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An Economic Analysis of the Fisheries Bycatch Problem*

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Bycatch is the incidental take of a species that has value to some other group. This paper compares open access and individual transferable quota equilibria to the equilibrium in which the joint value of the fisheries is maximized. The open access induced problems can be corrected by an individual transferable quota system only if both the target species and the bycatch species have tradable quotas, and only if the bycatch species does not have existence value. There exists a range of the bycatch-to-target species harvest levels for which the total harvest of each will be exactly taken by a given technology, even under open access. However, there may not even exist a unique open access equilibrium if bycatch is allocated by "rule of capture." Prohibitions on the sale of bycatch reduce the bycatch level, but they also reduce social welfare. © 1996 Academic Press, Inc.

> It is inevitable that [halibut] will be caught in various degrees and proportions when trawling for other species.
>
> F. H. Bell, 1981

1. INTRODUCTION

One of the most vexing problems facing managers of fishery stocks is the problem of incidental harvesting of non-targeted species. Bycatch, as the incidental catch is called, occurs with almost every fishery to some degree since the harvester does not observe exactly what he is catching until his gear is drawn to the surface.[1] However, the term "bycatch" is generally used to describe incidental catch in a fishery for which there exists another constituency with a claim on the bycatch species. Though sonar fish finders, improved technologies in trawl net design, increased use of pots, and other gear substitution may reduce bycatch, as long as the target and the non-target species intermingle it is often impossible to eliminate it entirely.[2] Public pressure (e.g., concerning dolphin bycatch in the tuna fishery in the Pacific Ocean and the Gulf of Mexico or green sea turtle bycatch in the Gulf of Mexico shrimp fishery), legal requirements such as the Endangered Species Act (e.g., concerning Columbia River chinook salmon), and political pressure from competing interest groups (e.g., concerning incidental take of halibut, crab, and salmon in the North Pacific groundfish fisheries and incidental take of chum

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[1] Mortality rates in ocean fisheries bycatch are high because the fish being taken are pulled to the surface too quickly or in too great a mass to survive the pressure (e.g., [18]).

[2] The cod and pollock trawl fisheries in the North Pacific are moving toward nets which have square shaped spaces rather than diamond shaped spaces. The diamond shaped spaces become elongated under pressure, reducing the chance that smaller and flatter fish (e.g., halibut) can escape. The square spaces technology is an attempt to reduce this type of bycatch. However, even this method cannot exclude bycatch of different but similar sized species. (See [23, April 1993, p. 61].) An exception is the turtle excluder devices (TEDs) which have virtually eliminated turtle bycatch in the Southeast shrimp fishery [25].

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salmon in the Aleutian Islands sockeye salmon intercept fishery) all force managers to impose limits on bycatch of certain species.

Thus bycatch presents several unique problems to managers. First, the manager is faced with the efficiency (and political) problem of determining the allocation of the bycatch between competing interests. Second, once the manager has determined an allocation, the allocation may not be internally consistent (i.e., may not maximize profits for individuals participating in the fishery) while at the same time satisfying resource conservation constraints. For example, if the total allowable catch (TAC) for the bycatch species is reached before the TAC for the target fishery species, the TAC in the target fishery may not be harvested, escapement may be higher than desired, and fish may be "left on the table," in the jargon of fishermen.[3] Thus the bycatch problem presents a challenge to managers' attempts to control harvest and escapement simultaneously in the target and bycatch fisheries. Third, bycatch will likely change as factors such as technology and prices change. Thus a program which is successful in one state of the world may fail in another. This point is particularly apt for fisheries managers since most of the current direction in regulation of bycatch is toward gear restrictions or time and area closures. While these methods may reduce bycatch, it is the exceptional case in which these restrictions eliminate bycatch or give fisherman an incentive to internalize the full costs of bycatch.[4] Furthermore, while such restrictions may be effective at reducing bycatch, their economic viability is often questionable.[5]

This paper presents a stylized model of bycatch in a fishery. The problem is examined from the perspective of a single season. Although there are exceptions (such as predator–prey relations between species), TAC limits on levels of harvest for both the target and bycatch species can be treated as predetermined within a

[3] For example, in the North Pacific groundfish fishery, halibut bycatch TAC limits forced early closure of the 1992 longline cod fleet, with approximately 27,000 metric tons of the cod TAC not taken [23, Aug. 1992]. In 1990, the domestic flatfish fisheries in Zone 1 of the Bering Sea were closed on February 27, 1990 because of *C. bairdi* crab bycatch, though it later resumed in March. On March 14, 1990, the domestic flatfish fishery was again closed due to halibut bycatch, and on March 19, 1990, the entire Bering Sea and Aleutian Islands fishery was closed to domestic flatfish fisheries because of halibut bycatch [23, May 1990]. After noting that more than 47,000 metric tons of sole ($22.8 million, gross value) were unharvested by the domestic fleet and that about half the 127,000 metric tons of sole would be unharvested by the joint-venture fleet, both because the 1990 halibut bycatch TAC constraint was reached in the Bering Sea, National Marine Fishery Service Biologist Janet Smoker observed "It looks like a lot of money will be left in the ocean this year" (quoted in [23, June 1990, p. 63]).

[4] The turtle excluder devices (TEDs) have been reported to be quite successful in the shrimp fisheries. However, green sea turtles are only one source of bycatch. The shrimp fisheries are reported to catch more finfish biomass than shrimp [23, May 1992, p. 25] and more uneconomic mollusks [17, pp. 18–19]. Similarly, in the North Pacific, time and area closures have protected halibut spawning grounds from the groundfish fleets. However, halibut bycatch is almost impossible to eliminate fully given that halibut and cod coexist in similar ecological niches (e.g., [5]). In the "Area M" salmon fishery in the Bering Sea, which targets sockeye salmon destined for Bristol Bay, there is bycatch of chum salmon destined for Norton Sound [9]. As the two species are similar in size and in migration patterns, simple time and area closures will not eliminate bycatch without shutting down the target fishery.

[5] A disadvantage of technologies created by the regulatory process is that it is not clear such technologies are economically sound. This is not true for technologies adopted under an ITQ or tax system. If fishermen adopt new technologies, the technology is economically viable. Ward [25] has developed a model to show the effect on stocks and allocations if a new technology is adopted, but there are no costs of adopting the technology. Thus, while his model tells us something about what might happen if new technology is adopted, he tells us nothing about the viability of the technology. In addition, fishermen have complained that the process of testing new gear types is too slow under the command and control management in the North Pacific groundfish fishery [23, Apr. 1993, p. 61.].

season due to resource conservation constraints.[6] In addition, it is assumed that the bycatch is produced incidentally by the target fishery, as pollution is produced incidentally in the production of steel or sawdust is produced incidentally in the production of lumber. The model is also determinant as there is assumed to be no uncertainty regarding harvest rates or prices. Finally, since the viability of gear restrictions is mainly an empirical question, the focus is on what effect taxes or individual transferable quotas (ITQs) have on bycatch. Looking at the problem from the context of a single season and treating the fisheries as distinct allocations, accurately represents the manner in which many fisheries are managed. Legal requirements force managers to set season limits on the catch of the target species to maintain sustainability of the stocks. Thus, even if the species are treated as part of a multi-species fishery, harvest TACs may exist for individual species. In addition, fisheries are often managed on a multi-species basis, so limits on bycatch are set in the general context of allocation of the resource among competing uses.

This paper focuses on three questions: (1) How should the bycatch species be allocated among its competing uses? (2) How does open access affect bycatch rates? (3) Can rationalization through individual transferable quotas or taxes achieve the social optimal allocation of bycatch and effort?

Of the assumptions made in this paper, the assumption regarding the bycatch technology is the most restrictive. Bycatch is treated as a function solely of the harvest rate of the target species. This is a very restrictive form of a multi-product production function. In part, it may be defended by an appeal to the fact that in many fisheries, the bycatch is actually quite small relative to the harvest level. For example, bycatch of salmon in the North Pacific groundfish fisheries is roughly one salmon per fifty tons of groundfish. This becomes economically significant only when the amount of groundfish is quite large. Bycatch of Washington and Oregon salmon by Alaska trollers targeting salmon from Alaskan rivers is even less. Clearly, however, objections can be raised to this defense. Shrimp fisheries, for example, regularly have bycatch of "trash fish", mollusks and other bottom dwellers, that is in excess of the quantity of shrimp recovered on a pound to pound basis. Other fisheries are truly multi-species fisheries. For example, the "Area M" fishery which intercepts sockeye salmon en route to Bristol Bay in Alaska also catches large proportions of chum salmon bound for the Yukon River and Norton Sound [9]. In cases such as this, depicting the fishery as a target fishery (sockeye salmon) with bycatch (chum salmon) is clearly a stretch. However, in such cases the present model may serve as a useful simplification of a difficult problem.

2. MODEL AND ASSUMPTIONS

Assume that there exist two biological species, the target and bycatch species.[7] The target stock is harvested by fisherman in Fishery One. The bycatch species

[6] For examples of papers where the interdependent biological relationships are considered in the context of bioeconomic models see [11] and [26].

[7] The simplification of treating the target species as a single species and the bycatch as a single species is justified on the grounds that in the North Pacific cod, pollock, and sablefish are managed as single species in the Gulf of Alaska [20]. However, in the Bering Sea, the groundfish resource (yellowfin sole, pollock, Pacific ocean perch, turbot, Atka mackerel, Pacific cod, and sablefish) is managed as a complex (i.e., as a multi-species fishery) [21]. This paper focuses on the simpler case where the target species and bycatch can be considered as separate single species.

may be the target stock in Fishery Two (e.g., in the North Pacific, crab is bycatch to the groundfish fishery), or it may be a species not targeted by any commercial fishery (e.g., dolphins to the tuna fishery). The bycatch species may have existence value (e.g., [15]) even if it has no commercial value.[8] The bycatch species is taken incidentally in Fishery One while pursuing the target species. Let S_1 denote the total allowable catch of the target species which may be removed within a season by Fishery One, and let S_2 denote the TAC of the bycatch species which may be removed by Fishery One and Two together. S_1 and S_2 are determined prior to the season, say by biological (escapement) or legal requirements. The bycatch species might be a stock which is protected by the Endangered Species Act, a stock managed independently (in which case a proportion B might be allocated to Fishery One and $S_2 - B$ allocated to Fishery Two), or it might be a stock jointly allocated between Fishery One and Fishery Two on a first come, first served, basis.

A. Technology Assumptions

Assume that fisherman within each fishery are homogeneous in terms of opportunity costs, fishing skills, and technology, although there may be differences between the technologies used in the two fisheries. In addition, assume that there are no stock or congestion externalities in either fishery. These assumptions imply that stock and aggregate effort levels do not enter into the profit function [6]. Let variable profits for harvest of the target species for vessel j in Fishery One be defined as $\pi_1(h_{1j}; P_1)$, where h_{1j} is the harvest per day of the target species by vessel j, and P_1 is the output price of the target species. (Since the output level h_{1i}, is the only choice variable, input prices are ignored.) Assuming fishermen are homogeneous, the j subscript on the harvest level is omitted except where doing so will cause confusion, i.e., $h_{1j} = h_1$, $j = 1, \ldots, N_1$, where N_1 is the maximum possible number of entrants into Fishery One. Variable profits in Fishery Two are denoted by $\pi_2(h_{2j}; P_2)$. Variable profits in each fishery have the following properties (dropping the P_i arguments):

*Assumption A.*1. $\pi_i(0) = 0$; $\pi_i'(h_i) > 0$ for all $h_i \geq 0$; $\pi_i''(h_i) < 0$ for $h_i > 0$.

The first two parts of A.1 imply that zero harvest yields zero profits and that profits increase as the harvest rate increases. The third part of A.1 states that profits are concave in h_i.

The bycatch technology assumption is that there is a single species model with unwanted (or desired) production of bycatch being a function of the output of the target species (not necessarily in fixed proportions). Let $b(h_1)$ denote the per day removal of the bycatch species by Fishery One for a harvest level h_1 of the target species. Fishery Two is assumed to have no bycatch of the targets species for Fishery One.[9] As the rate of harvest of the target species is the only variable

[8] The existence value aspect of some bycatch was suggested by an anonymous referee.

[9] Bycatch is usually asymmetric in this sense. A very clear set of examples has to do with the salmon fisheries in the North Pacific. The bycatch of Columbia River sockeye salmon by the Southeast Alaska troll fishery is not symmetric; there is no corresponding Southeast Alaska salmon bycatch in the Columbia River area. Similarly, in the Area "M" intercept sockeye salmon fishery, bycatch of Norton Sound and Yukon River chum salmon occurs, but no bycatch of sockeye salmon occurs in the Norton Sound or Yukon River chum salmon fisheries. While bycatch of cod and pollock may also occur in the halibut and crab fisheries, such bycatch is trivial.

available a fisherman controls, input substitution is ignored in the analysis. The Fishery One bycatch function is assumed to have the following properties:

Assumption A.2. $b(0) = 0$; $b(h_1) > 0$, $b'(h_1) > 0$, and $b''(h_1) \geq 0$, for all $h_1 > 0$.

The first three parts of A.2 says that zero bycatch is possible only with zero output of the target species, and that bycatch is positive and increases as output of the target species increases. Thus bycatch is "essential" to the target fishery [13]. Regarding the fourth assumption, when $b'' = 0$, there is a fixed-proportion relationship between bycatch and harvest of the target species (i.e., $b(h_1) \equiv \alpha h_1$, for some non-negative constant α), and when $b'' > 0$, the ratio of bycatch to the target species increases as the harvest rate increases.[10] This functional relationship assumes that methods to reduce bycatch require greater care be taken in harvesting the target species, slowing down that harvest rate, but that it is impossible to fully eliminate bycatch with the given technology. The costs of separating, counting, and either selling or disposing of the bycatch are assumed to depend on the harvest level, so these costs are already accounted for in the π_1 function. Thus part of the reason for the decline in marginal profits ($\pi_i'' < 0$) is due to the increase in the bycatch proportion as harvest of the target species increases. Bycatch is being modeled as though it were "pollution" being generated with output (e.g., [7]), with part of the cost being internalized (sorting, counting, etc.) and part being external (the reduction in available stock to others). However, the pollution analogy is incomplete since part of the external cost is borne by others within the industry in the bycatch case due to the TAC constraint. Pollution controls generally are stated in terms of pollution allowed per firm.

To consider several cases within the context of a single model a pair of parameters (δ, γ) will be used to differentiate between the cases. Let $\delta \in \{-1, 0, 1\}$ be the weight associated with bycatch in the objective function of a vessel (or society) in Fishery One. When $\delta = 1$, the vessel is allowed to sell the bycatch (at price P_2) in addition to the selling target species harvest at price P_1. When $\delta = 0$, the vessel derives no direct value from the bycatch. When $\delta = -1$, each unit of bycatch costs society P_2, say from foregone existence value. The parameter $\gamma \in \{0, 1\}$ is used to switch between having an active commercial fishery (Fishery Two) targeting the bycatch species and not having one. When $\gamma = 0$, the bycatch species has no commercial value, although it may have existence value if $\gamma = 0$ and $\delta = -1$.

Given a season length of T_1 (e.g., the number of days the fishery is open), a market price of P_1 for the target species (dollars per fish), P_2 for the bycatch species (dollars per fish), and an identical fixed but avoidable cost k_1 (dollars per vessel), season profits to vessel j in Fishery One are[11]

$$v_{1j} = T_1\left[\pi_{1j}(h_{1j}) + \delta P_2 b(h_{1j})\right] - k_1, \qquad j = 1, \ldots, N_1. \tag{1}$$

[10] When $b'' = 0$, there is no way to reduce the ratio of bycatch to target species harvest ratio. However, if $b'' > 0$, the bycatch to target species harvest ratio may be reduced by slowing down the harvest rate on each vessel. Berger, *et al.* [6] have found that there is considerable variability in bycatch to harvest ratios in the Bering Sea groundfish trawl fisheries. The North Pacific Fisheries Management Council considered plans to kick individual fishermen out of the fishery if their bycatch rate was too high. This suggests that fishermen can control bycatch to some extent with the given technology.

[11] Note that when $\delta = -1$, the term in square brackets is identical in form to a pollution model with the firm paying P_2 per unit pollution, $b(h_1)$, emitted.

When $b'' > 0$, if $\delta = 1$, it is possible for the term in square brackets to not be concave. (This is not a problem if $\delta = -1$ or $\delta = 0$.) Thus, our final assumption is:

Assumption A.3. $\pi''(h_1) + \delta P_2 b''(h_1) < 0$ for $h_1 > 0$, so $\pi_1(h_1) + \delta P_2 b(h_1)$ is sufficiently concave such that second-order conditions hold.

If Fishery Two exists, then given a season length of T_2, bycatch market price of P_2, and a fixed but avoidable cost k_2 (also identical across fishermen), season profits to vessel j in Fishery Two are

$$v_{2j} = T_2 \gamma \pi_{2j} - k_2, \qquad j = 1, \ldots, N_2. \tag{2}$$

Suppose that $n_1 \leq N_1$ vessels participate in the fishery targeting the target species. The TAC constraint for the target species is

$$S_1 - T_1 \sum_{j=1}^{n_1} h_{1j} = S_1 - T_1 n_1 h_1 \geq 0, \tag{3}$$

where the equality holds due to fishermen being homogeneous. Similarly, for the bycatch species, the bycatch TAC constraint is

$$S_2 - T_1 \sum_{j=1}^{n_1} b(h_{1j}) + T_2 \sum_{j=1}^{n_2} h_{2j} = S_2 - T_1 n_1 b(h_1) + T_2 n_2 h_2 \geq 0, \tag{4}$$

where the equality holds due to fishermen being homogeneous.[12] The constraint in (4) could be rewritten as two constraints, one for each fishery, if the allocation were to be divided up between Fishery One and Fishery Two as,

$$S_2 - B - T_2 n_2 h_2 \geq 0, \qquad \text{and} \qquad B - T_1 n_1 b(h_1) \geq 0, \qquad \text{for } 0 \leq B \leq S_2. \tag{5}$$

The advantage of writing the constraint as (5) is that it shows that a positive bycatch allocation is necessary for Fishery One to exist given assumption A.2. In the event that $\gamma = 0$, and $\delta = 1$, $B \leq S_2$ denotes the share of the possible total (S_2) allowable bycatch that the fishery is allocated. Note that both (3) and (4) are quasi-convex in (T_i, n_i, h_i, B). This is used below to establish sufficiency for the Kuhn–Tucker conditions.

In addition, assume that there exists an upper bound on the length of the season for each fishery. For example, these constraints could be due to the seasonal nature of spawning of the target and bycatch species. Given the fixed-but-avoidable costs of entering, such a constraint is necessary to solve the social planner's problem (cf. Clark [8, pp. 240–43]). Thus we require[13]

$$T_1 \leq \bar{T}_1, \qquad \text{and} \qquad T_2 \leq \bar{T}_2. \tag{6}$$

[12] It is assumed that bycatch cannot be simply discarded without being counted toward one's quota. In the North Pacific groundfish fishery, this is enforced by an "observer program" where trained observers monitor what is being caught on each vessel. In the case where bycatch can be sold, this problem would not occur except for high-grading (e.g., [1], [2]).

[13] The assumption of a fixed-but-avoidable cost is necessary to obtain a determinacy for n and T (where the i subscripts have been dropped). In the simple model with no bycatch, if $k = 0$ the first-order conditions to the social planner's problem reduce to the two equations in three unknowns: $\pi' = \pi/h$ and $S = Tnh$. While h is determined exactly, T and n are not. The constraint on T is also necessary. If $k > 0$ and there is no constraint on T, then the solution to the social planner's problem involves the non-solvable equations $T\pi = k$, and $n\pi = 0$. Both assumptions are plausible for the real world. Most fisheries require some reworking of gear or travel to the fishery to participate, thus $k > 0$. Also, in many fisheries, the species is economically viable to harvest only at certain times of the year due to biological or market conditions, so the assumption of a maximum season length is also plausible.

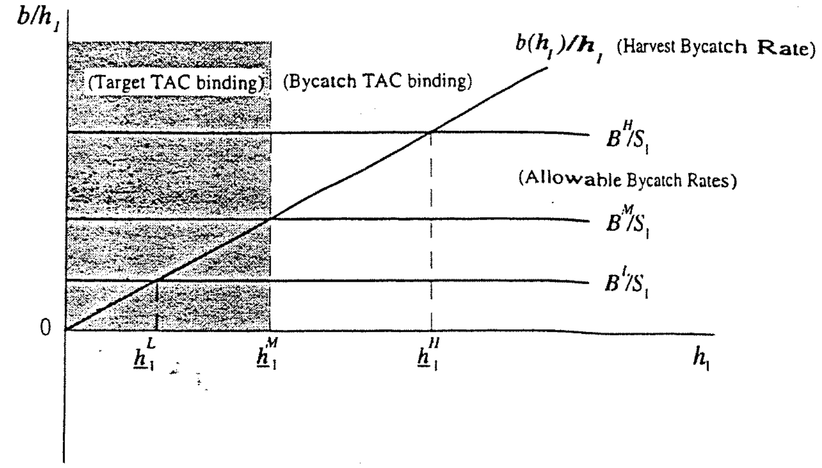

FIG. 1. Relationship between harvest level in Fishery One and which TAC constraint binds.

Finally, there are also non-negativity constraints for the h_{ij}, and n_i, and the T_i.[14]

B. Which Constraint Will Bind?

The ratio of bycatch to harvest of the target species Fishery One is defined to be $b(h_1)/h_1$. Thus if n_1 vessels fish T_1 time periods, they will take $T_1 n_1 b(h_1)$ of the bycatch and $T_1 n_1 h_1$ of the target species. Thus for a given h_1, the binding constraint will be determined by whether

$$b(h_1)/h_1 \lesseqgtr B/S_1. \tag{7}$$

If the bycatch ratio b/h is greater than Fishery One's bycatch species TAC to target species TAC ratio B/S_1, then the bycatch constraint will be binding; otherwise the target species TAC constraint will be binding. For future reference, define the point $\underline{h}_1$ as the value of h_1 for which (7) is an equality. When $b'' > 0$, the bycatch ratio increases as h_1 increases (i.e., $d[b/h]/dh_1 = [b'h_1 - b]/h^2 > 0$). Thus, for $h_1 > \underline{h}_1$, the bycatch species TAC constraint binds, and for $h_1 < \underline{h}_1$, the target species TAC constraint binds. Figure 1 shows three possible $\underline{h}_1$ values corresponding to three different levels of the bycatch constraint. Since $B^H > B^M > B^L$, the corresponding $\underline{h}_1$ levels are ordered as $\underline{h}_1^H > \underline{h}_1^M > \underline{h}_1^L$.[15]

3. THE SOCIAL PLANNER'S PROBLEM

A. Optimization Problem for Social Planner

Given fixed output prices, the value society obtains from the two fisheries is given by

$$V = T_1 n_1[\pi_1(h_1) + \delta P_2 b(h_1)] - k_1 n_1 + T_2 n_2 \gamma \pi_2(h_2) - k_2 n_2, \tag{8}$$

[14] The constraints that $n_i \leq N_i$ are ignored. In open access, N_i is unlimited, and the social planner may use up to the same amount as in open access.

[15] Note that the sign of the slope of b/h and all other lines drawn in the figures can be shown to be correct, but whether the line is linear, convex, concave, or otherwise is indeterminate.

which is simply the sum of economic profits in the two fisheries. Equation (8) can be shown to be quasi-concave in (T_i, n_i, h_i, B). This plus the quasi-convexity of the constraints (3)–(6) ensure sufficiency for the Kuhn–Tucker conditions the Arrow–Enthoven sufficiency theorem, assuming the constraint qualification is met. The Lagrangian for this problem is

$$L = V + \lambda[S_1 - T_1 n_1 h_1] + \mu_1[B - T_1 n_1 b(h_1)] + \mu_2[S_2 - B - T_2 n_2 h_2]$$
$$+ \sigma_0 B + \sigma_2[S_2 - B] + \sum_{i=1}^{2}\left\{\tau_i[\bar{T}_i - T_i] + \phi_i h_i + \theta_i n_i + \psi_i T_i\right\},$$

where the Lagrange multipliers λ, μ_i, σ_0, σ_2, τ_i, ϕ_i, θ_i, and ψ_i, $i = 1, 2$, correspond to the constraints (3), (5), (6), and the non-negativity constraints, respectively.

In fisheries such as the North Pacific groundfish fishery, bycatch of crab, halibut, and salmon are of commercial value, but they are not allowed to be sold by the groundfish fishery. (The bycatch is disposed of by dumping it back into the sea.) By the envelope theorem, it may be seen that this restriction is not based on efficiency.[16]

PROPOSITION 1. *Assuming that the bycatch species is of commercial value* ($\delta \neq -1$), *society would be better off if the target fishery were able to sell the incidental catch* ($\delta = 1$) *than not* ($\delta = 0$).

Thus the prohibition in many fisheries on Fishery One selling bycatch is based on something other than efficiency. More likely, it is based on a desire by Fishery Two to reduce the incentive for Fishery One to benefit from the bycatch. Allowing Fishery One to sell the bycatch gives them an incentive to incur higher bycatch rates. Thus it increases the competition for the bycatch species, reducing the number of vessels in Fishery Two (cf. [18]).

Assuming the social planner chooses the bycatch allocation B, effort in each fishery h_i, $i = 1, 2$, the number of entrants in each fishery n_i, $i = 1, 2$, and the season length in each fishery T_i, $i = 1, 2$, the system of first-order conditions to the social planner's problem include the constraints (3)–(6) and (with arguments of the functions suppressed)[17]

$$\partial L/\partial B = \mu_1 - \mu_2 + \sigma_0 - \sigma_2 = 0,$$
$$\sigma_0 \geq 0, \quad B\sigma_0 = 0, \quad \sigma_2 \geq 0, \quad \sigma_2[S_2 - B] = 0, \tag{9}$$
$$\partial L/\partial h_1 = T_1 n_1[\pi_1' + (\delta P_2 - \mu_1)b' - \lambda] + \phi_1 = 0,$$
$$h_1 \geq 0, \quad \phi_1 \geq 0, \quad h_1\phi_1 = 0, \tag{10}$$
$$\partial L/\partial h_2 = T_2 n_2[\pi_2' - \mu_2]\gamma + \phi_2 = 0,$$
$$h_2 \geq 0, \quad \phi_2 \geq 0, \quad h_2\phi_2 = 0, \tag{11}$$
$$\partial L/\partial n_1 = T_1[\pi_1 + (\delta P_2 - \mu_1)b - \lambda h_1] - k_1 + \theta_1 = 0,$$
$$n_1 \geq 0, \quad \theta_1 \geq 0, \quad n_1\theta_1 = 0, \tag{12}$$

[16] Proofs to all propositions are available from the author.

[17] Second-order conditions can be shown to hold for all interior solutions. They are available from the author.

$$\partial L/\partial n_2 = T_2[\pi_2 - \mu_2 h_2]\gamma - k_2 + \theta_2 = 0,$$
$$n_2 \geq 0, \quad \theta_2 \geq 0, \quad n_2\theta_2 = 0, \tag{13}$$
$$\partial L/\partial T_1 = n_1[\pi_1 + (\delta P_2 - \mu_1)b - \lambda h_1] - \tau_1 + \psi_1 = 0,$$
$$T_1 \geq 0, \quad \psi_1 \geq 0, \quad T_1\psi_1 = 0, \tag{14}$$
$$\partial L/\partial T_2 = n_2[\pi_2 - \mu_2 h_2]\gamma - \tau_2 + \psi_2 = 0,$$
$$T_2 \geq 0, \quad \psi_2 \geq 0, \quad T_2\psi_2 = 0. \tag{15}$$

Equation (9) shows that if the bycatch is allocated to each fishery, then $\mu_1 = \mu_2$; i.e., the marginal value of the bycatch is equal across the fisheries. Otherwise, bycatch will be allocated entirely to the fishery with the largest μ_i. If the harvest level of the target species is positive ($h_1 > 0$), (10) says the harvest level is chosen such that the marginal profit equals the sum of the scarcity rents on the target λ and bycatch species $\mu_1 b'$. When $h_2 > 0$, (11) shows that the optimal harvest level equates marginal profit from harvesting the bycatch species with marginal scarcity rent μ_2. Equation (12) shows that when $n_1 = 0$, $\theta_1 = k_1$, and that when $n_1 > 0$, the return on the target species (and the bycatch species if $\delta = 1$) over the entire season *net* of harvesting costs and scarcity rent, λ or $\mu_1 b$ (plus the existence value cost if $\delta = -1$), just equals the cost of an additional vessel, k_1. Equation (13) has a similar interpretation as (12), with $\theta_2 = k_2$ when $n_2 = 0$, and net returns over the entire season equal the entry cost of an additional vessel if $n_2 > 0$. Equations (14) and (15) are composed of two sets of terms. The expressions in the square brackets are seen to be the net return per vessel per unit time. The value of an extension in the season lengths are thus the net return per vessel per unit time times the number of vessels n_i.

Let us now state:

PROPOSITION 2. *If the bycatch species has commercial value the social planner will allocate the bycatch and fish each fishery as follows*:

(i) *If* $0 = \mu_1 < \mu_2$, $B = 0$, *Fishery Two takes the entire bycatch allocation utilizing the entire season, and Fishery One does not fish* (*i.e.*, $T_1 = n_1 = h_1 = 0$, $T_2 = \bar{T}_2$, $n_2 > 0$, $h_2 > 0$, *and* $\lambda = 0$);

(ii) *If* $R\mu_1 > \mu_2 = 0$, $B = S_2$, *Fishery One takes the entire bycatch allocation, but not all of the target species TAC, utilizing the entire season available to it, and Fishery Two does not fish* (*i.e.*, $T_2 = n_2 = h_2 = 0$, $T_1 = \bar{T}_1$, $n_1 > 0$, $h_1 > 0$, *and* $\lambda > 0$);

(iii) *If* $\mu_1 = \mu_2 > 0$, $0 < B < S_2$, *and both Fishery One and Fishery Two operate for the entire season, taking the full allocation of the bycatch species* (*i.e.*, $T_1 = \bar{T}_1$, $T_2 = \bar{T}$);

(iv) *If* $S_2 = 0$, *neither fishery operates* (*i.e.*, $T_1 = n_1 = h_1 = T_2 = n_2 = h_2 = 0$).

Proposition 2 shows that if both stocks have commercial value, it is optimal to either utilize both stocks (case iii), with bycatch being utilized fully, or to fish only in the Fishery which has the highest marginal value for an additional unit of bycatch (cases i and ii). If the bycatch TAC were also a choice variable (say in a multi-season model with maximization of (8) within each season), then it is clear that the bycatch species will always be fully utilized (either as a target species, as bycatch, or as both). Thus the long run trade-off is between increasing the bycatch

TAC now and in the future. There would be tremendous short-term pressure to increase the TAC of the bycatch now, especially if one of the fisheries is shut down as a result of the low bycatch species TAC.

A corollary to Proposition 2 has to do with the case where the manager has no control over the bycatch allocation to Fishery One. In this case, B may be chosen by another agency (e.g., halibut and groundfish in the North Pacific) or as a legal limit imposed on the take of species for which there is no commercial value, but for which society has existence value (e.g., dolphins in the tuna fishery). Since there are no stock effects [6, 8],

COROLLARY 2.1. *If the allocation of bycatch to Fishery One is chosen by means other than maximizing* (8), *then Fishery One will harvest over the entire allowable season* (*i.e.*, $T_1 = \bar{T}_1$), *for whichever allocation*(*s*) *it fully utilizes.*

B. *Optimal Solution When Bycatch Has No Commercial Value*

Next, let us characterize the solution under several different scenarios, beginning with the case where no Fishery Two exists (so $B = S_2$) and the target species TAC constraint binds ($\lambda > 0$).

1. *TAC for target species binding.* Let $\gamma = 0$, implying that there is no Fishery Two, and assume $\lambda > 0$, implying that the target species TAC binds. Given Corollary 2.1, let $\mu_1 = 0$. Then from (10), $\lambda^* = \pi_1' + \delta P_2 b'$, where x_1^* denotes the solution when $\gamma = 0$ and $\lambda > 0$, for $x = h, n, T, \lambda$. Using Corollary 2.1 (so $T_1 = \bar{T}_1$) and plugging λ^* into (12), the optimal harvest rate must satisfy

$$k_1/\bar{T}_1 = \pi_1 - \pi_1' h_1^* + \delta P_2[b - b' h_1^*] = \Phi_1(h_1^*) + \delta P_2 \Gamma_1(h_1^*), \qquad (16)$$

where $\Phi_i \equiv \pi_i - \pi_i' h_i$, $i = 1,2$, and $\Gamma \equiv b_1 - b_1' h_1$. The function Φ_1 is the profit per day net of scarcity rent on the target species, ignoring bycatch. $\Phi_i' = -\pi_i'' h_i > 0$. $P_2 \Gamma < 0$ is the reduction in net profits per day when bycatch is sold.

If $\delta = 0$ or $b'' = 0$, the bycatch does not affect profits except through the increased costs in the π_1 function for disposal. In this case (16) says that $\Phi_l = k_1/\bar{T}_1$, or that the optimal harvest rate is set such that net profits per day equal fixed cost per day. When $\delta = 1$ and $b'' > 0$, the bycatch can be sold. Since $P_2 \Gamma < 0$, (16) implies that a larger harvest level is optimal. This relationship is shown in Fig. 2. If each bycatch removal results in lost existence value ($\delta = -1$) the optimal harvest rate decreases relative to the case where $\delta = 0$. These results, however, are contingent upon the convexity of the bycatch function. If $b'' = 0$, then $\Gamma = 9$, and the optimal harvest level is unaffected by δ.[18] It can also be shown that (10) and A.3 are sufficient to ensure that second-order conditions are satisfied for selection of h_1^*, given $T_1 = \bar{T}_1$ and (3) determines n_1^*.

2. *TAC for bycatch binding.* Now suppose that the bycatch TAC constraint binds rather than the target species TAC constraint. Then $\lambda = 0$ and $\mu_1 > 0$. Let

[18] When $\pi = P_1 h_1 - c_1(h_1)$, and $b(h_1) = \alpha h_1$ (so $b'' = 0$), (16) becomes $c_1'(h_1)h_1 - c_1(h_1) = k_1/T_1$. Which shows that the optimal harvest rate is independent of both P_2 and P_1. That is, the optimal harvest rate is chosen such that costs are minimized. So long as profits are positive, neither the output price nor the bycatch price affects this decision when $b'' = 0$. When $b'' > 0$, (17) shows that the output decision is affected by P_2 since an increase in bycatch affects the cost minimizing choice.

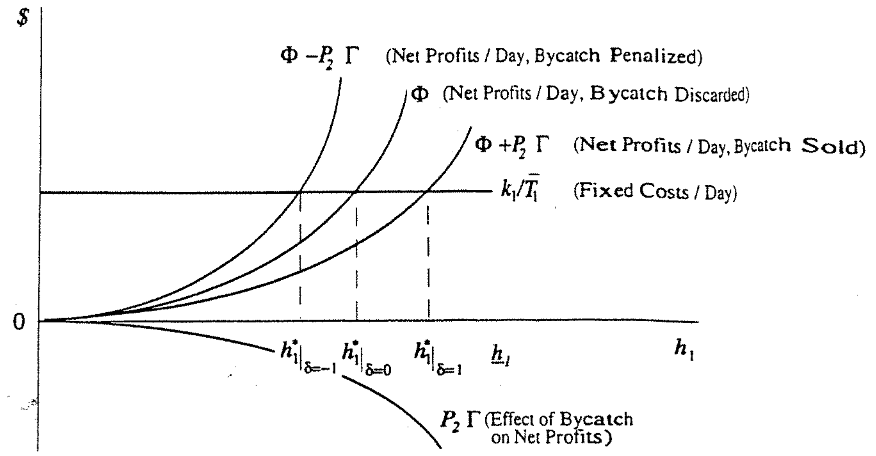

FIG. 2. Optimal harvest rate for Fishery One when target TAC is binding and no Fishery Two exists.

h_1^{**} denote the optimal level of harvest given that the bycatch constraint is binding. Using (10) to eliminate μ_1 in (12), the optimal harvest level h_1^{**} thus solves

$$k_1/\bar{T}_1 = \pi_1 - [b/b'h_1^{**}]\pi_1'h_1^{**} \equiv \Phi_1(h_1^{**}) + [1 - 1/\beta(h_1^{**})]\pi_1'(h_1^{**})h_1^{**}, \tag{17}$$

where $\beta \equiv b'h/b$ is the elasticity of bycatch with respect to harvest of the target species. A comparison of (17) and (16) shows that the difference is that in (17) the $\delta P_2\Gamma$ term from (16) is replaced by $(1 - 1/\beta)\pi_1'h_1$. However, when $b'' = 0$, $\beta = 1$ and $\Gamma = 0$, so the second term drops out in both expressions, and the optimal harvest level is the same whichever constraint is binding. When $b'' > 0$, $\beta > 1$. Thus $0 < 1 - 1/\beta < 1$. Since $\pi_1'h_1 > 0$, the optimal harvest level h_1^{**} is greater than h_1^*, the optimal harvest level when the target species TAC is binding or $b'' = 0$. However, note that $\partial h_1^{**}/\partial\delta = 0$, unlike the case where the target species TAC binds. If the bycatch constraint binds, being able to sell the bycatch has no effect on the harvest level.

A comparison of the equilibrium harvest levels is shown in Fig. 3 for the case where $\delta = 0$. For the case where $\underline{h}_1^L < h_1^{**} < h_1^*$, the target TAC cannot be binding since $h_1^* > \underline{h}_1^L$. Thus the bycatch TAC constraint is binding. When $h_1^{**} < h_1^* < \underline{h}_1^H$, the bycatch TAC cannot be binding since $h_1^{**} < \underline{h}_1^H$. Thus the target TAC constraint is binding. The next proposition shows what happens when $h_1^{**} < \underline{h}_1^M < h_1^*$:

COROLLARY 2.2. *When $h_1^{**} < \underline{h}_1^M < h_1^*$, the optimal solution is $h_1^{***} = \underline{h}_1^M$. Thus both TAC constraints bind simultaneously, so $b(h_1^{***})/h_1^{***} = B/S_1$.*

3. *The optimal of number of entrants.* Since the season length is always the maximum allowable length, the binding TAC constraint plus (16) or (17) determines the number of entering vessels. Thus for if the target species TAC is binding, $N_1^* = S_1/\bar{T}_1h_1^{**}$ and when the bycatch TAC constraint binds, $N_1^{**} = B/\bar{T}_1b(h_1^{**})$. In either case, an increase in h_1 means less entrants. This just show that the social planner is trading off marginal harvesting costs with marginal entry costs in (16)

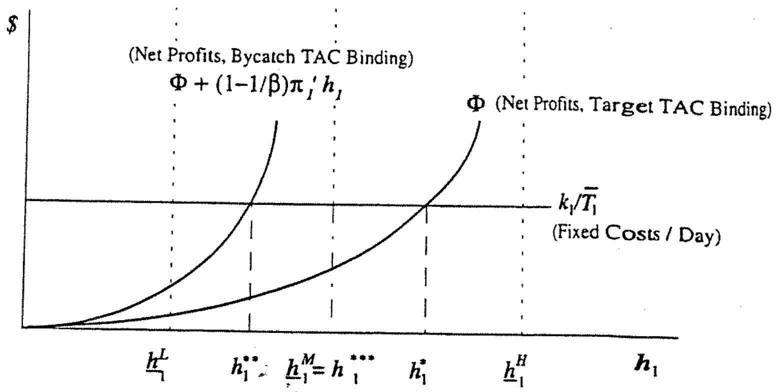

FIG. 3. Optimal harvest rate for Fishery One when bycatch TAC is binding and bycatch has no commercial value ($\delta = 0$).

and (17). In both (16) and (17), the right-hand side is an increasing function of the harvest rate. Thus, either an increase in entry costs, k_1 or a decrease in the length of the season, $\overline{T}_1$ results in an increased harvest rate per vessel. Thus with higher entry costs, the social planner uses each vessel more intensely so that the number of vessels may be reduced. Note that an increase in B or S_1 (whichever is binding) does not affect the optimal harvest per vessel, but does increase the number of vessels used.

C. *Both Stocks Exploited Commercially*

If both fisheries are exploited commercially, then $\gamma > 0$. Since the bycatch species has commercial value, assume that $\delta \neq -1$. First, consider the case where both stocks are fully exploited, so that $0 < B < S_2$.

1. *Both stocks fully utilized.* When both stocks are fully utilized, $T_1 = \overline{T}_1$, and $T_2 = \overline{T}_2$. In addition, the first-order conditions (9) and (11) imply,

$$\mu_1 = \mu_2 = \pi_2'(h_2), \tag{18}$$

which says that the marginal value of another unit of the bycatch stock is equal to its value in production in the Fishery Two, which targets that stock. Similarly, from (10):

$$\lambda = \pi_1'(h_1) + \delta P_2 b'(h_1) - \pi_2'(h_2) b'(h_1). \tag{19}$$

This says that the value of an additional unit of the target species stock equals the value of a marginal unit of production from that stock minus the marginal value of an additional unit of bycatch. Using (18) and (19), the optimal levels of harvest per vessel are given by

$$k_1/\overline{T}_1 = \Phi_1(\hat{h}_1^{***}) + \left[\delta P_2 - \pi_2'(\hat{h}_2^*)\right]\Gamma(\hat{h}_1^{***}), \tag{20}$$

$$k_2/\overline{T}_2 = \Phi_2(\hat{h}_2^{***}), \tag{21}$$

where Φ_i and Γ are defined as before, and where a caret ($\hat{\ }$) denotes the difference between the cases where Fishery Two exists and where it does not exist, and $\hat{h}_1^{***}$, $i = 1, 2$, indicates that *both* TAC constraints are binding. In the event that $\lambda = 0$, it can be shown that (20) collapses to (17).

Figure 4 shows that analysis. From Eq. (16), the solution is h_1^* in Fig. 4. Comparing (20) with (16) shows the difference made by taking account of the second fishery (the $-\pi_2'\Gamma$ term). When profits in both fisheries are maximized simultaneously, the harvest level in Fishery One is smaller than it would be if Fishery Two did not exist. This is because the cost of bycatch includes foregone revenues in Fishery Two when it exists. However, this result only holds if $b'' > 0$. In the event that $b'' = 0$, $\Gamma = 0$, so (20) and (16) are identical. On the basis of (16), (17), and (20), we state:

PROPOSITION 3. *If bycatch is a fixed proportion of total catch of the target species (i.e. $b'' = 0$), then the optimal harvest rate in Fishery One depends only upon entry costs k_1 relative to the marginal harvesting profits of the target species.*

Let us now compare the optimal harvest rate in Fishery One for the case where bycatch affects the optimal harvest rate in Fishery One (i.e., $b'' > 0$). As in Fig. 2, the net marginal profits when $\delta = 0 (\Phi_1 - \pi_2'\Gamma)$ lies above the net marginal profits curve $[\Phi_1 + (P_2 - \pi_2')\Gamma]$ when $\delta = 1$ since $\Gamma < 0$. Thus, the harvest rate in Fishery One increases as δ increases. When the target fishery is allowed to sell the bycatch the cost of the bycatch constraint declines, and vessels increase the harvest rate, incurring a higher bycatch rate.

The optimal number of vessels are given by the TAC constraints for the target and bycatch species, respectively, i.e.,

$$\hat{n}_1^{***} = S_1 / \overline{T}_1 \hat{h}_1^{***}, \tag{22}$$

$$\hat{n}_2^{***} = \left[S_2 - \overline{T}_1 \hat{n}_1^{***} b\left(\hat{h}_1^{***}\right) \right] / \overline{T}_2 \hat{h}_2^{***}, \tag{23}$$

Note that due to the recursive nature of the solution (20)–(23), n_2^{***} is determined by what is left over after Fishery One takes its share. (I.e., $\hat{h}_2^{***}$ solves (21); $\hat{h}_1^{***}$ solves (20); $\hat{n}_1^{***}$ solves (22); so $\hat{n}_2^{***}$ solves (23).)

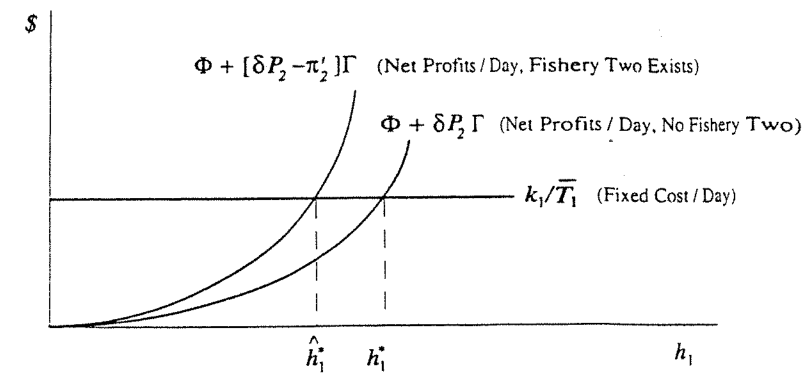

FIG. 4. Optimal harvest rate for Fishery One when bycatch is commercially harvested by Fishery Two, and both fisheries are active, compared with cost where no Fishery Two exists.

It was remarked below (20) that if $\lambda = 0$, (20) collapses to (17). It is now shown that $\lambda = 0$ is not optimal:

COROLLARY 2.3. *If the marginal value of the bycatch stock is identical across each fishery* ($\mu_1 = \mu_2$), *then the only unique solution occurs when both stocks are fully harvested.*

Thus each stock is exploited for the entire possible season, and over the course of that season, the entire TAC is removed for the bycatch stock, and maybe for the target stock. The optimal allocation of the bycatch species is thus $\hat{B}^{***} = \overline{T}_1 \hat{n}_1^{***} b(\hat{h}_1^{***})$ to Fishery One, and $S_2 - \hat{B}^{***} = \overline{T}_2 \hat{n}_2^{***} \hat{h}_2^{***}$ to Fishery Two.

2. *Bycatch allocated entirely to fishery two.* When the bycatch is allocated to Fishery Two, Fishery One is shut down since bycatch is essential to production in Fishery One by A.2. The harvest level in Fishery Two is given by (21) (denoted as $\hat{h}_2^*$, to distinguish from the case where both stocks are fully utilized), and the number of entrants solves

$$\hat{n}_2^* = S_2 / \overline{T}_2 \hat{h}_2^*. \tag{24}$$

3. *Bycatch allocated entirely to fishery one.* If $\mu_1 > \mu_2$, then all of the bycatch species TAC is allocated to Fishery One. Since $\mu_1 > 0$ it implies that the bycatch TAC constraint is binding for Fishery One. Thus, unless $S_2/S_1 = b/\hat{h}_1^{**}$, where $\hat{h}_1^{**}$ solves (17), $\lambda = 0$. Thus the solution is given by $\hat{h}_1^{**}$ solving (17) and the number of entrants is given by

$$\hat{n}_1^{**} = S_2 / \overline{T}_1 b(\hat{h}_2^{**}). \tag{25}$$

4. OPEN ACCESS EQUILIBRIA

Under open access each entrant chooses a harvest rate to maximize profits, but entry drives economic profits to zero. Thus

$$\pi_1(h_{1j}) + \delta P_2 b(h_{1j}) = k_1/T_1, \quad \text{and} \quad \pi_2(h_{2j}) = k_2/T_2, \forall j. \tag{26}$$

The season profits for vessel j in Fishery One depends upon which TAC constraint(s) is (are) binding. If the target species TAC is binding in Fishery One, the season length is $T_1 = S_1/\Sigma_{j=1}^{n_1} h_{1i}$. If the bycatch constraint is binding and $\gamma = 0$, then $T_1 = S_2/\Sigma_{j=1}^{n_1} b(h_{1j})$. If $\gamma = 1$ and the bycatch is allocated on a "rule of capture" basis between the target and bycatch fisheries, then $T_1 = S_2/[\Sigma_{j=1}^{n_1} b(h_{1j}) + \Sigma_{j=1}^{n_2} h_{2j}]$.

A. Only Fishery One Commercially Exploited

1. *TAC for target species binding.* If the target species harvest constraint is binding, then using the season profits (2) with the season length substituted out using (4) as above, the level of harvest which maximizes profits can be shown to satisfy[19]

$$\pi_1'(h_1) + \delta P_2 b'(h_1) = [\pi_1(h_1) + \delta P_2 b(h_1)]/n_1 h_1. \tag{27}$$

[19] Second-order conditions require: $[\pi_1'' + \delta P_2 b''][n_1 h_1]^2 - [\pi_1' + \delta P_2 b']n_i h_1 < 0$. This condition is satisfied by A.2. Similar conditions can be derived for the case where the bycatch TAC constraint is binding.

The term on the right hand side of (26) is the value placed on the stock by individual j. Note that (26) involves n_1, which is endogenous. The open access equilibrium when the target species TAC is binding are the values $\{h_1^\circ, n_1^\circ, T_1^\circ\}$ that solve (26), (27), and (4). Using (4) to eliminate T_1 in (26), and using (26) to eliminate n_1 in (27), gives an expression involving only h_1:

$$\pi_1'(h_1^\circ) + \delta P_2 b'(h_1^\circ) = k_1/S_1. \tag{28}$$

Rewriting (27) in this fashion is convenient in that the comparative statics can be derived simply by totally differentiating (28). In particular, note that $\partial h_1^\circ/\partial\delta = -b'/[\pi_1'' + \delta P_2 b''] > 0$, by A.3. Thus allowing Fishery One to sell bycatch has the expected effect that the harvest rate (and hence, the bycatch rate) is increased. Of course, this also implies that a tax on bycatch equal to P_2 would *reduce* the harvest level. It can also be shown that $\partial h_1^\circ/\partial k_1 > 0$, and $\partial h_1^\circ/\partial S_2 > 0$, and that the equilibrium values of n_1° and T_1° are inversely related to h_1°. In contrast, in the social optimum, T_1 is independent of h_1.

2. *TAC for bycatch binding.* When the bycatch constraint is binding, from (6) the season length is $T_1 = S_2/\Sigma_{h=1}^{n_1} b(h_{1j})$. Thus the harvest level which maximizes profits is

$$\pi_1'(h_1) + \delta P_2 b'(h_1) = \{\beta(h_1)[\pi_1(h_1) + \delta P_2 b'(h_1)]\}/n_1 h_1. \tag{29}$$

Thus (29) and (27) differ by the term β in the numerator of the right-hand side. Recall that $\beta \geq 1$ as $b'' \geq 0$. Thus if $b'' = 0$, then (29) and (27) are identical. That is, if bycatch is a constant proportion of catch, then the optimal harvest level under open access is unchanged by having the bycatch TAC bind instead of the target species TAC. In the social optimum condition (17), the same effect was noted. However, the solution in (17) did not depend upon δP_2. This is not the case in the open access equilibrium (29).

Note also that in (29), h_1 depends upon n_1. The equilibrium $\{h_1^{\circ\circ}, n_1^{\circ\circ}, T_1^{\circ\circ}\}$ must satisfy (29), the zero profit equation (26), and the bycatch TAC constraint (5). Using (5) and (26) to eliminate n_1 in (29), the open access harvest level $h_1^{\circ\circ}$ is given implicitly by:

$$\pi_1'(h_1^{\circ\circ}) + \delta P_2 b'(h_1^{\circ\circ}) = b'(h_1^{\circ\circ})[k_1/S_2], \tag{30}$$

which uniquely solves for $h_1^{\circ\circ}$ by A.3. Again, comparative statics can be conducted on (30) by a total differential approach. Thus, $\partial h_1^{\circ\circ}/\partial\delta > 0$, $\partial h_1^{\circ\circ}/\partial k_1 < 0$, and $\partial h_1^{\circ\circ}/\partial S_2 > 0$. It can also be shown that both $n_1^{\circ\circ}$ and $T_1^{\circ\circ}$ are inversely related to $h_1^{\circ\circ}$.

The solutions in (28) and (30) are compared in Fig. 5. From (28) and (30), it is clear that whether $h_1^{\circ\circ}$ or h_1° holds depends upon whether $b'(h_1)/S_2 \lessgtr 1/S_1$. As in Fig. 3, if $h_1^{\circ\circ} < h_1^\circ < \underline{h}_1^H$, then the target TAC must bind. Conversely, if $\underline{h}_1^L < h_1^{\circ\circ} < h_1^\circ$, then the bycatch constraint is binding. Finally, in the event that $h_1^{\circ\circ} < \underline{h}_1^M < h_1^\circ$, *both* constraints are binding. Let $h_1^{\circ\circ\circ} = \underline{h}_1^M$ denote this solution. Then the zero profit condition (26) determines $T_1^{\circ\circ\circ}$, and either the target or bycatch TAC constraint determines $n_1^{\circ\circ\circ}$. Even though each fisherman fishes at the optimal harvest level, the season length will be too short and the number of entrants too large under open access since an individual fisherman ignores the cost he imposes on other fishermen by his removals of the target and bycatch stocks.

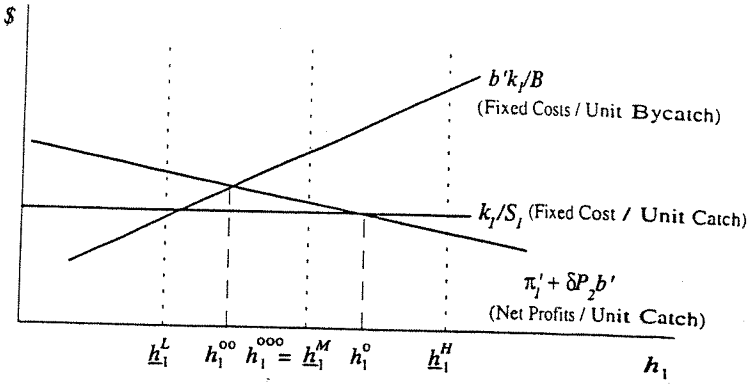

FIG. 5. Open access harvest rate in Fishery One when target TAC is binding and no Fishery Two exists.

B. *Two Fisheries, One TAC Constraint on the Bycatch Species*

Now suppose that the bycatch species can be used either as bycatch or as a target species, and the allocation is decided by the "rule of capture." Each fishery shuts down once the bycatch TAC is taken. Thus, $T_1 = T_2 \leq \min(\overline{T}_1, \overline{T}_2)$, which is given by:

$$T_1 = T_2 \equiv T = S_2/[n_1 b(h_1) + n_2 h_2]. \tag{31}$$

A representative vessel in Fishery One chooses harvest level h_1 to maximize (2) given the season length is determined by (31). The harvest level which maximizes profits to a vessel in Fishery One and Fishery Two are, respectively,

$$\pi_1'(h_1) + \delta P_2 b'(h_1) = \{[\pi_1(h_1) + \delta P_2 b(h_1)] b'(h_1)\}/[n_1 b(h_1) + n_2 h_2], \tag{32}$$

$$\pi_2'(h_2) = \pi_2(h_2)/[n_1 b(h_1) + n_2 h_2]. \tag{33}$$

However, using the zero profit condition (26), and the equilibrium harvest, effort, and season length levels given by (31)–(33), the following can be shown:

PROPOSITION 4. *Management of the bycatch as a single stock is unstable if the bycatch constraint is binding for Fishery One. Either there does not exist a unique solution in terms of n_1 and n_2, or there does not exist a solution in h_1 and h_2.*

Proposition 4 suggests that an open access fishery which allocates bycatch by the rule of capture will be unstable. Thus, once a bycatch species becomes commercially viable, even if each fishery remains open access, the bycatch species is explicitly allocated between the bycatch user group (Fishery One) and the target user group (Fishery Two). To do otherwise would induce multiple equilibria, meaning that the manager would be unable to predict the economic consequences of their actions.

C. *Two Fisheries, Separate TAC Constraints on the Bycatch Species*

However, as we shall see in this section, the allocation may be contentious.

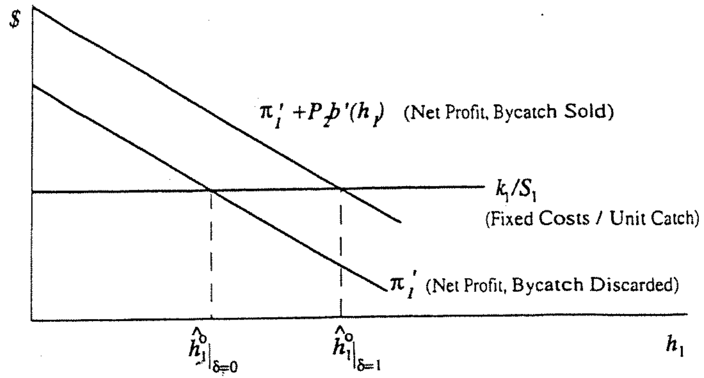

FIG. 6. Effect of allowing Fishery One to sell bycatch under open access when target TAC is binding and no Fishery Two exists.

COROLLARY 4.1. *If the bycatch constraint is binding, there does not exist an open access allocation* $(B, S_2 - B)$ *such that the season lengths are identical* $(T_1 = T_2)$ *and each fishery has an identical marginal valuation of the bycatch stock* $(\pi_1' + \delta P_2 b' = \pi_2')$ *at the vessel level.*

Corollary 4.1 shows that even if the manager is able to set a bycatch allocation such that a unit of the bycatch has equal value to each fishery, one of the fisheries will close before the other, creating an incentive for fishermen in the fishery with the shorter season to request a larger allocation. If the manager sets the allocation such that $T_1 = T_2$, then fishermen in one fishery or the other will have a higher value at the margin for the bycatch, creating an incentive for fishermen in the fishery with the higher marginal valuation of the bycatch to request a larger allocation. In either case, the fishery manager will face pressures to reallocate the bycatch, and ultimately, to raise TAC limits.

D. Effect of Prohibiting Sales of Bycatch by Fishery One

In the North Pacific groundfish fisheries, bycatch of halibut, salmon, and crab cannot be sold, although this is not true for all fisheries.[20] In Fig. 6, the equilibrium (28) is shown for the case where the target species TAC is binding for Fishery One. When the bycatch is able to be sold ($\delta = 1$), both (28) and (30) show that the harvest level per vessel is higher than if it cannot be sold ($\delta = 0$). The total bycatch removals in Fishery One are $H_b = T_1 n_1 b(h_1) = S_1 b(h_1)/h_1$, where the second equality is obtained by using the zero profit condition (26) and the target TAC constraint (4). Thus,

PROPOSITION 5. *If the target species TAC constraint is binding for Fishery One, prohibiting Fishery One from selling bycatch reduces the total bycatch removed by Fishery One.*

This helps to explain the prohibition on selling bycatch by Fishery One, even though it is socially inefficient (see Proposition 1). If Fishery One can sell its bycatch, it decreases their incentive to reduce bycatch. This causes a larger

[20] An anonymous referee reports that in the Mid-Atlantic scallop fishery, there is substantial bycatch of summer flounder, black sea bass, lobster, and monkfish, and that these species are all sold.

bycatch, which decreases the take available to the second fleet. Prohibiting the first fleet from selling its bycatch therefore increases the number of vessels who can participate in the second fishery (cf. [12, 14]).[21]

The prohibition on Fishery One from selling bycatch supports the position that bycatch is morally wrong. This allows Fishery Two (or whoever gets value from the bycatch) to maintain the higher moral ground in the bycatch debate, which is very useful in the political arena. A similar result has been observed by Hahn [10, p. 30] with respect to the position taken by environmentalists against marketable pollution permits. In each case, a prohibition on selling the bycatch or pollution reduces the legitimacy of the claim by the bycatch fleet or the polluter, and in both cases, a prohibition on trades reduces social welfare. Thus in each case, the prohibition has to do with one group wishing to prevent transfers to the other group.

5. RATIONALIZING BYCATCH WITH TRANSFERABLE QUOTAS

Suppose that managers rationalize the fishery using an individual transferable quota system.[22] Assume that there are *two* quota systems, one for the target species, and one for the bycatch species. Indeed, two quota systems are necessary for the system to fully rationalize the bycatch problem for all possible outcomes. Since there are no congestion or stock externalities, an ITQ system will be capable of generating the social optimum [6]. This result is extended here to the case of bycatch, but only if there exists a competitive quota market for whichever species is the binding constraint, and only if taking the bycatch imposes no lost existence value.

A. Both Species Commercially Harvested

Let m_1 and m_2 be the market clearing competitive season (rental) prices for quotas of the target and bycatch species, respectively. Assume each vessel j in Fishery One which participated in the open access fishery is given an identical quota for the target and bycatch species, q_{1j}^1 and q_{1j}^2, and that each vessel in Fishery Two which participated in the open access fishery is given a quota of the bycatch species q_{2j}^2. Assume also that the TAC for each fishery is completely allocated as quota shares. Let z_{1j}^1 and z_{1j}^2 denote purchases ($z_{ij}^k > 0$) or sales ($z_{1j}^k < 0$) of the quotas of the target ($k = 1$) and bycatch ($k = 2$) species, respectively, at the market prices m_i by vessel j in Fishery One, and let z_{2j}^2 denote the quantity of bycatch quotas bought or sold by vessel j in Fishery Two.

As each vessel is free to fish over the entire possible season $(0, \bar{T}_1)$ or $(0, \bar{T}_2)$, the season lengths are constrained by the upper bounds, $\bar{T}_1$ and $\bar{T}_2$ as in (6). In addition, for an individual vessel the harvest of the target and bycatch species is limited by his initial quota allocation net of purchases or sales

$$q_{1j}^1 + z_{1j}^1 \geq T_{1j} h_{1j}, \qquad j = 1, \ldots, N_1, \tag{34}$$

[21] It can also be shown that if the bycatch TAC binds for Fishery One, the prohibition on selling bycatch *increases* the total harvest of the target species.

[22] See [1, 2, 6, 14] for discussions of ITQ systems.

$$q_{1j}^2 + z_{1j}^2 \geq T_{1j}b(h_{1j}), \qquad j = 1,\ldots, N_1, \tag{35}$$

$$q_{2j}^2 + z_{2j}^2 \geq T_{2j}h_{2j}, \qquad j = 1,\ldots, N_2. \tag{36}$$

The objective of a vessel in Fishery One is to choose $\{h_{1j}, z_{1j}^1, z_{1j}^2, T_{1j}\}$ to maximize

$$v_{1j} = T_{1j}[\pi_{1j} + \delta P_2 b] - k_1 - m_1 z_{1j}^1 - m_2 z_{11j}^2, \qquad j = 1,\ldots, N_1, \tag{37}$$

subject to (6), (34), and (35). Similarly, the objective of a vessel in Fishery Two is to choose $\{h_{2j}, z_{2j}^2, T_{2j}\}$ to maximize

$$v_{2j} = T_{2j}\pi_{2j} - k_2 - m_2 z_{2j}^2, \qquad j = 1,\ldots, N_2, \tag{38}$$

subject to (6) and (36).

Finally, to participate in the fishery a vessel owner must earn at least as much from entering the fishery as from selling his quotas, i.e.,

$$T_{1j}[\pi_{1j} + \delta P_2 b] - k_1 \geq q_{1j}^1 m_1 + q_{1j}^2 m_2, \tag{39}$$

$$T_{2j}\pi_{2j} - k_{2j} \geq q_{2j}^2 m_2. \tag{40}$$

Let λ_j, μ_{1j}, τ_{1j}, μ_{2j}, and τ_j denote the multipliers for the constraints in (34)–(36) and (6), with the notation for λ and μ identical to that used in the Lagrangian for (9). Then the first-order conditions for vessel j in Fishery One include the zero profits equation (39), and the season length constraints (6), the quota constraints (34) and (35), and (dropping the vessel notation since each fishermen is identical)

$$\pi_1'(h_1) + \delta P_2 b'(h_1) - \lambda - \mu_1 b'(h_1) = 0, \tag{41}$$

$$m_1 = \lambda_1, \quad m_2 = \mu_1, \tag{42}$$

$$\pi_1(h_1) + \delta P_2 b(h_1) - \lambda_1 h_1 - \mu_1 b(h_1) = \tau_1. \tag{43}$$

Similarly, for vessel j in Fishery Two, the first-order necessary conditions include the season length constraint (6), the quota constraint (36), the zero profits condition (40), and (dropping the vessel subscripts)[23]

$$\pi_2'(h_2) - \mu_2 h_2 = 0, \tag{44}$$

$$m_2 = \mu_2, \tag{45}$$

$$\pi_2(h_2) - \mu_2 h_2 = \tau_2^2, \tag{46}$$

Equations (43) and (46) plus (39) and (40), respectively, can be rearranged to show that $T_{1i} = \bar{T}_1$ if $m_1 > 0$ and that $T_{1i} = \bar{T}_2$ if $m_2 > 0$. Furthermore, $T_{2j} = \bar{T}_2$ for all j. From (42) and (45), $\lambda_{1i} = m_1$, and $\mu_{1j} = \mu_{2j} = m_2$. Thus to each individual the shadow value of additional units of the two stocks equals the market

[23] The second-order conditions are satisfied by the Arrow–Enthoven sufficiency theorem for Kuhn–Tucker problems, since the objective function is quasi-concave in (T_{ij}, h_{ij}, z_{ij}), the constraints are quasi-convex in (T_{ij}, h_{ij}, z_{ij}), and the second-order partial differentials of the objective function exist at the solution.

price of those stocks. The only values of m_1 and m_2 which hold in the system of equations (34)–(36) and (39)–(46) are $m_1 = \lambda$ and $m_2 = \mu$, where λ and μ are the multipliers in the system of Eqs. (10)–(15). (Note, however that m_1 may equal zero.) Therefore:

PROPOSITION 6. *If the bycatch species has no existence value, a competitive individual transferable quota system is capable of maximizing social welfare, as defined by* (8), *but there must exist a market for both quotas.*

Both quotas are traded, since individuals in Fishery One will either be buying or selling bycatch quotas. Note also that the following corollary to Proposition 1 holds:

COROLLARY 1.1. *While the ITQ system is capable of maximizing the constrained social welfare problem where Fishery One is restricted from selling bycatch, there are gains from trade by allowing Fishery One to sell the bycatch.*

B. Bycatch Has Existence Value

Suppose that the bycatch species has no commercial value, but it does have existence value. For example, sea lions are occasionally taken as bycatch in the Bering Sea pollock fishery and the tuna fishery has bycatch of dolphins. Since the bycatch has no commercial value, it is not harvested. To the social planner, this corresponds to the case where $\delta = -1$ and $\gamma = 0$. Thus the solution involves Eqs. (10), (12), (14), plus the constraints (4) and (6). However, $\delta = 0$ to the commercial vessel in Fishery One with tradable quotas for both the pollock and the sea lions, since he cannot sell the bycatch. Thus:

PROPOSITION 7. *An ITQ system will not be sufficient to maximize social welfare (defined by* (9)) *unless there also exists a charge (e.g., a user fee or a tax) of P_2 for each unit of bycatch taken.*

The problem is that even if $m_2 > 0$ in this case, m_2 only reflects the scarcity of the bycatch TAC to Fishery One. It does not reflect the full social cost of taking additional units of bycatch.

C. Using Taxes Instead of ITQs

There is nothing unique about the ITQ system from a pure efficiency viewpoint. Indeed, the prices m_1 and m_2 (along with a tax of P_2 if the bycatch has existence value) could be used as taxes instead, and the same allocation would be achieved. However, a tax system would be much less politically viable since the tax would charge vessels for use of every unit of harvest and bycatch, while a tradable quota system would only charge them explicitly once they have used up their initial quota (e.g., [7]).

ITQs will not produce an efficient allocation if production externalities are present [6]. A tax system might be thought to be less sensitive to this criticism. However, for either a tax or an ITQ system to remedy the production externalities, there must be additional markets or taxes. For example, if there are congestion externalities present, then either an entry fee or a tradable limited entry permit would be necessary in addition to the taxes or tradable quotas on harvesting.

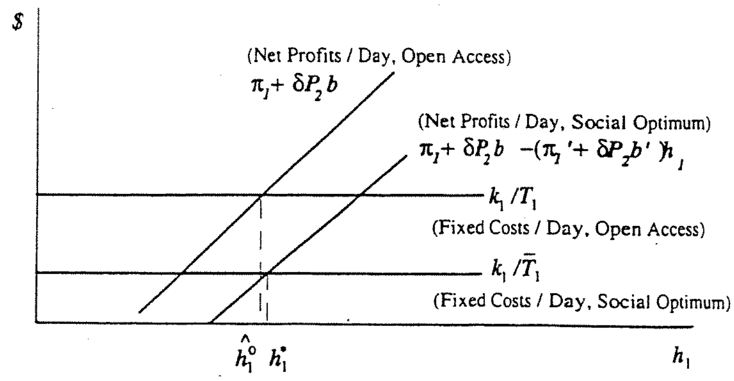

FIG. 7. Optimal and open access harvest rates for Fishery One, bycatch not commercial harvested.

D. Will Vessels Fish "Cleaner"?

When the bycatch problem in the North Pacific groundfish fishery began to become quite serious in the late 1980s, managers were surprised at the large quantities of target species TAC left unharvested. "[We] assumed the fleet would modify its behavior when faced with bycatch caps and closures," said one management official.[24] One question that remains with rationalization is will it have discernible effects in regard to lowering the ratio of bycatch to the target species? That is, will vessels fish "cleaner"?

Figure 7 shows the relationship between the harvest rate under open access and under the social optimum. Figure 7 is based on the zero profit condition (26) for open access and the equilibrium condition for the harvest rate when only Fishery One is active and the target TAC is binding, given in (16), for the social optimum. For open access, the season length is shorter, so $k_1/T_1 > k_1/\bar{T}_1$. However, since $-(\pi_1' + \delta P_2 b')h_1 < 0$, the net profits per day for the social optimum lies below the net profits per day for the open access. Thus, the two effects are of opposite sign, and it is ambiguous whether an individual's harvest rate is higher under open access than under ITQs. Hence:

PROPOSITION 8. *Fishery One will have lower aggregate bycatch if it is rationalized, but this will be due to the reduction in the number of vessels. Bycatch per vessel may increase or decrease.*

6. DISCUSSION AND CONCLUSIONS

This paper examined a stylized economic model of the fisheries bycatch problem. It was assumed that there are no production externalities (e.g., [6]); vessels within each fishery are homogeneous; prices are not affected by changes in harvest rates or total harvest levels; the target fishery is treated as a single species fishery [24]; there are no multiple grades or high grading problems [1, 3]; and the bycatch rate depends only on the harvest rate of the target species. All of these assumptions are

[24] National Marine Fishery Service regional director Steve Pennoyer (quoted in [23, June 1990, p. 64]).

over-simplifications of the environments in which managers face the bycatch problem.

Even within this simplified framework, it has been shown that open access solutions under the "rule of capture" allocation may be unstable. When bycatch is explicitly allocated between different uses, the harvest rate under open access may be optimal, but the number of entrants will be too large. These results should give policy makers an added incentive to work toward some form of rationalization. Unfortunately, this paper has given reason to be cautious about how the bycatch problem is integrated into the general problem of rationalizing fisheries. Here, the correct incentives can be given to vessels only by creating transferable quota systems for *both* the target and bycatch species which are tradable between fisheries. Even this will not be sufficient if there are externalities beyond the simple common properties externality due to lack of ownership. In particular, if the bycatch species has existence value an ITQ system will not be sufficient to eliminate the external cost of bycatch removals. Similar conclusions would be reached if there also existed production externalities.

The model in this paper has focused entirely on the in-season problem. Most of the fisheries economics literature has been concerned with optimization over an infinite planning horizon. To fully appreciate the subtleties of the problem, the model proposed here would have to be placed inside of a model such as proposed by McKelvey [16]. In this context, the present model shows that for a given technology, there may be many instances where the joint TAC constraints for the bycatch and target species are incompatible in the sense that both will not be fully harvested. This result can occur under a rationalized system as well as under an open access system. It is not surprising that in the face of such short-term pressures, managers have sought to solve the problem with a command and control focus on technology. However, it is not clear that the gear restrictions are necessarily good economic policy. Even if such restrictions were good economic policy, a command and control system is probably the least likely means of finding such a technology. Furthermore, as is shown in Figs. 3 and 5, the open access harvest rate per vessel may well equal the social optimal harvest rate (for a given technology) for a range of bycatch ratios. Just because the observed bycatch ratio equals the allowable bycatch ratio does not mean that rents are being maximized.

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