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Regulation of fisheries bycatch with common-pool output quotas

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ABSTRACT

Many fisheries around the world are plagued with the problem of bycatch—the inadvertent harvesting and discard of non-targeted species. Bycatch occurs when targeted and non-targeted species coincide in the same habitat and gear is imperfectly selective. One of the prevailing methods of controlling bycatch is the common-pool quota system. Under this system, biologists set total allowable catches (TACs) for both the targeted and non-targeted species, and the fishing season is closed when one of these TACs binds. We develop a predictive model of a renewable resource that is regulated with this kind of common-pool quota system. The model demonstrates that the equilibrium will generally be characterized by excessive discards, shortened seasons, and foregone target species harvest. These results occur even with very efficient (low bycatch) fishing gear. We examine the sensitivity of our predictions to changes in technological parameters and degrees of spatial correlation of target and non-target species. Finally, we derive the optimal bycatch penalty function and describe its significance in light of various policy options available to regulators.

"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. The spatial coexistence of marine species, imperfectly selective gear, and incentive-distorting managerial policies cause a significant portion of catch to diverge from the desired species, sex, or size. Some of this bycatch finds its way into (typically low-valued) markets, but the vast majority is returned to the sea as discards. Early estimates placed the volume of discards at 17.9 metric tons a year, approximately 25% of global landings [1], although a recent reassessment [13] places the proportion at around 8%.

The sheer volume of these discards and their mortality, the charismatic nature of some bycatch species (e.g. sea turtles and dolphins), and the spillovers between fisheries has led to a vociferous outcry from conservation organizations, industry groups, and the general public to reduce bycatch mortality. The upshot, particularly in developed countries with command

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and control fisheries practices, has been new policies directed at curtailing the bycatch problem.[2] Along with mandated bycatch-averting gears and time and area closures to protect vulnerable aggregations of bycatch species, a common instrument has been the use of industry-wide quotas on both target and bycatch species. These quotas are enforced by seasonal closure of the fishery upon attainment of any of these quotas. In some cases, the quotas are allocated on an individual vessel basis (as for halibut bycatch quota in the Alaska sablefish fishery) and freely transferable across vessels (as in the New Zealand and Iceland individual fishing quota (IFQ) programs). However, it is more often 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 North Pacific groundfish fisheries, but similar management institutions exist for a number of fisheries.[3]

In one of the first papers to address the economics of bycatch, Boyce [5] 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 IFQ system, Anderson [2], Arnason [3], and Turner [23] 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.[4]

All of this prior research has followed the bioeconomic modus operandi, comparing open access outcomes with first-best optima. By contrast, there has been little research examining what actually is in the real world, as opposed to what might be.[5] This paper is motivated by the desire to understand some common features of real-world fisheries for which bycatch is an important management focus. These fisheries have several characteristics in common, including: (1) high capital costs and other economic barriers to entry; (2) imperfectly selective gear; (3) management with common-pool quotas on both targeted and bycatch species, enforced with season limits; and (4) limited entry programs restricting fleet size. This combination creates the possibility of strategic behavior in the harvest decisions of fishermen.[6] In such cases, fishermen know that regulators will either close or drastically curtail the target fishery when one of the quotas becomes binding. In small numbers settings, fishermen have incentives to consider the impact of their harvest behavior (conditional on the anticipated behavior of their competitors) on the equilibrium season length. Strategic behavior combined with the complexities of joint production yield a rich array of behaviors. Illuminating the connection between regulatory institutions, fishermen's incentives and bycatch outcomes is worthwhile for understanding the status quo and aiding in the development of more effective alternative policies.

To this end, we develop a simple static and deterministic game in which fishermen jointly harvest target and bycatch species in a multiple common-pool quota setting.[7] This stylized model captures a sufficient number of the aspects of actual bycatch regulation to provide a useful "metaphor" for analyzing fishermen's incentives under these programs relative to the first-best situation. The objective in our quota-constrained problem is to maximize industry profits rather than a broader social welfare maximization. Such a perspective is justified for common cases where bycatch quotas for a target fishery can be taken as given and pre-determined by regulators, rather than determined as part of an optimal solution (or, alternatively where bycatch species have little or no non-market value from a social perspective).

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, face no significant stock or congestion externalities and minimally discount intra-seasonal rents so that a static framework can be employed. We also presume 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 $0 \leqslant h_X \leqslant \bar{h}$.[8]

[2] 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" [15].

[3] For instance, the Hawaiian longline swordfish fisheries and the New Zealand arrow squid fishery both face common-pool quotas on key bycatch species [8,17].

[4] This summary of the conceptual bycatch literature is necessarily selective. There is also a growing empirical literature relying on multiple output production technologies and advances in the characterization of undesirable outputs to analyze bycatch and discards [9,18,19].

[5] A notable exception is Larson, House and Terry [14], who utilize a clever combination of linear programming and empirical production economic techniques to examine the reallocation of multispecies quotas across target fleets in the Bering Sea pollock fishery.

[6] Herrera [11] and Jensen and Vestergaard [12] consider the problem of strategic interactions between catch-discarding fishermen and a regulator, but their work concerns the moral hazard problem of discards, whereas ours focuses on the intra-seasonal game played amongst fishermen and between fishermen and regulators even when complete and perfect information is available on all sides.

[7] This paper defines bycatch as the catch of non-target species. Our model does not apply to highgrading.

[8] In reality, catch rates are quite variable on a daily basis given the stochastic environment in which fishing often occurs. Our model can be interpreted as determining the *expected* levels of harvest and bycatch chosen by risk-neutral fishermen in industrial fisheries, where expected profit maximization is a reasonable objective.

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

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

These technological assumptions imply that bycatch avoidance generates a cost in the form of reduced target species harvest and that these costs are increasing in the degree of intended avoidance.[9] In the language of the literature on undesirable outputs, harvest and bycatch arise from a null-joint production technology and the frontier embodies a restrictive form of weak disposability [7,9]. While this increasing returns technology does not capture the wide array of possible production frontiers that may follow from the spatial and temporal overlap of species, it nonetheless serves as a useful approximation to the average pattern of tradeoffs observed in many fisheries with substantial bycatch problems.[10]

To simplify, we propose the following form for the bycatch function:

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

Harvest fetches the price p. Fishermen also face a unit cost due to potential processing, yield and product losses from the diversion of resources toward the sorting and discard of bycatch; represented by c. Daily variable rents are thus

$$\pi(h_X)=ph_X-ch_B(h_X). \tag{2}$$

Note that this function is concave, although not necessarily increasing, for all feasible values of h_X. Note as well 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, there is no obvious a priori relationship mapping the daily expenditure of variable inputs (such as fuel) to fishing output.[11] For the sake of expositional clarity, bycatch is assumed to have no revenue value. In many fisheries, the landing of bycatch is either economically prohibitive or expressly forbidden (although this may understate the public value of some charismatic or ecologically important bycatch species).[12]

The regulator is charged with enforcing quotas on both the target and bycatch species, denoted by Q_X and Q_B, respectively. They accomplish this by manipulating the season length, T. We assume that cumulative harvest and bycatch is perfectly observable. As a result, the regulator closes the entire fishery when one of the quotas is met or the maximum season ($\bar{T}$) is achieved. This decision rule is

$$T(h_X^1,\ldots,h_X^N,Q_X,Q_B,\bar{T})=\min\left\{Q_X/\sum_j h_X^j,\; Q_B/\sum_j h_B(h_X^j),\; \bar{T}\right\}. \tag{3}$$

In effect, this rule represents the regulator's reaction function. Before presenting the solution to the regulator's problem, we adopt the following assumption:

Assumption 2. $N \geqslant \max\{(Q_X/\bar{T}h_{\max}),\,(Q_B/\bar{T}h_B(h_{\max}))\}$ where $h_{\max}=\min\{\bar{h},h_{\pi\max}\}$ and $h_{\pi\max}=\operatorname{argmax}\pi(h_X)$.

This assures that there is sufficient overcapacity in the fishery so that both quotas can be exhausted when all vessels harvest at their maximum feasible rate. Thus, the quotas bind the decision making of fishermen and the regulator. The maximum harvest rate may be less than the physical upper bound on harvest if bycatch sorting and discard costs cause daily rents to peak at a smaller rate (i.e. if $h_{\pi\max}<\bar{h}$).

We can now express the objective of the quota-constrained social planner as

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

The planner maximizes seasonal rents subject to the constraints of the quota allocations and the maximum season length.[13] Note that Assumption 2 precludes any case in which $\bar{T}$ binds alone.

Given the concavity of daily variable rents, it is optimal to set harvest 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

[9] This technical description has an analogous relationship to the prototypical model of the polluting firm [5]. Note, as well, that by presuming a homogeneous technology for all fishermen, we are ignoring real-world variations in the production technologies of fishermen [10,20,24]. Alterations to accommodate such variations are relatively straightforward for the case of a discrete number of efficiency classes.

[10] For instance, in a heterogeneous marine environment, population densities of bycatch and target species are often highly positively correlated spatially [2,3]. The process of finding local exceptions to this global correspondence (likely through exploratory fishing) may entail substantial investments of time, is likely subject to diminishing returns and, even when located, these areas are likely to be short-lived and possess lower densities of the targeted species on an average basis due to the overarching pattern of positive correlation.

[11] This is, admittedly, an assumption of convenience. Input costs and the quantity of harvest for full participants are likely related, but the nature of this relationship is highly dependent on the spatial, temporal, and technological aspects of the fishery. Incorporation of the usual increasing and (weakly) convex costs in the harvest rate has no material impact on our results.

[12] 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 species which are themselves the valuable targets of separate fisheries.

[13] Of course, few real world fisheries have as their primary management objective the maximization of seasonal rents. Nonetheless, the purpose of this analysis is to show that such a desirable objective can be achieved within the confines of the implicit longer run biological and social objectives embodied in the quota allocations.

increases in profits from a longer fishing season–always exceed the costs incurred from smaller daily harvests. This logic is summarized in

Theorem 1. *The quota-constrained optimal program (h_X*,T*) is as follows*:

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

The determination of the binding quota depends upon the number of 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 correspond to low bycatch rates and so Q_X binds. Not surprisingly, the larger the ratio of Q_X to Q_B the wider the range of fishery sizes for which Q_B binds and vice versa. Finally, these conditions prescribe a steady decline in the rate of harvest, and the bycatch rate, as N increases so that high bycatch rates are associated with lightly capitalized fisheries when the harvest/bycatch rate is managed optimally.

3. Nash equilibrium

In many commercial fisheries, fishermen compete without secure access privileges for the allowable harvest. Quota allocations in many managed fisheries are transparent and announced prior to the opening of the season. As a result, we should expect that fishermen would incorporate the quota rule into their decision process. The shared nature of quotas means that each individual fishermen imposes external costs on all other fishermen. When coupled with the "small numbers" situations fostered by limited entry programs, this induces strategic interactions between fishermen. Therefore, fisherman i solves

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

where h_X^{-i} is a $(N-1)x1$ vector of the harvest choices of other fishermen. We condense a finitely repeated game between fishermen into a single choice of daily harvest and bycatch for the season, allowing us to focus on common-pool quota outcomes without the added complexity of a dynamic framework.[14]

Given homogeneity of fishermen, we focus on symmetric, pure strategy Nash equilibria. 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 shared conjecture of the binding season length and quota are supported in equilibrium by the induced behavior of the regulator. If a fisherman foresees a particular quota will bind in equilibrium, then his reaction function is defined as follows:

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

The choice of harvest rate balances marginal benefits of increased daily rents (the left hand side of (6)) with the personal marginal costs of a reduction in fishing opportunities from an increase in the harvest rate. Fishermen do not, however, consider the external costs of their choice on the rest of the fleet.

Eq. (6) is not an exhaustive characterization of an agent's reaction function. First, constraints on the maximum season length and harvest rate result in cases in which the equality of marginal costs and benefits cannot be satisfied. Secondly, while the regulatory decision function (3) is continuous in h_X, it is not differentiable at the breakpoints between quotas. Accordingly, when agents consider a harvest rate that alters the binding quota regime, they must conduct a non-marginal comparison of whether such a shift is in their best interest.

Fig. 1 reveals the substance of these observations for illustrative parameter values. The first row is for $N = 2$, and the first panel shows the seasonal iso-profit lines for a particular vessel for levels of its own harvest and that of its competitor (higher rents lie in the north–west of the panel). These level sets are kinked, indicating the boundaries of quota regimes in N-dimensional harvest space—boundaries which are demarcated in the second panel on the first row. By finding the highest iso-profit line for each level of competitor harvest, we can graphically define fishermen's reaction function—as demonstrated by the dotted line in both panels. A glance at this reaction function shows a number of qualitatively distinct phases; understanding these phases is crucial to understanding the analytical solutions to the problem.

Given our choice of parameters, it is possible for a sole fisherman to cause Q_B to bind. However, it is instead optimal to choose harvests along the knife-edge of the $Q_B/\bar{T}$ boundary—reacting to increased harvest on the part of his competitor by decreased own catch. Recall from the social planner's problem, system-wide marginal benefits of increasing harvest are always exceeded by the marginal costs. When a single competitor harvests little, our fisherman effectively dominates the fishery and, therefore, internalizes a sufficiently large quantity of the full marginal costs of his harvest so that his behavior

[14] In the absence of in-season stock effects, time-varying opportunity costs and production relationships, and variable participation rates, the Nash equilibria in the repeated game consist of repeated play of the Nash equilibrium strategies for the stage game.

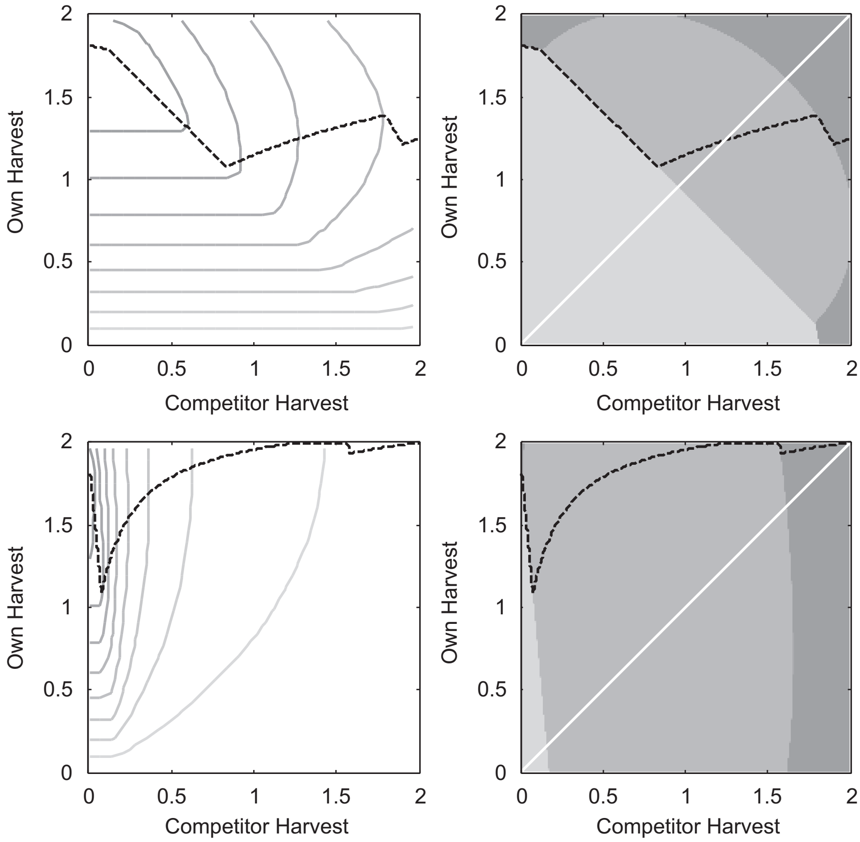

Fig. 1. Graphs of variable profit contours (with reaction function), and binding quota contours (light gray = Tbar binds, medium gray = Q_X binds, dark gray = Q_B binds) for $N = 2$ (top row) and $N = 12$ (bottom row).

mimics the social planner's. Similar logic applies at the boundary between $\bar{T}$ and Q_X. In either case, the constraint on the maximum season length makes our fisherman willing to incur a cost proportional to the wedge between the personal marginal costs and benefits of increased harvest to raise $\bar{T}$. This excess of marginal costs over marginal benefits can be seen in the first panel by noting that at low levels of competitor harvest, the level sets are bowed backwards from the cusps along the $Q_X/\bar{T}$ boundary.

This behavior cannot stand in the face of increased competition, however. Greater harvests by competitors increasingly dilute the proportion of the full marginal costs of harvest that are borne by the individual, so that eventually the marginal benefits of increased harvest exceed marginal costs at $\bar{T}$. It is no longer rational to meet increased competition by decreasing one's own fishing. Personal benefits and costs are instead equalized at a season length below the maximum and increases in competitors' harvests are responded to in kind.[15] This can be seen in the first increasing stretch of the reaction function in Fig. 1.

For larger values of competitor harvest, an individual agent faces a similar scenario to that experienced on the boundary with $\bar{T}$, except that the decision is whether to preserve the Q_X constraint by lowering one's own harvest. The decision depends on the relative magnitude of personal marginal benefits and costs evaluated where Q_B strictly binds. If marginal costs exceed marginal benefits, the target quota has a positive shadow value and it is best to draw back on own harvest in response to an increase in harvest from competitors—explaining the second downward phase of the reaction function in the first row of Fig. 1. The dilution of marginal costs with increases in competitor harvest ultimately causes the captain to raise effort so that Q_B strictly binds and marginal benefits and marginal costs are again equalized.

The second row of Fig. 1 presents the same analysis for $N = 12$. The close spacing of the level sets in the first panel shows how even small harvest rates from the eleven competitors quickly decrease one's own profits, while the nearly vertical frontiers between binding quota contours in the second 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, except that 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 rate of harvest, personal marginal costs are driven to a level exceeded by marginal benefits at even the highest harvest intensity. This explains the flat stretch of the reaction function in Fig. 1.

[15] In the language of game theory, harvest switches from a "strategic substitute" to a "strategic complement".

Table 1
Equilibrium conditions for game when either quota is capable of binding[a]

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

[a] 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) will equal $\bar{T}$.

The symmetric Nash equilibria for both of these scenarios are indicated by the intersection of the reaction function and the 45° line in the second column of Fig. 1. 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. These cases demonstrate two of six qualitatively distinct 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. Proofs for all conditions are available in an appendix, available at JEEM's online archive of supplementary material, which can be accessed at http://www.aere.org/journal/index.html.

These mathematical conditions yield interesting generalities on closer inspection. The conditions exhaust the range of fishery sizes fulfilling Assumption 2 and yield a unique Nash equilibrium for a given number of fishermen and set of parameters. The equilibria in the first and fourth rows of Table 1 are interior in that marginal personal benefits and costs are balanced and so the equilibrium harvest rate is increasing in the number of participants. They correspond to equilibria occurring in the increasing stretches of the reaction function where one of the quotas is strictly binding. The equilibrium described in the first row of the table corresponds with that shown in the first row of Fig. 1.

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 yields lower values of N than do non-binding cases. This class of equilibrium occurs when a putative equilibrium at an 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 too small for an interior Q_B solution and also too small for Q_X to bind. The second set of conditions describes a situation in which N is too large to sustain an equilibrium where Q_X binds and too small for an interior equilibrium in Q_B to bind for $T < \bar{T}$. In either case, equilibrium occurs where the harvest rate just exhausts Q_B at $\bar{T}$. For both the Q_X and Q_B corner solutions, the equilibrium harvest rate is decreasing in fishery participation as in the social planner's solution. Indeed the symmetric Nash equilibrium harvest rates correspond exactly with those of the social planner's solution in this (very) small-numbers case.

The solution depicted in the third row occurs for an intermediate range of N and reflects a situation where N is too large for Q_X to bind and yet too small for Q_B to uniquely bind as well. 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 capacity levels. This equilibrium occurs in the downward sloping phase of the reaction function along the Q_X/Q_B frontier.

The solution in the sixth row of Table 1 occurs when the fishery is so large that marginal benefits cannot be reconciled with marginal costs for the bounded range of possible harvest rates. This case corresponds with the second row in Fig. 1. Fishermen are compelled to harvest at maximum intensity throughout the season. For fisheries with natural or regulatory controls on vessel catch effectiveness, an increase in the number of competitors over a critical threshold will carry no significant short-run behavioral effects in this class of equilibrium (although the length of season and average variable rents will decline with entry).

Fig. 2 demonstrates the spectrum of Nash equilibrium harvest rates, season lengths, and total rents for a range of fishery sizes, comparing them against those associated with the quota-constrained optimal solution. It also displays the percentage of each quota harvested in equilibrium for both cases. The underlying parameter values are purely illustrative and chosen so that discard costs are relatively high while daily variable rents are strictly increasing over the range of

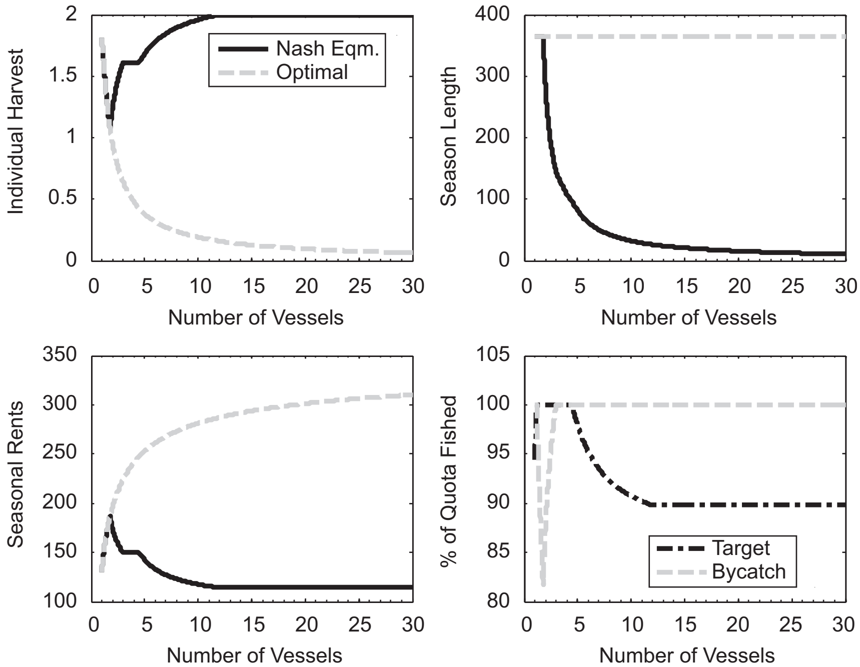

Fig. 2. Nash equilibrium and optimal harvest, season length, and variable rents and percentage of quotas fished under the Nash equilibrium solution for various fishery sizes.

allowable harvest rates.[16] Qualitative observations on real-world fisheries suggest that costs are often low compared to marginal revenues and so our parameterization is skewed to give fishermen strong incentives to avoid bycatch. The technological parameters and quota allocations are similarly conservative; only when all agents harvest more than 80% of daily capacity can bycatch possibly bind the fishery. These parameter choices depict the common quota system under conditions conducive to its success.

Despite these concessions, 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. When very small numbers of fishermen participate in the fishery, the equilibrium harvest rates correspond to the quota-constrained social optimum, and so decrease with increased participation. Nevertheless, the lack of full internalization of the marginal costs of harvest manifests itself quickly, leading to a phase in which Q_X binds at less than the maximal season length before entering a brief transitional plateau (between $N = 3$ and 4.5) in which both quotas bind and harvest rates are inelastic to changes in fishery participation. The effects of imperfect cost internalization are evident in the equilibrium season length and variable rents. As N increases, season durations rapidly fall below the optimal level, opening a chasm between the socially optimal short-run rents and the level achieved when fishermen act noncooperatively.

The allocation of a common quota to all fishermen 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. Rather, it is a symptom of the underlying problem—the mutually destructive incentives generated by the common quota structure that cause fishermen to ignore the effects of their behavior on the equilibrium season length. Except for very small fisheries, this leads to wasted quota of either bycatch or target species and sub-optimal rents due to shortened seasons and excessive discard costs. Furthermore, the role of imperfectly selective gear and inadequate quota allocations in this tragedy may be quite limited. Even fisheries with relatively "clean" gear and adequate bycatch quota, can deviate markedly from the optimum solution when sufficient competition is present in the fishery.

4. Model sensitivity and policy considerations

To explore the implications of perturbations in the technological parameters of the model, we now conduct a sensitivity analysis.

[16] Specifically, $b = 0.45$, $\alpha = 1.5$, $Q_X = 700$, $Q_B = 400$, $p = 0.5$, $c = 0.5$, $\bar{T} = 365$, and $\bar{h} = 2$.

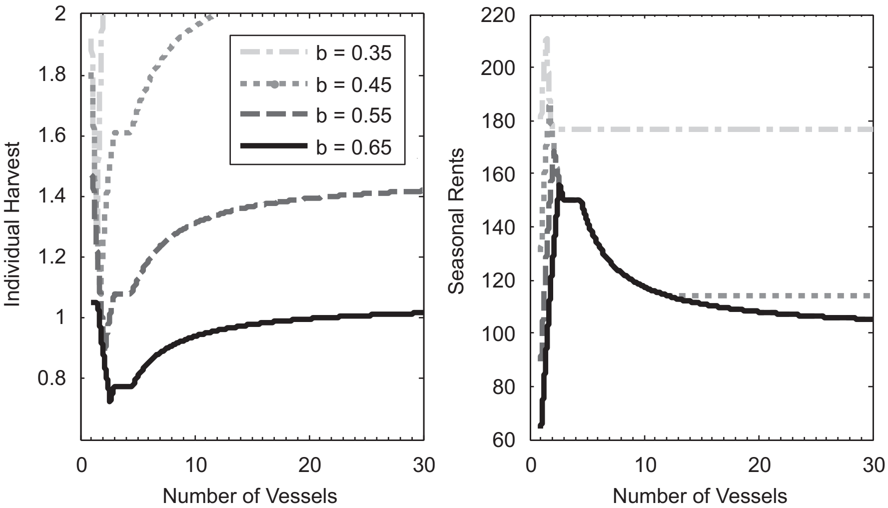

Fig. 3. Nash equilibrium harvest and variable rents for differing values of *b*.

4.1. Changes in technological parameters

A decrease in b reduces the bycatch rate for any level of targeted harvest, thus approximating bycatch saving gear modifications [6,21]. Fig. 3 shows various technology changes depicted by shifts in b. Note that "cleaner" technologies actually induce higher harvest rates of the target species because a decrease in b lowers the effective marginal cost of a unit of harvest. The increased incentive to harvest outweighs the increase in harvesting efficiency so that cleaner technology typically leads to decreases in the equilibrium season length.

To illustrate the effect on rents, consider $N>5$ in Fig. 3. If b is sufficiently large to cause $h_{\pi\max}<\bar{h}$ (so that $h_{\max}=h_{\pi\max}$), then marginal improvements in bycatch efficiency (e.g. b falling from 0.65 to 0.55) yield no improvement in rents. Increased harvest and lower costs of discard are offset by the reduction in season length. However, if the improvement in bycatch efficiency is large enough to drive the equilibrium harvest rate to $\bar{h}$ for a particular N, then average rents may increase in the short run.

There are several management implications. First, mandating a small improvement in selectivity will, when starting with "dirty" technology, yield, at best, 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 potential increase in efficiency, the greater the range of fishery sizes that will exhibit an increase in short-run rents. Finally, these increase rents are due to short-run capacity limits that prevent agents from equalizing marginal benefits and costs and dissipating the potential gains from the new technology. We would expect "capital-stuffing" behavior to eradicate these rent gains in the longer term.

Ward [25] utilized a dynamic, multi-fleet model to show that decreases in bycatch species catchability will generate few long-run benefits due to the compensating effects of increased effort in the targeted fishery for the bycatch species. Our results complement this result by suggesting that technological improvements may be of limited utility even in the short-run where no targeted fishery for the bycatch species exists. Furthermore, the lack of 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.[17]

Although not shown here, the results for perturbations of α are broadly similar in many respects to those for b (since both b and α have a positive effect on the marginal cost of harvest). Increases in α result in decreases in daily harvests and thus longer seasons (at least for moderate to large fisheries). A notable difference, however, between changes in α and b is that rents are increasing in α. One can think of α as summarizing the interaction of the production possibilities of the gear and the ecological system, the gear is utilized within. With that interpretation, b would represent the intrinsic efficiency of a particular fishing gear, while α captures the effect of intrinsic characteristics of the physical/biological system—particularly those aspects associated with the spatial cross-correlation of species densities. Since α is a curvature parameter, when it is large, high daily harvests of the target are associated with very large bycatch rates whereas bycatch rates at low harvest levels are quite low. If a fisherman fishes in a single locale in a given period, the bycatch rate for that period is indicative of the relative local biomass of the two species. It follows that large values of α coincide with high

[17] This result accords with the findings from the common property literature that public improvements to a common property resource are particularly under-provided voluntarily [4].

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.[18]

Surprisingly, this spatial autocorrelation in bycatch and targeted species leads to more conservative harvest behavior and increased rents. The pursuit of attractive clusters of target catch in high-α situations implies that the harvest of those clusters will often result in significant discard costs. Low-α fisheries weaken this behavioral nexus since the average penalty for exploiting high-density areas is lower.

4.2. The optimal penalty for bycatch

While we have motivated c as the internal "production" cost of bycatch due to sorting and discards, 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 short-run marginal cost of bycatch is $c+\tau$. At what level must this penalty be set to cause the Nash equilibrium to mimic the quota-constrained social planner's solution?

For brevity, consider only the case where the fishery is large enough such that Q_X binds for the regulator. The task 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 the Pigouvian tax where the marginal benefits of increased harvest just equal the personal marginal costs ($c+\tau$) at the optimum season length of $\bar{T}$. Setting $\hat{T} = \bar{T}$ and solving for τ yields:

$$\tau^* = \frac{p(1 - 1/N)}{b(\alpha - 1/N)} \left(\frac{\bar{T}N}{Q_X}\right)^{\alpha-1} - c \tag{7}$$

This penalty is increasing in the price of the targeted species and the number of participants and decreasing in the intrinsic costs of sorting and discard. Inefficient gears characterized by high values of b necessitate lower unit penalties, since the cost disincentives of higher harvests are magnified via b.

While the discussion supposes a unique optimal penalty for a particular situation, there are a range of penalties in excess of τ^* that would induce optimal behavior. All these penalties are sufficiently large to induce a non-negative shadow value for the season length constraint at the optimal harvest rate. One implication is that penalties that are 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. Among this range of penalties, τ^* yields optimal behavior at the least cost to fishermen.

The bycatch penalty could also be assessed via other mechanisms to yield similar results. For instance, fishermen could purchase quota for every unit of bycatch and τ^* would represent the appropriate quota price. Alternatively, τ^* could represent the monetary equivalent of the mutual "social pressure" that is brought to bear by their peers on individual vessels for each unit of excess bycatch in order to induce optimal harvest and bycatch behavior. Finally, a cooperative could be formed where allocations of target and bycatch quota are distributed among members according to their harvest of each species in the optimal solution. Atomistic behavior on the part of fishermen would then lead to the optimal outcome.

5. Discussion and conclusions

We have developed a model that explains characteristics of an important group of fisheries for which bycatch and targeted catch is 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 profits—providing further insights into the linkages between behavior, technology, regulations, and fishery performance. An important insight 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. However, while common-pool quotas may be effective instruments to address biological objectives, they exacerbate rather than solve the fundamental economic problem of insecure harvesting privileges. The outcome of this system is rent dissipation on a number of fronts, from wasted target quota, high discard costs, and shortened seasons, all of which reduce rents and may lead to losses in the product market from reduced product quality and skewed product mixes.

Our modeling is based on a number of simplifying assumptions. First, we simplified an inherently spatial and dynamic problem into one that is static and largely aspatial. While relaxing these assumptions would likely yield rich results, it would substantially reduce analytical tractability. Second, we have presumed a deterministic world where fishermen and regulators are privy to the same complete and perfect information and the harvest process is fully controllable. Expanding our model to allow for stochasticity in bycatch or asymmetric information is perhaps a worthy endeavor.[19] Third, while our model is very much a short-run construct, it is likely that long-run entry into the fishery, both in terms of additional vessels and "capital-stuffing" on vessels, will substantially reduce any positive rents remaining from the intra-seasonal dissipation

[18] This spatial reasoning does rely on the implicit assumption that the two species are seasonally uniformly distributed over the grounds with a degree of spatial correlation. We thank an anonymous reviewer for this comment.

[19] In a recent working paper, Segerson [17] conducts a very insightful analysis of the efficiency properties of multiple policy instruments for bycatch control under stochastic bycatch.

we have demonstrated. One can envision a dynamic game where entry occurs between seasons to dissipate anticipated rents subject to announced quotas and regulators set quotas, based upon stock levels, which are predicted in the model through biological growth equations. The long-run equilibrium of such a system would be contingent upon the strength of stock effects for the two species, the technological interplay between abundances of target and bycatch species and the regulator's biological objectives.[20] A final simplification of our approach was to ignore the possibility of positive within-season opportunity costs for fishermen. However, if fishermen can participate in other fisheries at a relatively low cost, then some of our specific results (e.g. that it is optimal to fish the entire season or that participation is fixed within-season) no longer follow. Extensions to the case of a fixed positive opportunity cost are relatively straightforward. However, many real-world fisheries are likely to exhibit heterogeneous and time-varying costs (e.g. due to closures in alternative fisheries or seasonality in target abundance or quality) that would substantially complicate modeling efforts. Furthermore, these opportunity costs may be endogenous if participation decisions influence regulatory and economic outcomes in alternative fisheries. While undoubtedly complex, the behavioral implications of these costs are clearly worthy of investigation.

This work ultimately poses the question of how to best regulate bycatch in complex multispecies fisheries. While much of the fisheries science and management literature regards the problem as intrinsically technical and best addressed by the development of alternative gears or spatial closures, our analysis suggests that observed bycatch is actually a much more complicated outcome of gear design, spatial ecology, and regulations, and is fundamentally behavioral. The range of viable policy options is broader than those addressing technological aspects. 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 problem poses an important fundamental question: how much of the problem is inherently technological and how much of it is behavioral and institutional? This issue has not been addressed adequately, and suggests a worthwhile and challenging research agenda.

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[20] Repeated play also creates the possibility of cooperation arising as a subgame perfect equilibrium strategy without regulatory intervention. Cooperation may be sustainable regardless of whether individual actions are observable or not [16,22].