions of species may produce scenarios in which the closure of an area to reduce bycatch of one species induces the increased bycatch of another species as effort is diverted to alternative grounds.⁴

Given the potential inadequacy of these remedies, it should come as no surprise that regulators have sought more direct methods of bycatch management. In many cases this has taken the form of explicit industry-wide quotas, demarcated by gear class, space and/or time, for catch or landings on both target and bycatch species. These quotas are enforced by the seasonal closure (or extreme curtailment) of the fishery upon the attainment of any of these quotas. Of economic importance is that if the bycatch quota is attained before that of the target species, then the fishery is effectively terminated for the remainder of the season. In some cases the quotas are allocated on an individual vessel basis (as for halibut bycatch quota in the Alaska sablefish fishery) and may even be freely transferable across vessels (as in the New Zealand and Iceland IFQ programs). But it is frequently the case that the quotas are allocated to an entire fleet and are thus common pool resources to many fishermen. This is most notably the case in several valuable

⁴ This notion has received little attention in the fisheries literature but is a leading hypothesis to explain the turn of events following the closure of an area to flatfish trawl fishing in the Eastern Bering Sea in 1995. Crab bycatch (the motivation for the closure) fell following its implementation but halibut incidental catch showed a significant increase (Gauvin, Haflinger and Nerini, 1995).

North Pacific fisheries where fishermen for a variety of groundfish species (most notably cod, flatfish and rockfish) operate on a common quota basis.

The implications of open access have been extensively cataloged since Gordon's seminal 1954 contribution. Consequences of open access institutions in fisheries may include biological overexploitation, distorted capital inputs, reduced product quality, and excessive habitat destruction to name but a few. Homans and Wilen (1997) extended the pure open access case by examining a regulated open access fishery in which access is open, but participants are quota-regulated. They show how the profit responsiveness of effort, in combination with purposeful regulation of season length to ensure output targets are not exceeded, leads to the dissipation of rents and abbreviated seasons. In one of the first papers to specifically address the economics of bycatch, Boyce (1996) characterized the open access outcome in a two species system with a joint harvesting technology and found that open access leads to excessive entry and a shortened season relative to the optimal static outcome. Writing about the related topic of discards in an individual fishing quota (IFQ) system, Anderson (1994), Arnason (1994), and Turner (1997) conclude that IFQs on landings tend to generate incentives that promote excessive discards of lesser valued grades or species (a practice known as highgrading). This occurs despite Boyce's finding that IFQs (which are based upon *catch* in his formulation) could generate the static optimal outcome provided none of the species involved possessed a non-market value.

It should be noted that all of this bycatch research has focused on somewhat polar examples (e.g. first best optimum or IFQs vs. open access) of fishery management institutions rather than the "middle ground" that often characterizes many real-world fisheries. Many fisheries operate under limited access whereby a restricted group of users competes with imperfectly selective gear under multiple fleet-wide quotas. 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.⁵ In

⁵ Strategic behavior in the arena of bycatch and discards is not a foreign topic in the literature. Herrera (2004) 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

these real-world fisheries, 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 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 Section 2 we lay out the model structure and solve the quota-constrained social planner's problem. In Section 3 we present the symmetric, pure-strategy Nash equilibrium to the game theoretic model and show how it relates to the optimal solution. Section 4 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 5 concludes the analysis.

2. 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

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 the heavily monitored North Pacific groundfish fisheries) it may be of lesser importance.

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 $0 \leq h_X \leq \bar{h}$.

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

$$\text{Assumption 1. } h_B(0) = 0, \quad h'_B > 0, \quad h''_B > 0.$$

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.⁶

This technical description has an analogous relationship to the prototypical model of the polluting firm (a relationship first noticed by Boyce (1995)). 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:

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

⁶ 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, Haflinger and Nerini, 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.

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:

$$\pi(h_X) = ph_X - ch_B(h_X) \quad (2)$$

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 bycatch species is either economically prohibitive or expressly forbidden. For instance, in the groundfish fisheries of Alaska, the retention of halibut and certain crab bycatch is prohibited in order to diminish the incentives to target these valuable species while putatively pursuing groundfish.

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:

$$T(h_X^1, \dots, h_X^N, Q_X, Q_B, \bar{T}) = \min \left\{ \frac{Q_X}{\sum_j h_X^j}, \frac{Q_B}{\sum_j h_B(h_X^j)}, \bar{T} \right\}. \quad (3)$$

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

Assumption 2: $N \geq \max \left\{ \frac{Q_X}{\bar{T}h_{\max}}, \frac{Q_B}{\bar{T}h_B(h_{\max})} \right\}$ 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 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:

$$\max_{h_X} \min \left\{ \frac{Q_X}{Nh_X}, \frac{Q_B}{Nh_B(h_X)}, \bar{T} \right\} * N\pi(h_X) \quad s.t. \quad 0 \leq h_X \leq \bar{h}. \quad (4)$$

The planner maximizes seasonal rents subject to the constraints of the quota allocations and the maximum season length. Note that Assumption 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 1. The quota constrained optimal program (h_X^, T^*) is as follows:*

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

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

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. 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:

$$\max_{h_X^i} T(h_X^i, h_X^{-i}, Q_X, Q_B, \bar{T}) \cdot \pi(h_X^i) \quad \text{s.t.} \quad 0 \leq h_X^i \leq \bar{h}, \quad (5)$$

where h_X^{-i} is a $(N-1) \times 1$ 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.⁷ The equilibria we henceforth describe as Nash equilibria are thus actually subgame-perfect equilibria, although in an unusual 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.

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:

$$T(h_X^i, h_X^{-i}) \cdot \pi'(h_X^i) = -\frac{\partial T(h_X^i, h_X^{-i})}{\partial h_X^i} \cdot \pi(h_X^i). \quad (6)$$

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 (5)) 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 (5) 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

⁷ 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.

whether such a shift is in their best interest.

Figure 1 reveals the substance of these observations in graphical form for the choice of parameter values given in Table 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 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.

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 / \bar{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 \bar{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 \bar{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 / \bar{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 \bar{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 1.

For sufficiently large values of competitor harvest, an individual agent faces a similar scenario to that experienced on the boundary with \bar{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 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 2 presents the same information for the case in which $N = 12$.⁸ 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

⁸ 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.

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 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 1 and 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 1 for the most general case in which it is technologically feasible for either Q_X or Q_B to bind.⁹ Equilibrium conditions for the alternative case in which only Q_X can bind as well as proofs for all conditions are presented in the Appendix.

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 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 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

⁹ Formally, this entails that the maximum possible bycatch rate exceeds the ratio of bycatch to target quota,

$$Q_B/Q_X \leq h_B(h_{\max})/h_{\max}.$$

shown in Figure 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 .

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, individuals have an incentive to nudge their effort upward until the target quota is exhausted just as $T = \bar{T}$. The fifth row shows two cases in which Q_B binds at $T = \bar{T}$. 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 $T \leq \bar{T}$. In either of these cases, a symmetric Nash equilibrium occurs where the harvest rate just exhausts Q_B at \bar{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 \bar{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 1 and 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 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 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.¹⁰

Figure 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 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. 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 strong incentives to avoid bycatch. Figure 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

¹⁰ 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 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.

rate to its upper bound.¹¹ 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 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 best, this is a symptom (albeit a strongly suggestive one) of the underlying disease, and, as shown in Figure 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 target quotas are more often reached before bycatch 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

¹¹ In an effort to emphasize the transition between the different solution phases shown in Table 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.

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.

4. 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 2 as our point of reference and conduct sensitivity analysis.¹² We consider the effects of changes in prices and bycatch disposal costs, quota allocations, and technological parameters.

4.1 Changes in p

Figure 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 1 that the social planner's harvest rate exhibits no dependence on the 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.

When prices fall to a sufficiently low level (such as $p=0.4$ in Figure 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

¹² A MATLAB program that utilizes the analytical conditions in Table 2 to produce the graphical output in this paper is available upon request.

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.

4.2 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. Stone and Bublitz, 1995; Bublitz, 1995; Pikitch et al, 1995) 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 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 7.

The effect of increased selectivity on rents is similarly mixed. Consider when $N > 5$ in Figure 7. 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 α , as shown in Figure 7, are similar in many respects to those for b . This similarity is driven by the fact that both b and α have a positive effect on the marginal cost of harvest. As a result, increases in α (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 α .

What is the real-world analog to changing α ? On first glance it seems difficult to imagine a modification of fishing gears that does not confound a change in α 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 α may be roughly decomposed along these same lines with b representing the intrinsic efficiency of a particular fishing gear and α capturing the effect of intrinsic characteristics of the physical/biological system – particularly those aspects associated with the spatial cross-correlation of species densities.

Consider Figure 8. Note how when α 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 α 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- α situation carries with it the strong possibility that the harvest of those clusters will result in significant costs to oneself. Low- α 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.

4.3 Changes in quota allocations

Given the short-run nature of this model, the technological parameters (b , α 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 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 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.

4.4 The optimal penalty for bycatch

A cursory examination of the necessary conditions in Table 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” τ 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.¹³ The task then is to adjust the penalty so that the conditions for the equilibrium described in the second row of Table 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 1). Setting $\hat{T} = \bar{T}$ and solving for τ yields:

$$\tau = \frac{p(1 - 1/N)}{b(\alpha - 1/N)} \left(\frac{\bar{T}N}{Q_X} \right)^{\alpha-1} - c. \quad (6)$$

¹³ 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).

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 τ 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 (6) that would work equally well in inducing optimal behavior, although (6) 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 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.¹⁴

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 τ would represent the appropriate quota price. Alternatively, τ 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

¹⁴ 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 \bar{T} . This would result in leaving behind un-fished quota at the end of the year which is clearly suboptimal.

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.¹⁵ Figure 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.

5. DISCUSSION AND CONCLUSIONS

The structure of our simplified model matches conditions encountered in many real-world fisheries in which a common-quota form of management has been implemented. A good example is the case of the yellowfin sole trawl fishery in the Eastern Bering Sea. This fishery, the largest flatfish fishery in the U.S. in terms of catch, has regularly fallen well short of its biologically determined sustainable allocation of yellowfin sole (see Figure 11). An examination of the yellowfin sole fishery's bycatch of Pacific halibut over the same time period (Figure 12) suggests why, namely that the bycatch allocation of halibut has been fully exhausted in nine of the last twelve years. In this fishery, meeting the halibut bycatch quota triggers severe restrictions on the retention of yellowfin sole that effectively close the fishery.¹⁶ Indeed, fishermen in the yellowfin fishery have had their target fishery closed for a month or two every year due to halibut bycatch, despite efforts on the part of regulators to lengthen the season by subdividing quota on an intra-seasonal basis. In many years the quotas of halibut bycatch were exceeded by significant amounts before the fishery could be closed as the rapid pace of fishing and the associated high bycatch rates frequently overwhelmed the information processing capabilities of regulators.

¹⁵ 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.

¹⁶ The three years in which the halibut quota did not bind saw spatial closures due to Tanner and red king crab bycatch that also severely limited the fishery.

In the public discussions over bycatch in the yellowfin sole fishery, a variety of factors have been used to explain the consistent underfishing of yellowfin sole and overfishing of halibut relative to their quotas. Some observers point to trends of larger recruitment to the halibut biomass that have not been matched with corresponding increases in allocation of halibut bycatch quota and/or relatively low prices for yellowfin sole as possible explanations (Holland and Ginter, 2004). However, others are coming to believe that these causes are minor compared to those inherent to the common property quota system (Gauvin, Haflinger and Nerini, 1995). Fishermen have begun to voluntarily experiment with a range of policies that alter economic incentives to “fish dirty” including providing information about high bycatch areas, identifying high bycatch vessels and shaming them by publicizing information, and joining “penalty box” programs that force high bycatch fishermen to sit out ongoing fisheries. In fact, the current campaign by Alaskan flatfish fishermen to form a harvesters’ cooperative similar to that established under the American Fisheries Act for the Bering Sea/Aleutian Islands pollock fishery is motivated in large part by the desire of fishermen to implement their own individual incentive based system of bycatch accountability.

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 both 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 is 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 in fact, common pool quotas and season closure instruments are generally successful in this regard when properly monitored with timely information dissemination.¹⁷ However, while common pool quotas may be effective instruments to address biological objectives, they exacerbate rather than solve the fundamental economic problem, which is insecure harvesting privileges. The fruit of this system is rent dissipation on a number of fronts, from wasted target quota, high discard costs, and shortened seasons which can increase costs and lead to losses in the product market from reduced product quality and skewed product mixes.

Our paper 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 paper suggests that observed bycatch is actually a much more complicated outcome of gear design, spatial ecology, regulations, and ultimately, of human strategic behavior. This suggests that the range of policy options is certainly broader than simply 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

¹⁷ 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.

inherently technological and how much of it is behavioral or institutional. This is an issue that has not been addressed adequately, and it is suggestive of a broad and challenging research agenda.

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Table 1: Equilibrium Conditions for Game when Either Quota is Capable of Binding¹⁸

Quota	Conditions	\hat{h}_X	\hat{T}
Q_X	$f(p, c, b, \alpha, Q_X, \bar{T}) \leq N \leq \frac{1 - \left(\frac{cQ_B}{pQ_X} \right)}{1 - \alpha \left(\frac{cQ_B}{pQ_X} \right)}$	$\left(\frac{p}{cb} \cdot \frac{(1 - 1/N)}{(\alpha - 1/N)} \right)^{\frac{1}{\alpha-1}}$	$\frac{Q_X}{N\hat{h}_X^\alpha}$
Q_X	$\frac{1}{\bar{T}} \left(\frac{bQ_X^\alpha}{Q_B} \right)^{\frac{1}{\alpha-1}} \leq N \leq \min \left\{ f(p, c, b, \alpha, Q_X, \bar{T}), \frac{1 - \left(\frac{cQ_B}{pQ_X} \right)}{1 - \alpha \left(\frac{cQ_B}{pQ_X} \right)} \right\}$	$\frac{Q_X}{NT}$	\bar{T}
Q_X / Q_B	$\max \left\{ \frac{1}{\bar{T}} \left(\frac{bQ_X^\alpha}{Q_B} \right)^{\frac{1}{\alpha-1}}, \frac{1 - \left(\frac{cQ_B}{pQ_X} \right)}{1 - \alpha \left(\frac{cQ_B}{pQ_X} \right)} \right\} \leq N \leq \frac{\alpha \left(1 - \left(\frac{cQ_B}{pQ_X} \right) \right)}{1 - \alpha \left(\frac{cQ_B}{pQ_X} \right)}$	$\left(\frac{Q_B}{bQ_X} \right)^{\frac{1}{\alpha-1}}$	$\frac{Q_B}{Nb\hat{h}_X^\alpha}$
Q_B	$\max \left\{ g(p, c, b, \alpha, Q_B, \bar{T}), \frac{\alpha \left(1 - \left(\frac{cQ_B}{pQ_X} \right) \right)}{1 - \alpha \left(\frac{cQ_B}{pQ_X} \right)} \right\} \leq N \leq \frac{\alpha(p - cbh_{\max}^{\alpha-1})}{p - acbh_{\max}^{\alpha-1}}$	$\left(\frac{p}{cb} \cdot \frac{(1 - \alpha/N)}{(\alpha - \alpha/N)} \right)^{\frac{1}{\alpha-1}}$	$\frac{Q_B}{Nb\hat{h}_X^\alpha}$
Q_B	$N \leq \min \left\{ \frac{1}{\bar{T}} \left(\frac{bQ_X^\alpha}{Q_B} \right)^{\frac{1}{\alpha-1}}, \frac{\alpha \left(1 - \left(\frac{cQ_B}{pQ_X} \right) \right)}{1 - \alpha \left(\frac{cQ_B}{pQ_X} \right)} \right\} \text{ or } \frac{\alpha \left(1 - \left(\frac{cQ_B}{pQ_X} \right) \right)}{1 - \alpha \left(\frac{cQ_B}{pQ_X} \right)} \leq N \leq g(p, c, b, \alpha, Q_B, \bar{T})$	$\left(\frac{Q_B}{bNT} \right)^{\frac{1}{\alpha}}$	\bar{T}
Q_B	$N \geq \frac{\alpha(p - cbh_{\max}^{\alpha-1})}{p - acbh_{\max}^{\alpha-1}}$	h_{\max}	$\frac{Q_B}{Nb\hat{h}_X^\alpha}$

Table 2: Base Parameter Values for Policy Simulations

B	0.45	α	1.5
Q_X	700	Q_B	400
P	0.5	c	0.5
\bar{T}	365	\bar{h}	2.0

¹⁸The 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} .

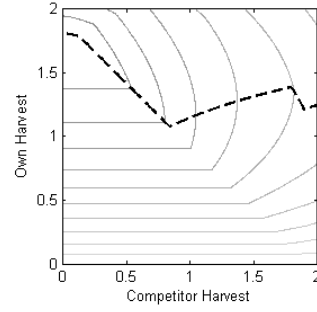
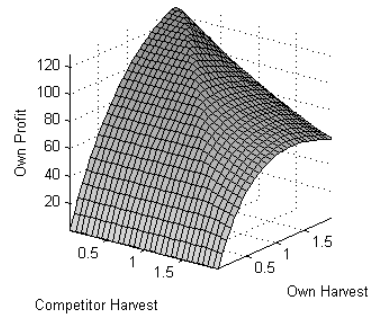


Figure 1: Graphs of Own Profit Function, Profit Contours (with Reaction Function), and Binding Quota Contours (light gray = T_{bar} binds, medium gray = Q_X binds, dark gray = Q_B binds) for $N=2$.

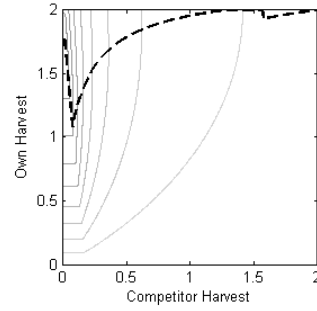
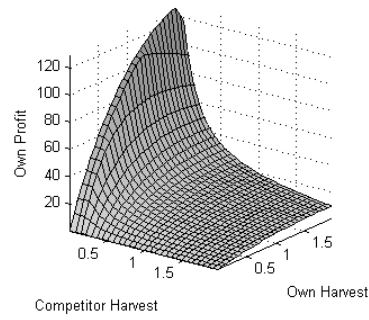
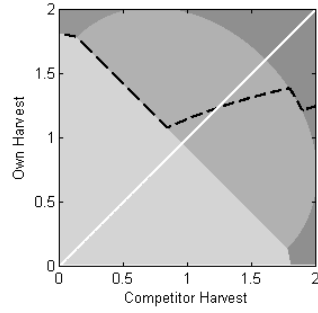
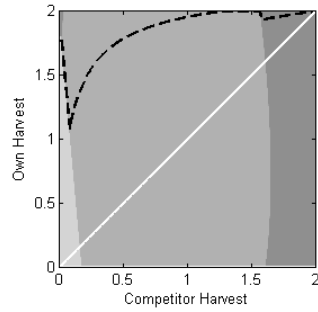


Figure 2: Graphs of Own Profit Function, Profit Contours (with Reaction Function), and Binding Quota Contours (light gray = T_{bar} binds, medium gray = Q_X binds, dark gray = Q_B binds) for $N=12$.



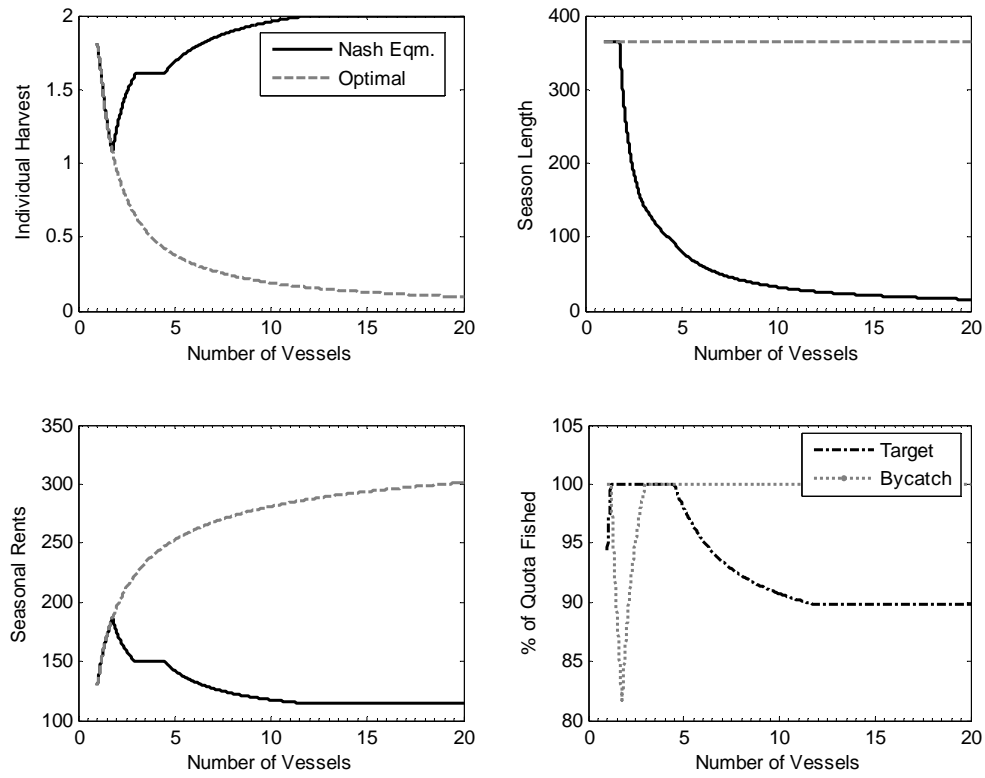


Figure 3: Nash Equilibrium and Optimal Harvest, Season Length, and Rents and Percentage of Quotas Fished Under the Nash Equilibrium Solution for Various Fishery Sizes.

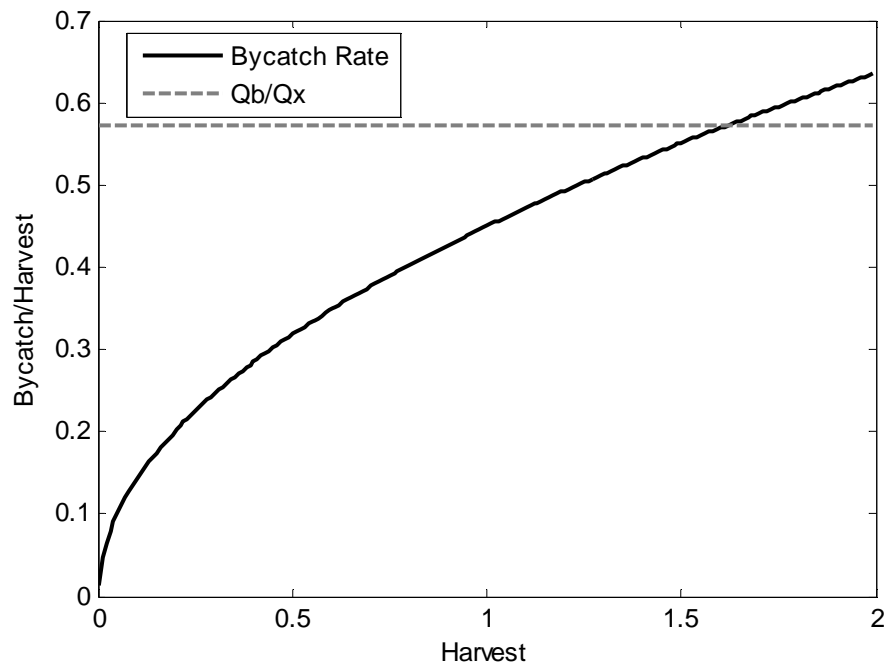


Figure 4: Bycatch Rate for Various Harvest Rates at Base Parameter Values

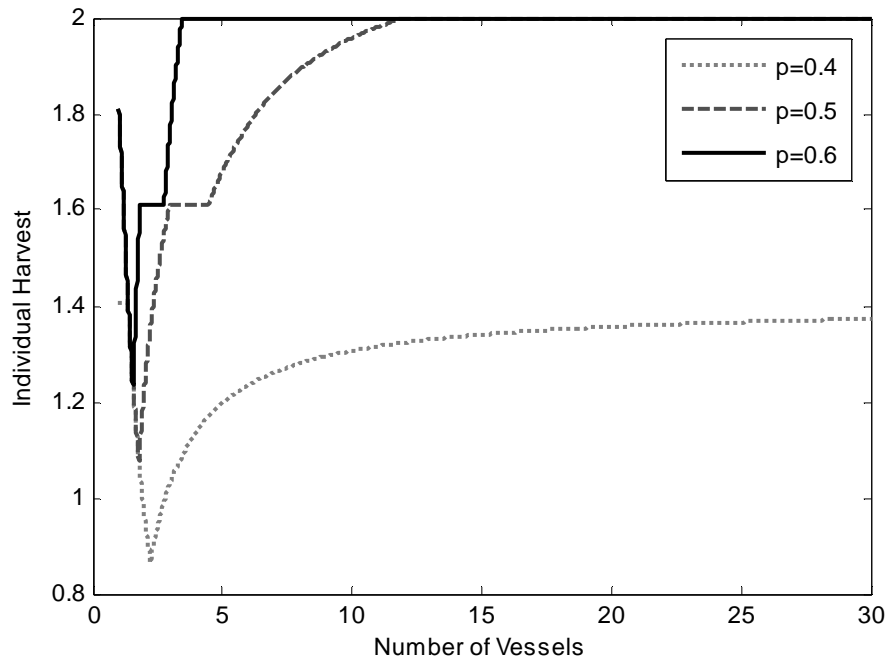


Figure 5: Nash Equilibrium Harvest Rates for Various Target Species Prices

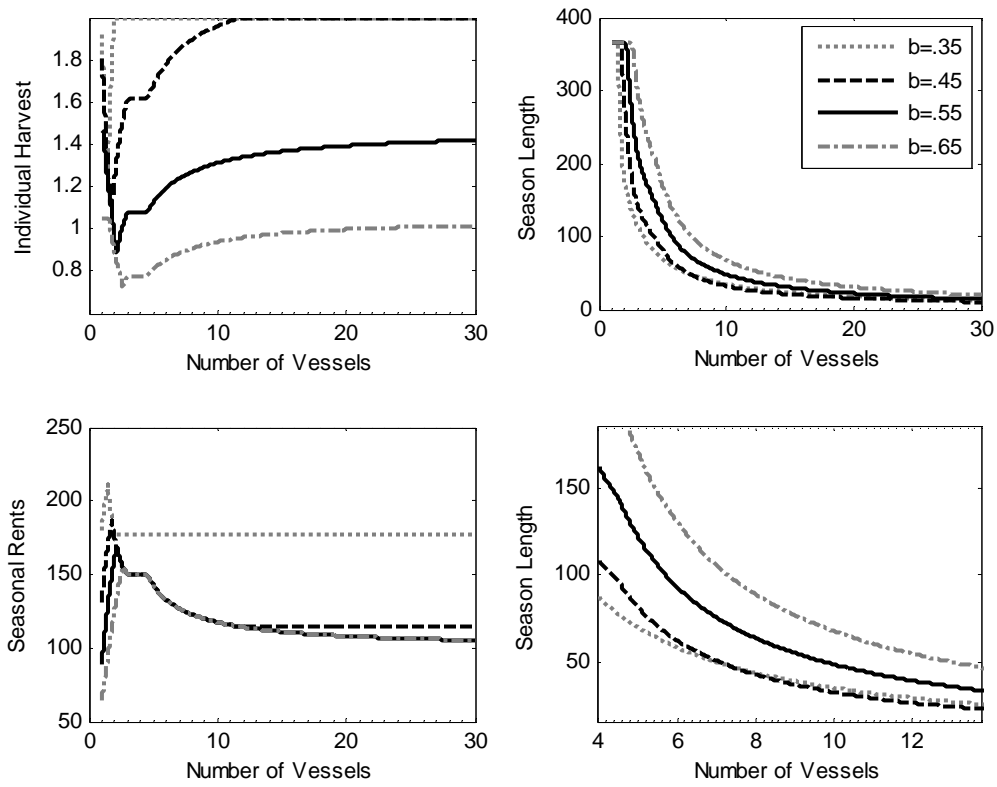


Figure 6: Nash Equilibrium Harvest, Season Length, Rents, and Season Length (detail) for Differing Values of b

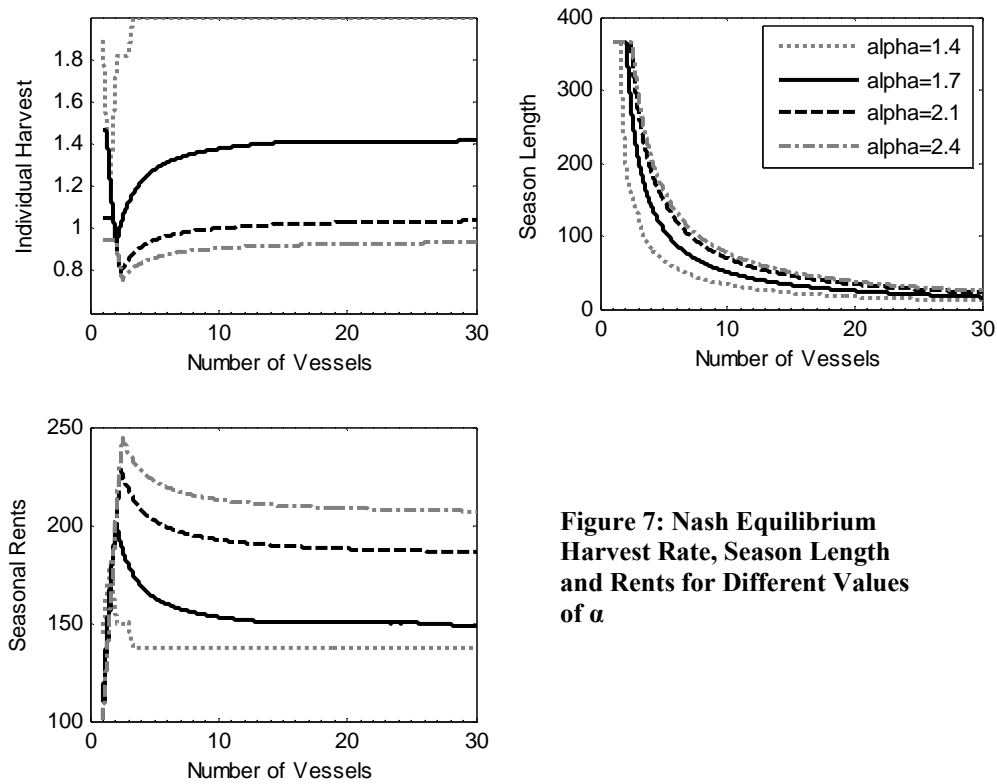


Figure 7: Nash Equilibrium Harvest Rate, Season Length and Rents for Different Values of α

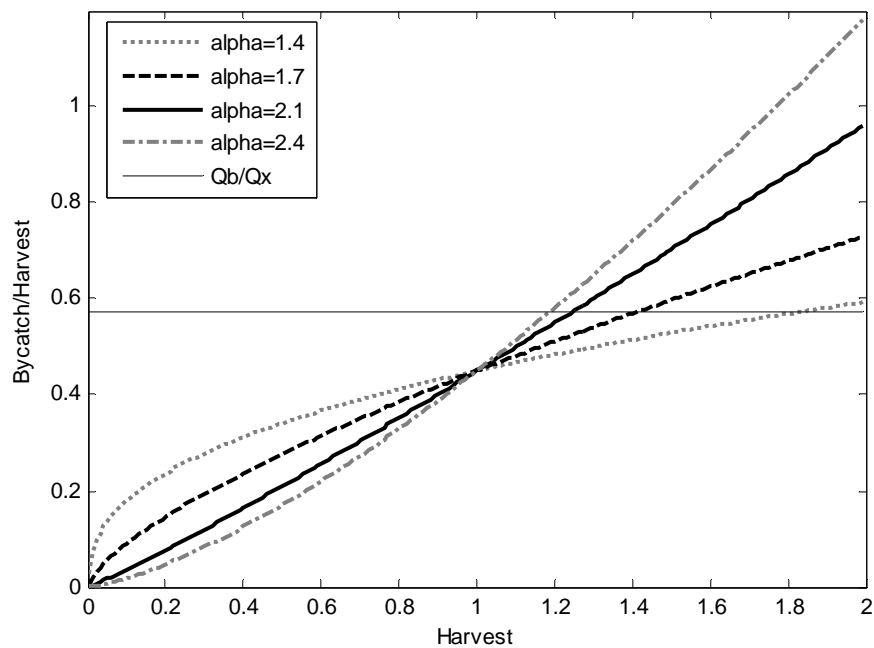


Figure 8: Comparison of Bycatch Rates as α Changes.

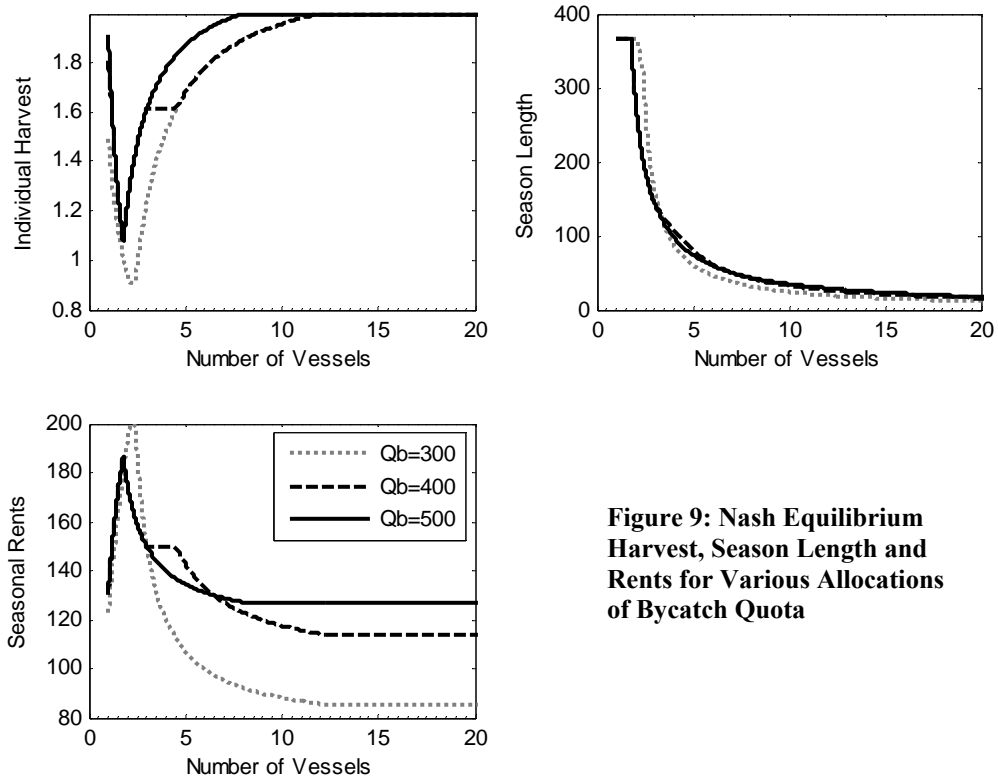


Figure 9: Nash Equilibrium Harvest, Season Length and Rents for Various Allocations of Bycatch Quota

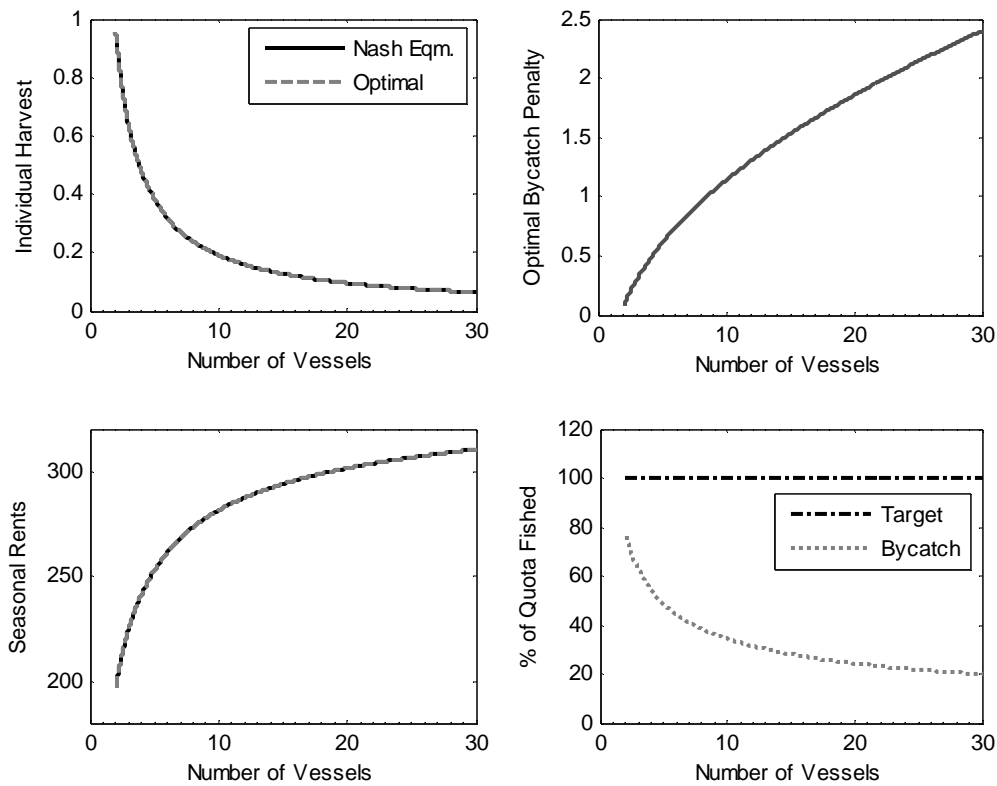


Figure 10: Nash Equilibrium Harvest, Rents and Quota Utilization Compared Against Social Planner Levels when the Optimal Bycatch Penalty is Assessed.

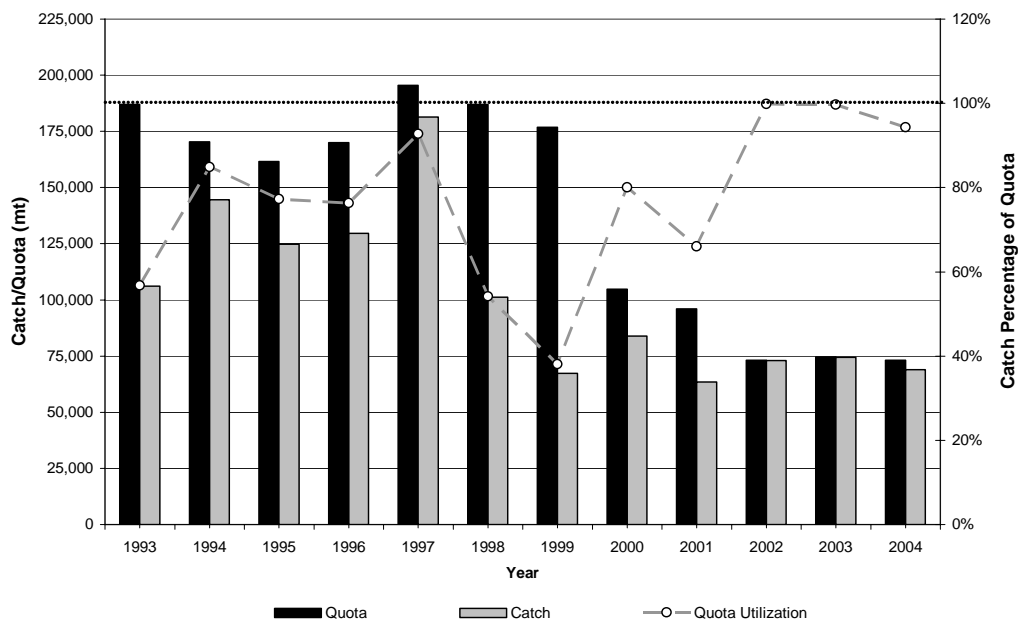


Figure 11: Catch, Quota and Percentage Quota Utilization in the Eastern Bering Sea Yellowfin Sole Fishery.

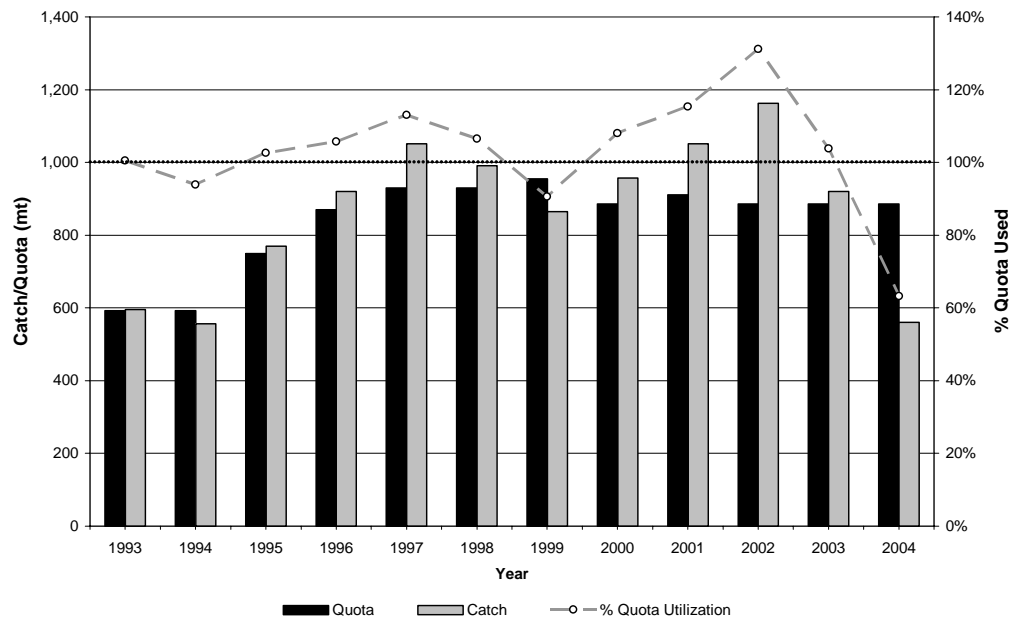


Figure 12: Catch, Quota and Percentage Quota Utilization of Halibut Bycatch Quota in the Eastern Bering Sea Yellowfin Sole Trawl Fishery.

APPENDIX: DERIVATION OF 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.¹⁹

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

A. Q_X Binding – Interior Solution

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

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

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

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 $\hat{h}_X \leq h_{\max}$ given (N1) and the assumptions underlying Case 1.

¹⁹ All MATLAB code is available upon request from the authors.

Given the interiority of this solution there is obviously no marginal incentive to deviate.

B. Q_X Binding – Corner Solution

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

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

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

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

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

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

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

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

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

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 $\bar{h} \leq h_{\pi \max}$; 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)

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

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

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

or

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

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

(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 \bar{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

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

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

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

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

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 \bar{T} rather than the bycatch species. As a result, every fisherman employs the minimal amount of effort consistent with their belief that bycatch

binds, causing the season length to decline below its 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)

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

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

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 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.

$$\textbf{Case 2: } \frac{Q_B}{Q_X} > \frac{h_B(h_{max})}{h_{max}}$$

G. Q_X Binding – Interior Solution

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

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

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

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

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

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

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

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

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

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)

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

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

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

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

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 this 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.

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 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 2: If $N \geq \frac{1 - \left(\frac{cQ_B}{pQ_X} \right)}{1 - \alpha \left(\frac{cQ_B}{pQ_X} \right)}$, 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 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 2: If $N \leq \frac{\alpha \left(1 - \left(\frac{cQ_B}{pQ_X} \right) \right)}{1 - \alpha \left(\frac{cQ_B}{pQ_X} \right)}$, 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.²⁰

²⁰ We do not argue for the uniqueness of these solutions in the class of pure strategy, symmetric equilibria although this seems likely.