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Economies of Scope in the Management of Multiple Species Fisheries

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Abstract. This paper considers the problem of multiple-species fishery management when targeting individual species is costly and at-sea discards of fish by fishermen are unobserved by the regulator. A dynamic model is developed to balance the ecological interdependencies among multiple fish species, and the technological interdependence which captures costly targeting. Stock conditions, ecosystem interaction, technological specification, and relative prices under which at sea discards are acute are identified. Three regulatory regimes, species-specific harvest quotas, landing taxes, and revenue quotas, are contrasted against a hypothetical sole owner problem. An optimal plan under any of these regimes precludes discarding. For both very low and very high degrees of technological interdependence, first best welfare is close to that achieved through regulation. In general, landing taxes welfare dominate species-specific quota regulation; a revenue quota fares the worst.

JEL Classification: Q2
Keywords: scope economies, multiple species fishery management, costly targeting

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1. Introduction

The Food and Agricultural Organization (FAO) estimates that 8% of the worldwide fish harvest is of non-target species, also called bycatch, that is subsequently discarded at sea (FAO, 2005). Even more alarmingly, wasteful discards in US fisheries are estimated to be as high as 22% of the total harvest (Harrington et al., 2005). By catch problems in US fisheries have led to the introduction of new national standard 9 of the Magnuson-Stevens Fishery Conservation and Management Act which states:[1] *"Conservation and management measures shall, to the extent practicable, (A) minimize bycatch and (B) to the extent bycatch cannot be avoided, minimize the mortality of such bycatch."*

As a follow up, the US National Oceanic and Atmospheric Administration's National Marine Fisheries Service launched a National Bycatch Strategy in March 2003, which includes a standardized bycatch reporting program, a bycatch reduction engineering program, on-board observer programs to monitor bycatch, and a host of regulatory actions (gear restrictions, area closures, bycatch quotas and trip limits) designed to reduce discards of non-target species (Benaka and Dobrzynski, 2004). The bycatch strategy however is tilted heavily towards policing at-sea fishing practices, which is reflected by the fact that approximately two-thirds of the 2004 Bycatch Strategy budget was allocated to onboard observer programs (Benaka and Tanya, 2004).

Recent statistics however raise serious doubts regarding the success of observer program in stemming the bycatch problem. For example, in the US west coast ground fish fishery, approximately 66.8% of the catch of "overfished" species – the stocks that managers have been trying to rebuild – was discarded into the sea in 2004 (Hastie and

[1] National standard 9 was introduced in the 1996 reauthorization of the Magnuson-Stevens Fishery Conservation and Management Act, which regulates fisheries within the US exclusive economic zone.

Bellman, 2006).[2] Given that the fishermen in this example could legally keep only one-third of their catch, their at-sea "wasteful" behavior begs for an understanding of their incentives within the economic and the regulatory environment they face. Understanding this behavior is essential for the design of appropriate bycatch management policies. However, the bioeconomics literature offers little guidance for *optimal* (bycatch) management in *multiple-species* fisheries. This paper is a step in this direction.

One reason that bycatch of non-target species is widespread is that the gear used to capture fish (e.g., nets, baited hooks, fish traps) intercepts multiple species unless fishermen actively avoid non-target species. More specifically, by employing different gear types at different locations, times of the year, times of the day, and depths, fishermen can *target* the mix of species that is harvested.[3] These actions however may incur substantial costs that also depends on the absolute as well as the relative abundance of various species in the sea.

Contrary to the above observed practice, past academic research on multiple species fisheries management either assumes cross-species cost independence (i.e., costless targeting of individual species) or, on the other extreme, unrealistically assumes that fishermen passively harvest multiple species in fixed-proportions to their relative abundance

[2] The "overfished' species are: Lingcod, Widow Rockfish, Pacific Ocean Perch, Darkblotch Rockfish, and Yelloweye Rockfish. On the other hand, for species that did not hit the regulatory caps, such as Dover Sole, Shortspine Thornyhead, Longspine Thornyhead, Sablefish, and Petrale Sole, the average discard is approximately 10%, which can be termed as idiosyncratic rather than systemic discards. Harrington et al., (2005) estimate the ratio of discards to landings in 27 major US fisheries. In five fisheries this ratio exceeds 1. In the Gulf of Mexico shrimp fishery discard/landings is 4.56.

[3] Commercial reef fish fishermen in the Gulf of Mexico target members of the reef fish complex by adjusting the location, timing and depth of fishing (Donald Waters and David Walker, personal communication, 2004). Pacific halibut longline fishermen can avoid sablefish by choosing particular sites, fishing in deeper water, and using larger hooks with salmon for bait instead of squid (Arne Lee and Paul Clampitt, personal communication, 2006). See Branch (2004) for further discussion and evidence of targeting behavior in Canadian and US west coast groundfish fisheries.

in the sea (i.e., targeting costs are infinite). These studies then derive optimal *steady state* harvest rules in competing species or predator and prey fisheries and show how these rules respond to various specifications of ecological interaction and/or to other parametric changes in the model (May et al., 1979; Clark, 1990; Flaaten 1991, 1998; Boyce, 1996; and Brown et al., 2005). Moreover, the static nature of these results are of not much use to the regulators interested in optimal rebuilding of depleted stocks, often due to the bycatch problem. By definition, rebuilding plans can only be examined in dynamic frameworks.[4]

To address these issues, we extend the multiple-species bioeconomics literature in two directions. First, we dispense with the assumptions of technical independence and fixed proportions across harvested species. In practice, a fisherman who targets one of several fish species must undertake costly actions to search out concentrations of the target species and/or take costly actions to avoid intercepting non-target species. To capture the unique form of economies of scope in fisheries, we introduce a technology that links the harvest of multiple species to the composition of the fish stock. Costs of harvesting rise as the targeted mix of species diverges from the mix of stocks in the sea.[5] As is standard, our technology also features stock effects such that the resources required to harvest a unit of fish decline when stocks are more abundant. Technical interactions among multiple species is an important feature of the harvesting technology. While "public" factors of production e.g., boats, gear, and labor create scope economies in

[4]The bioeconomics literature is largely silent on the determination of optimal approaches to the multiple-species steady states. Clark (1990) suggests that a “practical approach path” be chosen. Our analysis finds that identifying a practical approach to the steady state is not trivial.

[5]Turner (1995, 1997) recognized that fishermen can influence the mix of harvested species in a multiple-species fishery, but did not consider the role of stock abundance or its implications for dynamic management.

the standard manner, the product mix in our technology is also dictated by the relative abundance of various species.[6]

Second, we solve a *dynamic* multiple-species management problem in a model fishery that combines the above inter-species technological interactions with a Gause model of inter- and intraspecies ecological interaction (See Gause, 1935; Pianka, 1974). The harvest policies are dictated by scope economies implicit in the harvesting technology as well as the ecological interactions among multiple fish species. The novelty here is that the manager's harvest choices not only weigh current harvest revenues against future stock benefits, but also affect the future scope economies inherent in the harvesting technology.

Important new insights for the management of multiple species fisheries emerge. We show that at sea discards by fishermen, a hidden action problem, arise when the individual-species harvest goal set by the regulator diverges sufficiently from the mix of stocks in the sea. In such cases, fishermen can avoid targeting costs required to meet the regulator's harvest goal and simply discard any overages.

We focus attention on the manager's problem of regulating the harvest of multiple fish species under a costly targeting technology. We study three alternative regulatory schemes, namely, species-specific quotas, landings taxes, and a revenue quota introduced by Turner (1995); the first two are susceptible to discards, whereas the third, by design, rules out discards. We first identify the initial stock conditions, regulated harvest targets, and dockside fish prices under which fishermen have no incentives to discard,

[6] Public factors, once aquired for use in production of a good, are available costlessly for use in the production of other goods. Subadditive fixed costs refer to a situation where the sum of fixed costs required to produce multiple goods in separate firms exceeds the fixed cost requirement to produce the same bundle within a single firm (see Baumol, et al. 1982). Squires (1987), and others, study the effects of "standard" scope economies in fisheries in fisheries management.

i.e., we identify harvests that are *implementable* in a hidden action framework. We first show that the optimal management policies within each regulatory regime belong to the corresponding set of implementable regulated harvests. We then compute the optimal management policies by constraining the manager to choose from the set of implementable harvest targets only. As a result, there are no discards under "second-best" policies.

Our results show that, in general, management constraints tend to be most pronounced, and thus the potential for discarding most severe, when the mix of existing stock and the mix of target harvests diverge. Therefore, the second-best harvest policies trade off an ecologically desirable harvest that maximizes yields against the mix that minimizes harvesting costs. The yield-target cost trade-off in our model leads to harvest policies that substantially depart from conventional conservation principles. Consider for example a fishery with two competing species. Suppose that one of the species has been overfished while the other is abundant. Ecological considerations, and conservation principles, suggest that to rebuild the stock of the overfished species its harvest must be substantially reduced or stopped altogether, while to mitigate interspecies competition the harvest of the healthy stock must be increased. Our results show that a mismatch between target catch shares set by the regulator and the shares of each species' stock can undermine this rebuilding strategy. If the target catch of the abundant species is set too high, or the target catch of the depleted species is set too low, fishing mortality of the overfished stock can remain high. The mismatch between the target catch and available stock introduces an incentives to intercept and discard the overfished species at sea.

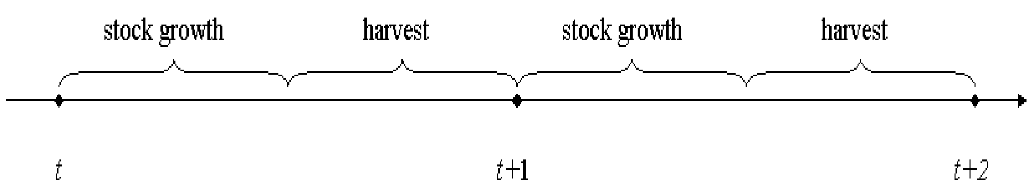
Optimal rebuilding may instead require only a modest reduction in the harvest of depleted stock, which allows a higher harvest of the abundant species and reduces inter-species ecological competition. Thus, the depleted stock can be rebuilt by manipulating ecological interactions rather than through costly reductions in harvest levels and wasteful at-sea discarding. As the optimal rebuilding plan depends on the flexibility allowed by a particular regulatory regime, for each regime we compute second-best plans that simultaneously balance the underlying ecological and technical trade-offs.

It is worth emphasizing that none of the regulatory regimes we consider can manage the fishery as a hypothetical sole owner would like to do. While fishermen's harvesting choices do not internalize their impact on future stock abundance, a sole-owner in contrast maximizes the present value of the fishery, which must link current actions with those in the future. In particular, the sole owner may sometimes choose harvest targets that under decentralized regulation lead to discards by fishermen. In the absence of discarding and the problem of harvest slacks, i.e., the case where fishermen do not choose to harvest less than the regulator's target, the sole owner harvest targets can be implemented simply by setting species-specific quotas at the optimal harvest levels. But such quotas may not be implementable now as the manager faces a hidden-action (unobservable discarding) problem. As a result, all three regulatory regimes are welfare-dominated by the optimal plans of a sole owner. Ranking the three, we show that landing taxes welfare dominate species-specific quotas while value-based quotas fare the worst.

The rest of the paper is organized as follows. Section 2 introduces the costly targeting technology and presents the dynamic model of the multi-species fishery. Section 3 characterizes fishermen's incentive to discard under alternative regulatory regimes. Analytical solutions to the sole owner's problem, the constrained-management problem, and their welfare rankings are provided in section 4. Regime-specific numerical results are presented in section 5. Section 6 provides concluding remarks and discusses some implications of the model for the design of multiple species fisheries management policy.

2. The environment

We consider a fishery that is exploited over an infinite number of discrete time periods. To simplify the analysis each period is divided into a stock growth phase and a harvesting phase. No harvesting occurs during the growth phase, and no growth occurs during the harvest phase. Thus, stock abundance is assumed to be fixed during the harvesting phase. This assumption allows us to treat the stock abundance simply as a constraint on the harvest possibilities. The timing of events is as follows:



There are two sources of species interaction in our model. First, harvesting costs will not only depend on the quantity of harvested species and their stock abundance, but also on the mix of harvested species relative to the mix of stock abundance. The latter captures the real world feature that intercepting a *mix* of species that is substantially different than their relative stock abundance requires extra efforts and is therefore costlier. Second, ecological interdependence occurs among individual species that results from competition for scarce habitat, and/or predation among fish species.

We first discuss the harvest technology. Presentation of the stock growth model follows.

2.1. Harvesting and discarding. Consider an arbitrary harvesting phase. Let $x \in R_+^m$ denote the stock of m species available at the beginning of the harvest phase and let $z \in R_+^n$ denote the vector of n inputs utilized during harvesting. The inputs in z include, for example, labor, capital, bait, and fuel. The harvest (catch) vector is denoted by $h \in R_+^m$. For any z and x, we define the *harvest possibilities frontier* by a multi-valued correspondence $H(z,x) : R_+^m \times R_+^n \to R_+^m$; $h \in H(z,x)$ implies that given x, input z is capable of intercepting the catch h for sale in downstream markets. For a given z and x, we denote $H(z,x)$ simply by H; it is assumed to be closed, bounded, and nonempty for $z > 0$, $x > 0$. Furthermore, $H(z,x) \supseteq H(\eta z, x)$ and $H(z,x) \supseteq H(z, \eta x)$ for $\eta \geq 1$. That is, the harvest frontier expands under proportional increases in inputs and/or the stock abundance of all species.

For any given fishing technology and the set of inputs employed, harvest composition in a multi-species fishery crucially depends on the composition of available fish stock. As a result, targeting any single species entails *costly avoidance* of intercepting other species. These costs in turn depend on the degree of targeting flexibility that the available technology permits. As in Turner (1995, 1997), costly targeting of individual species is modeled as weak output disposability. Figure 1 demonstrates this property for a two-species fishery.

Panel (a) in Figure 1 depicts three examples of harvest frontiers, denoted by superscripts $1, 2$, and 3. The three frontiers in panel (a) employ a common input bundle, z, and are conditional on common stock abundance, x. Stock abundance in panel (b) differs and is discussed below. Each frontier exhibits weak output disposability but differs in terms of the *flexibility* with which the mix of species can be adjusted by the fisherman. It should be noted that there is no reason to expect that, for a given input bundle, the

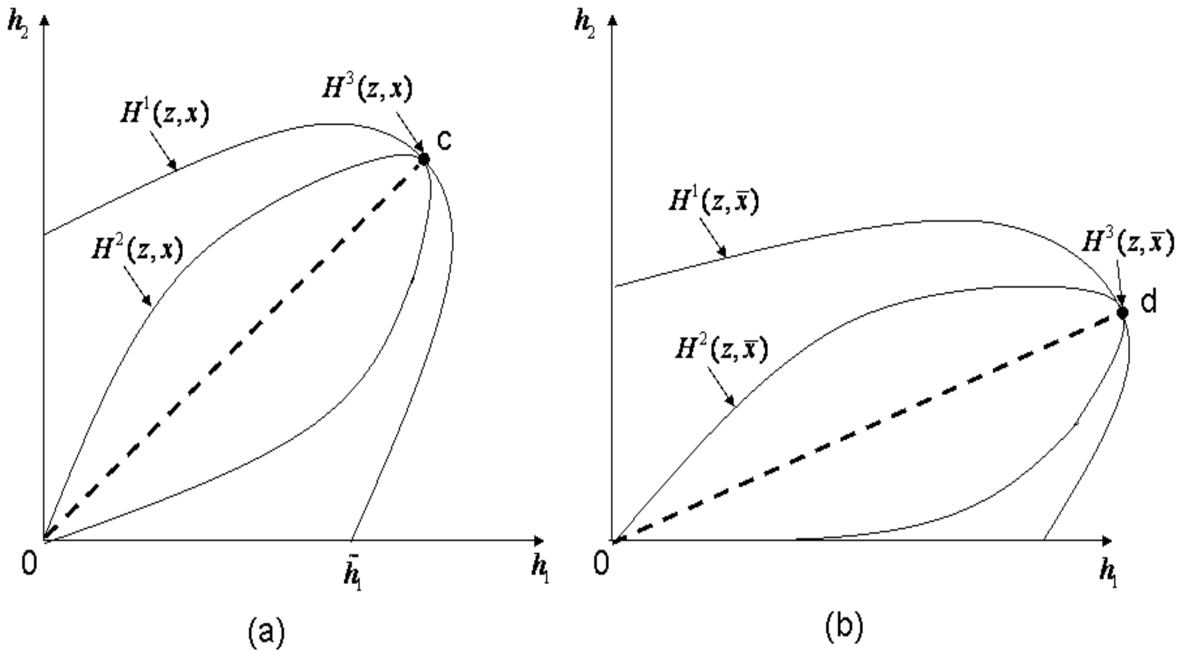


Figure 1: Multiple species harvest frontier under costly targeting technologies.

harvest frontiers under technologies offering different flexibility will be tangential to one another (point c in panel (a), point d in panel (b)). The frontiers in the figure are special examples only for expositional convenience.

Under technology 1, as exhibited by H^1, a complete specialization, i.e., zero catch of one species and strictly positive catch on the other is possible but costly. Since the input vector is fixed, the cost of targeting is reflected as foregone harvest. Here, a fisherman who only wants to harvest species 1 fish (and chooses $h_2 = 0$) can harvest at most $\widetilde{h}_1$. Under diversified harvesting however the catch of both species can increase to point c. Intuitively, specialization is costly because resources are used in searching for high concentrations of one particular species and/or in ensuring that the other species is not intercepted by the gear.

Within sets H^2 and H^3 zero harvest of one species is possible only if the harvest of the other species is also zero. Thus, complete specialization is ruled out. Notice that targeting under H^2 is generally more costly than under H^1. Finally, under the *fixed-proportions* technology, shown by H^3, harvest ratios are pre-determined; any attempt to cut back on the catch of one species will proportionally reduce the catch of the other species.

The single-species bioeconomics literature treats the fish stock as a normal input in the harvest technology—harvest is a non-decreasing function of stock abundance (see Clark, 1990; Smith 1968). With multiple species, however, the effect of stock increases on the harvest frontier is less clear. If no steps are taken to target any one species (or avoid the other), it is reasonable to expect that the mix of intercepted species will be proportional to the composition of the stock (Mayo et al., 1981; Murawski, 1984). Specifically, given fish stock x, a catch vector h with individual species shares $h_i/\sum_{i=1}^{m} h_i$ in proportion to their stock shares $x_i/\sum_{i=1}^{m} x_i$ is likely to require fewer inputs than a catch vector with shares that differ from the share of individual species stock abundance. As a result, the shape of the harvest possibilities set will depend on both absolute and relative abundance of the stock of individual species.

To illustrate the implications of costly targeting, suppose the share of species i in the harvest vector h is fixed in proportion to the initial stock composition and the stock vector changes to $\widehat{x}$ such that $\widehat{x}_i = x_i$ and $\widehat{x}_j > x_j$ for all $j \neq i$. It is now possible that more targeting inputs will be required to avoid intercepting the more abundant species $j \neq i$ so that the share of species i in the catch remains at the initially fixed level. This implies that, contrary to the assumption in the single-species literature, monotonicity in the stock does not hold globally. For a two-species case, Panel (b) of Figure 1 illustrates the hypothesized effect of an increase in the relative abundance of the species 1 stock. H^1, $H^2$and H^3 in panel (b) are conditional on the same input bundle z (unchanged from panel (a)) but new stock level $\widetilde{x}$. The relationship between x and $\widetilde{x}$ satisfies $\widetilde{x}_1/\widetilde{x}_2 > x_1/x_2$. On each harvest frontier, feasible species 1 harvest is increased relative to species 2, reflecting the increase in the species 1 stock. Notice that under the fixed-proportions technology, the mix of harvests H^3 simply rotates clockwise.

The discard set. If a fisherman chooses to discard fish at sea, the rest of the catch that is *landed* will be less than h. We assume that the act of discarding fish at sea is costless and that the mortality rate of discarded fish is 100%. As a result, the catch equals the fishing mortality.[7]

In order to consider the incentive to discard fish at sea, we first define the *efficient* harvest frontier as

$$H^e = \{h \in H(z,x) \quad \ni \quad \widetilde{h} \geq h;\ \tilde{h} \neq h \Rightarrow \ \widetilde{h} \notin H(z,x)\}.$$

Thus, if $h \in H^e$ it is not possible to increase the catch of any individual species without reducing the catch of some other species.

Consider the harvest frontier $H(z,x)$ in Figure 2. The efficient frontier H^e is shown as the segment bc. The catch vectors in H^e satisfy the condition that the marginal rate of product transformation between any two species is non-positive. In contrast, for all

[7] Arnason (1994) introduces a model in which discarding fish at sea adds costs. It is true that sorting a multiple species catch can be costly. However, since fish is marketed by species (and sometimes by weight class), the catch must be sorted regardless of whether it is landed or discarded. Discarding fish after sorting involves tossing it overboard rather than into a vessel fish hold, which would seem to add little additional cost. In this context, our assumption of costless discarding does not seem unrealistic.

other points in $H(z,x)$ that are not in H^e the rate of product transformation between two species is positive, i.e., $RPT_{ij} = \partial h_i / \partial h_j > 0$, $i \neq j$, and h_i, h_j.

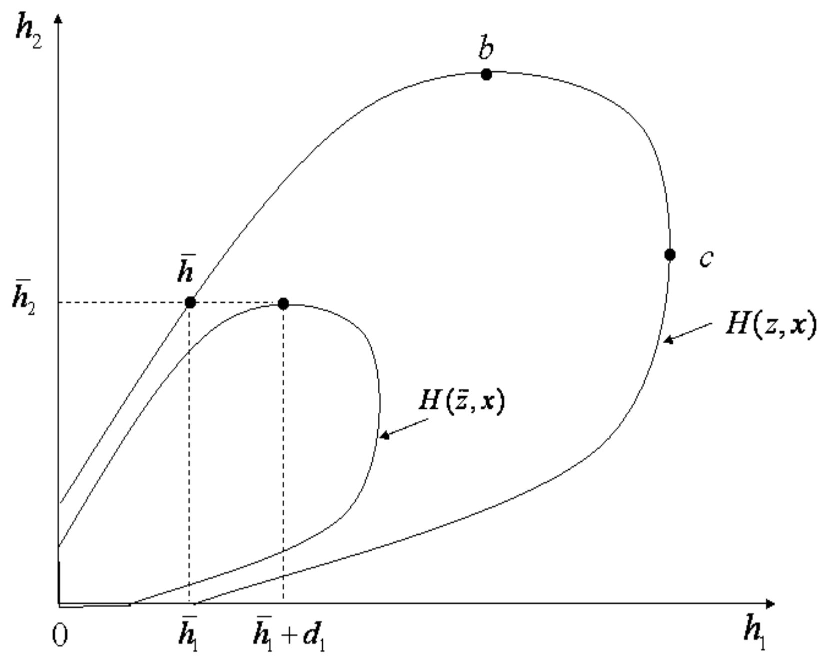


Figure 2: Discarding under weak output disposibility.

Assuming nonnegative prices for landed fish, profits can only decline if the intercepted fish is discarded at sea. Then $h \in H^e$ is a necessary condition for profit maximization in the absence of any regulations.

Under certain regulations, however, discarding fish at sea can increase fishermen's profits if their actions-at-sea are unobservable to the regulators. To see this, suppose that in response to some conservation goals the fishery manager attempts to regulate catch at $\overline{h} = \{\overline{h}_1, \overline{h}_2\}$ in Figure 2. Notice that $\overline{h}$ is an element of $H(z,x)$ but not $H^e(z,x)$. The inputs required to intercept $\overline{h}$ are z. Targeting inputs can be saved by intercepting a mix of species that more closely mirrors the relative stock abundance.

These input savings are maximized at $\left\{\overline{h}_1 + d_1, \overline{h}_2\right\} \in H^e(\widetilde{z}, x)$, with $\widetilde{z} < z$.

Hereafter, we assume that fishermen's actions-at-sea are unobservable to the manager of the fishery, who can only observe the fish landed at the port. As unobservable discarding can not be penalized, private fishing profits increase with the catch vector $\left\{\overline{h}_1 + d_1, \overline{h}_2\right\}$ since the fishermen *land* the regulated quantity at a lower cost.

The cost function. The harvest frontiers discussed above exhibit weak output disposability and therefore cannot be represented with single-valued production or transformation functions (Diewert, 1973). Instead a multiple-species cost function provides a convenient representation of the technology. We define the cost function as

$$c(w, h, x) = \min_{z \in Z}\{w'z | h \in H(z, x)\},$$

where w denotes a n-vector of strictly positive unit input prices. We assume that the cost function is non-decreasing and linearly homogeneous in w; since w is fixed, we suppress it in future to ease notation. It bears emphasis that the cost function is defined over intercepted fish (catch), as opposed to landed fish.

The weak output disposability property of the underlying technology implies that harvest costs are not everywhere increasing in catch h. For example, Figure 2 shows that costs decline as the catch of species 1 is increased along the ray from $\left\{\overline{h}_1, \overline{h}_2\right\}$ to $\left\{\overline{h}_1 + d_1, \overline{h}_2\right\}$. This implies that for $\overline{h} \in D(x)$ the marginal cost of the species that is discarded is negative. This allows us to redefine the discard set as

$$D(x) = \{h \in H(z, x)\,; \partial c(h, x)/\partial h_i < 0 \text{ for some } i\}.$$

In future, we let $c_i(h, x) \equiv \partial c(h, x)/\partial h_i$. The following cost function, which we utilize for our exercises in Section 5, captures the weak output disposability property in two species fisheries (a more general version of the following cost function appears in an appendix):

$$c(h,x) = \left[1 + \frac{1}{2}\gamma_s \left(\frac{h_1}{h_1+h_2} - \frac{x_1}{x_1+x_2}\right)^2\right]\left[\frac{\gamma_1}{x_1}h_1^\eta + \frac{\gamma_2}{x_2}h_2^\eta\right]; \ \gamma_s, \gamma_1, \gamma_2 > 0, \ \eta > 1. \quad (1)$$

Proposition 1. *The cost function expressed by (1) has the following properties: for any* $x_1, x_2 > 0$ *and* $h_1 = \bar{h}_1 > 0$*, there exist* $\hat{h}_2\left(\bar{h}_1, \frac{x_2}{x_1}\right)$ *and* $\tilde{h}_2\left(\bar{h}_1, \frac{x_2}{x_1}\right) \geq \hat{h}_2$ *such that for all* $h_2 \in \left[0, \hat{h}_2\right]$*,* $c_2(h,x) < 0$ *and for all* $h_2 > \tilde{h}_2$*,* $c_2 > 0$*.*

Proof. See Appendix 8.1. ■

Proposition 1 makes clear that any regulation that sets species-specific quotas at $\{\bar{h}_1, \bar{h}_2\}$ with $\bar{h}_2 < \hat{h}_2$, will lead to discards of species 2. Moreover, the threshold $\hat{h}_2$ depends on the permissible harvest for species 1 as well as the relative abundance of the two species. An observation of the cost function in (1) also clarifies that the result stated in Proposition (1) holds symmetrically for both species. The Proposition is however moot on the sign of marginal costs for $h_2 \in \left[\hat{h}_2, \tilde{h}_2\right]$. An appropriate choice of parameters $\{\gamma_1, \gamma_2, \eta\}$ ensures that the function is well behaved and the marginal cost crosses zero only once, in which case $\hat{h}_2 = \tilde{h}_2$ (see Section 5 below).

The cost function expressed by (1) requires some further elaboration. While γ_1 and γ_2 are scale parameters, the stock terms in the denominators within the second square brackets ensure that a higher stock abundance of any species reduces its own harvesting cost; $\eta > 1$ helps in ensuring that marginal costs are increasing in harvest levels. Finally, γ_s captures the degree of targeting flexibility permitted by the technology. If $\gamma_s = 0$, the harvest of the two species are independent of each other and the cost function reduces to the standard Schaefer model (see, for example, Brown et al. (2005)). On the other extreme, as $\gamma_s \to \infty$, the cost function represents a fixed proportions technology such as shown by the dashed line segment $0 - c$ (connecting origin with H^3) in Figure 1.[8]

2.2. Stock growth. Recall that in our model the growth phase precedes the harvest phase. We assume that the stock grows following a Gause model:

$$x'_i = s'_i + r_i s'_i \left(1 - s'_i - \sum_{j \neq i} \alpha_{ij} s'_j\right), \quad i = 1, ..., m. \tag{2}$$

where $'$ over a variable denotes its one-period ahead value; $s' (\equiv x - h)$ denotes the fish escapement at the end of the current harvest phase (equivalently, the beginning of the next period); x' denotes stock abundance at the beginning of next period. The parameter r_i is the intrinsic growth rate for species i, and α_{ij} represents inter-species competition. Positive values for α_{ij} indicate that species i and j compete with one another for common and limited resources, whereas a negative value for α_{ij} indicates that species i is a predator of species j.

3. Optimal choices under alternative regulatory regimes

Left unmanaged, fisheries are subject to overexploitation and resource rent dissipation. In most fisheries the manager determines the per-period aggregate harvest target, leaving it to fishermen to carry out harvesting operations. Regulations are then used to control the harvesting activities of the individual fishermen. In this section, we study common regulatory regimes and examine cases under which the harvest levels chosen by fishermen diverge from the aggregate harvest goal selected by the manager.

[8] One may object to our description of targeting costs as too simplistic. Modeling targeting costs that symmetrically penalize deviations between harvest and stock shares however comes naturally to mind. Empirical investigation could determine alternate specification that provide a closer approximation to real world targeting costs. It is easy to conjecture that as long as targeting costs rise with the difference between catch and stock shares, the results that follow will qualitatively remain unaltered.

We continue to assume that fishermen do not face penalties, either monetary or moral, for discarding fish at sea. Recall that the manager only observes landings. If the fishermen did not discard fish, landings and catch coincide and the manager can control catch through landings. However, with a fishing technology that exhibits weak output disposability, catch and landings are not identical if the manager's landings' target falls in the discard set. The question we ask here is: how shall the manager regulate harvest when discarding by fishermen is unobservable?

The answer will depend on the regulatory instrument used to *implement* the manager's harvest goal. Two forms of regulation common in the natural resources literature will be examined: landings taxes and individual or species-specific harvest quotas. A third less common regulatory instrument that we consider is a value-based revenue quota, which has been proposed as a way to address the discarding problem in multiple-species fisheries (Turner, 1997). Below, each of these instruments is studied sequentially.

3.1. Species-specific quotas. Under this form of regulation, the manager in every period issues species-specific landing permits that grant their owner an exclusive right to intercept and land specified quantities of each fish species. The manager can adjust these quotas to implement the desired aggregate harvest. We show that under this system fishing mortality, i.e., landings plus discards, can diverge from the target harvest either through discards at sea, or through slacks under which fishermen choose not to fully utilize their quotas. In what follows, we continue to denote the total catch (and fishing mortality) by h, but to make a distinction between catch and landings, the latter are now denoted by l; the quantity discarded at sea is denoted by d. Therefore, $h \equiv l + d$.

Suppose that the landings are regulated such that $l_i \leq \bar{l}_i$, where $\bar{l}_i$ is the landings quota for species i. Consider now a unit mass of identical fishermen, each endowed with an identical fishing technology. Assume further that there are no increasing returns to scale and therefore fishermen have no incentive to combine their harvest efforts. These assumptions together allow us to consider the decision problem of a representative fisherman; under this construct, per-fisherman outcomes coincide with the aggregate outcomes in equilibrium.

The profit maximization problem for a landings–constrained representative fisherman can be described as

$$\max_{0 \leq l \leq \bar{l}\ ,\ d \geq 0} \{p \cdot l - c(l + d, x)\},$$

where $p \in R_+^m$ denotes the vector of non-negative dockside prices for landed fish (vector conformability is assumed). The following proposition summarizes the properties of a discarding equilibrium under this form of regulation.

Proposition 2. *(i)Under a species-specific quota regime, an optimal discarding of species i occurs, that is $h_i^* > l_i^* = \bar{l}_i$, if and only if $c_i^* = 0$. (ii) The quota of species i is not fully utilized, that is $h_i^* = l_i^* < \bar{l}_i$, if and only if $c_i^* = p_i$.*

Proof. See Appendix 8.2 ■

The intuition behind the result stated in Proposition 2 is simple. Since landing can not exceed the quota, discarding occurs if the optimal catch exceeds the landing quota. Conversely, if the catch lies below the quota discarding is suboptimal with non-negative dockside prices. Further, if the quota for species i falls in the discard set its marginal harvesting cost is negative. Therefore, the overall costs may be lowered by increasing the species i catch above $\bar{l}_i$. In this case, the fishermen will land what is permissible and discard the rest after interception. The harvest of species i is increased to the point where the cost savings are exhausted, i.e., $c_i(l^* + d^*, x) = 0$. Beyond this harvest level, a marginal unit of harvest has a positive cost ($c_i > 0$) but no benefits since it has to be thrown back into the sea.

If the marginal cost evaluated at the landing constraint of species i is above its dockside price, the fisherman chooses to harvest and land less than the quota announced by the manager until the marginal cost falls down to the dockside price. In such cases the landing constraint is *slack.* However, if c_i evaluated at $\bar{l}_i$ is positive but falls below (or equals) the species' dockside price, the quota is fully utilized. In either case, no discard occurs.

A final observation is that if there are positive discards of species i fish for some $\bar{l}$, further reductions in the species i landings target will have no effect on species i mortality. This is because the catch h_i^* that minimizes fishing costs does not change if solely $\bar{l}_i$ is lowered; fishermen will continue intercepting h_i^*, land $\bar{l}_i$, and discard the rest, $h_i^* - \bar{l}_i$. The intuition follows from Figure 2 for the two-species case. Under our assumption that all discarded fish die, mortality is unaffected by further reductions in the species i landings constraint, thus only fishing revenues decline.

The results above imply that equilibrium lease prices of species-specific landings permits inform whether or not discarding occurs. Assume that a well-functioning quota lease market exists and let $r = (r_1 ..., r_m)$ denote the vector of equilibrium quota lease prices. Then Proposition 2 leads to the following corollary.

Corollary 1. *If fishermen can freely discard fish at sea, the equilibrium lease price for species i quota satisfies $r_i \in [0, p_i], i = 1, ..., m$.*

Proof. See Appendix 8.2 ■

To understand this result, observe that quota transferability implies an equilibrium condition in which all gains from quota trading are exhausted. In equilibrium, the quota lease price will be bid up to the marginal profit that the fisherman would obtain by using the quota himself. This condition may be written as

$$r_i = p_i - c_i(l^* + d^*, x), \quad i = 1, ..., m. \tag{3}$$

There are three possibilities to consider. If the manager sets a quota that exceeds the profit maximizing harvest quantity, the quota does not bind and the corresponding lease price will equal zero. On the other hand, if the manager announces a quota $\bar{l} \in D(x)$, fishermen will discard the species whose marginal harvest costs, evaluated at $\bar{l}$, are negative. Discarding of species i occurs until $c_i(\bar{l} + d, x) = 0$. At zero marginal cost, the marginal profit from landing an additional unit of species i fish is just equal to the dockside price. The remaining possibility is that the marginal cost of harvesting species i is positive but lies below its dockside price. Here, the lease price will be strictly positive but less than the species' dockside price.

The implementable set of species-specific quotas. The decision problem of the representative fisherman highlights that the species-specific quotas announced by the manager may not be implementable for two reasons: (1) fishermen may optimally choose not to utilize the full quota and (2) their optimal catch of some species may exceed its landings quota if its discarding reduces overall costs. It is then crucial that the manager be aware of the *implementable* set of quotas. Such sets are defined by Proposition 2.

Definition 1. *Let $I^Q(x, p)$ denote the manager's set of implementable target harvest* *levels. Then*

$$I^Q(x,p) = \left\{\bar{h} \leq x;\ \bar{h} \neq D(x);\ p_i \geq c_i(\bar{h},x),\ \ i = 1,...,m.\right\}.$$

The first condition states that aggregate harvest cannot exceed the available stock. The second indicates that implementable harvest vectors can not be elements of the discard set, and the third rules out harvest slacks. Definition 1 will be critical for formulating the manager's dynamic problem to be studied in the next section.

3.2. Landings taxes. Under a landings tax mechanism, the target harvest level is implemented by adjusting the net price of landed fish. Let $\tau = (\tau_1, \tau_2, ..., \tau_m)$, where τ_i denotes per-unit landings tax for species i fish.[9] A representative fishermen then chooses landings and discards to maximize profits:

$$\pi(p,\tau,x) = \max_{l\geq 0,\ d\geq 0} \{(p-\tau)\,l - c(l+d,x)\}.$$

The solution to this problem can be summarized by the following proposition.

Proposition 3. *Landing taxes can not implement a harvest target* $h \in D(x)$; *in such cases optimal discarding of some species* i *occurs with* $c_i^* = 0$.

Proof. See Appendix 8.3 ■

As under species-specific quotas, landing tax regulations are susceptible to discards. Why can landing taxes not eliminate discards? To answer this, suppose the manager wishes to implement a harvest target that is an element of the discard set, at which the marginal cost (without discarding) is negative for some species i. Even if the manager

[9] The per-unit taxes and transfers can be balanced through lump-sum taxes/transfers on all fishermen. These details are however immaterial for our analysis.

taxes away all the revenues, i.e., set $\tau_i = p_i$, the discards will still occur as the marginal cost of harvesting species i at an optimum equals zero. Setting a landings tax such that $\tau_i > p_i$ is clearly not feasible; fishermen will simply discard all species i fish to avoid the revenue loss from landing it.

On the other hand, a negative landings tax, i.e., per-unit subsidy can be used to encourage fishermen to harvest a larger quantity than would be harvested at dockside price p_i. This allows landing taxes to implement harvest targets that would be slack under a species-specific quota regulation.

The implementable set of harvests. Proposition 3 allows us to define the set of harvest levels that can be *implemented* under landing taxes.

Definition 2. *Let $I^T(x)$ denote the manager's set of implementable harvest targets. Then*

$$I^T(x) = \{h \leq x,\ h \notin D(x)\}.$$

In contrast to the implementable set under a species-specific quota regime (see Definition 1) the restriction that marginal costs at the desired harvest levels be less than the prices is no longer required. Consequently, the implementable set is independent of prices.

3.3. Value-based revenue quotas. The last regulation we study is a value-based harvest *revenue* quota. Under this regime the manager sets an upper bound for fishermen's revenues. Fishermen in turn choose a harvest vector such that the revenue cap is not exceeded. Turner (1995) shows that discarding is never part of a profit maximizing fishing strategy under this regime.

Proposition 4. *With strictly positive prices, the necessary conditions for revenue constrained profit maximization are given as*

$$\frac{c_1(h,x)}{p_1} = \frac{c_2(h,x)}{p_2} = ... = \frac{c_m(h,x)}{p_m} \leq 1$$

Proof. See Turner (1995). ■

The intuition for these results is straightforward. If the ratio of marginal costs to marginal revenues were not the same across all species, profits could be increased by tilting the output mix toward those species with a lower marginal cost-to-price ratio. The prices however must be at least as large as the marginal costs; otherwise, profits can be increased by reducing harvest quantities. The last inequality in Proposition 4 follows as a result.

The necessary condition can be expressed alternatively as

$$-\frac{p_i}{p_j} = -\frac{c_i(h,x)}{c_j(h,x)} = RPT_{ij}.$$

This condition states that for any two species, the rate of product transformation equals the negative price ratio of the two products. Expressed in this form, it is easy to see why there is no discarding under a value-based quota. Since prices are nonnegative, the rate of product transformation is non-positive. But this is the condition required for $h \notin D(x)$, i.e., revenue-constrained optimal harvest is never an element of the discard set.[10]

The implementable set of harvests. A downside of a revenue quota regime, recognized by Turner (1995), is that the manager has limited control over the aggregate

[10] If the dockside price for some species i is zero, fishermen will choose a harvest vector such that $c_i(h,x) = 0$. In this case, a positive quantity of species i fish is intercepted by the gear (otherwise targeting costs would be required to avoid this species). In the absence of discard costs the fisherman is indifferent between landing and discarding the fish at sea.

harvest goal in the fishery. Proposition 4 allows us to formally define these limitations.

Definition 3. *Let $I^V(x,p)$ denote the implementable set of harvest targets under a value-based quota regulation. Then*

$$I^V(x,p) = \left\{ \begin{array}{c} h \leq x;\ \frac{p_i}{p_j} = \frac{c_i(h,x)}{c_j(h,x)}\ \forall\ i,j = 1,...,m; \\ p_i \geq c_i(h,x)\ \ \forall\ i. \end{array} \right\}.$$

By characterizing the implementable sets under the instruments of our interest, we have laid out the constraints that an efficient management of fisheries must address in every period. The management problem must additionally incorporate the dynamic biological aspects that stems from the stock growth model in (2). This is the task we undertake now.

4. Optimal management under weak output disposability

In the previous section, we studied the optimal harvesting choices of fishermen under alternative regulatory regimes. In this section, our objective is twofold: first, to study rules, i.e., species-specific quotas, taxes, revenue caps that maximize welfare within their respective regimes, and second, to rank them against the problem that is faced by a hypothetical single owner, or equivalently, the problem of a manager who can perfectly observe at-sea activities of the fishermen and therefore command the fishermen to do what he desires. The task of ranking turns out to be easier and is shown below analytically. For computing constrained-optimal rules within each regime however we resort to numerical simulations, in which the sole-owner's harvest rules are used as the benchmark for understanding and evaluating alternative rules.

It is worthwhile to first highlight the difference between the sole-owner problem and the problem that is faced by the fishermen. First, irrespective of the technological specification, fishermen's harvesting choices do not internalize its impact on future stock abundance; essentially, the fishermen's problem is static. A sole-owner in contrast maximizes the present value of fishery which must link current actions with those in the future. In the absence of discarding and the problem of harvest slacks, the sole owner allocations can be implemented simply by setting species-specific quotas at the optimal harvest levels.

A sole-owner may choose a harvest vector that falls in the discard set or implies a harvest slack, if such a choice adjusts stock levels in a way that yields higher future returns. On the other hand, the sole objective of individualistic fishermen is maximize *current* profits, and therefore they do not internalize the impacts their current harvests have on future payoffs. The extent to which such divergent objectives of fishermen constrain the manager's implementable aggregate harvests and reduce fishery value is of particular interest in what follows.

Below, we first study the sole-owner problem. Management under the three regulatory instruments is addressed thereafter.

4.1. The sole owner problem. Since the sole owner controls all aspects of fishery exploitation, the implementable harvest set is constrained only by the available stock. Formally,

$$I^{SO}(x) = \{h \leq x\}$$

At the beginning of the harvest phase, the owner observes the available stock x and selects current harvest h. The owner's dynamic program can be written as

$$V(s) = \max_{h \in I^{SO}} \{ph - c(h, x(s)) + \beta\, V(\underbrace{x(s) - h}_{s'})\}. \tag{4}$$

The state vector in (4) is s, the control vector is s', and $\beta \in (0,1)$ is the discount factor. The solution to this problem is an escapement policy that specifies s' for all possible states s. The maximized value of the fishery for a given state s is $V(s)$.

First order conditions with respect to the optimal harvests can be written as

$$p_i - c_i(h,x) = \beta V_i(s'), \qquad i = 1 \text{ to } m,$$

where $V_i(s') = \partial V(s')/\partial s'_i$. Intuitively, the LHS expresses the net benefit of a marginal harvest of species i fish while the RHS represents its benefits if left in the sea. The Envelope conditions are:

$$V_i(s) = \sum_{j=1}^{m} \left(\beta \; V_j(s') - \frac{\partial c(h,x)}{\partial x_j} \right) \frac{\partial x_j}{\partial s_i}, \quad i = 1 \text{ to } m.$$

The marginal value of a unit of the escapement of species i equals its marginal benefit that it brings by reducing current cost of harvesting through increased stocks of species $j = 1, ..., m$, represented by the term $\sum_{j=1}^{m} -\frac{\partial c(h,x)}{\partial x_j}\frac{\partial x_j}{\partial s_i}$, plus its discounted marginal value in the next period $\sum_{j=1}^{m} \beta \; V_j(s') \frac{\partial x_j}{\partial s_i}$. The FOCs and the Envelope conditions can be combined to yield

$$p_i - c_i(h,x) = \beta \sum_{j=1}^{m} \left(p_j - c'_j(h',x') - \frac{\partial c(h',x')}{\partial x_j} \right) \frac{\partial x'_j}{\partial s'_i}, \quad i = 1 \text{ to } m. \tag{5}$$

The intuition directly follows from the ones offered before. At the margin, a unit of species i if harvested has a benefit given by the LHS. If instead it is left in the sea, it increases next period stock of species j by $\frac{\partial x'_j}{\partial s'_i}$, which in turn brings a marginal benefit $-\frac{\partial c(h',x')}{\partial x_j}$ by decreasing harvesting cost in the next period in addition to its direct marginal benefit of $p_j - c_j(h',x')$ when harvested in the next period. Aggregated over its impact on all species, the RHS represents the discounted value of an unharvested unit of species i fish. The RHS is often referred to as the *user cost* of the species i stock.

The necessary condition in (5) is a multiple-species modified golden rule (Clark, 1990, Flaaten, 1991).

Obviously, the sole owner will never discard any species if its dockside price is positive. This however does not imply that the sole owner never chooses harvest bundles belonging to the discard set $D(x)$. A relevant question to ask is: when will the optimal harvest be such that the marginal cost for some species i is negative? The answer to this question is provided in the numerical simulations to be discussed below.

4.2. The manager's problem. We now turn to the harvest policies that are implementable under decentralized management. It is worth reiterating that in the absence of harvest slacks and/or discarding due to weak output disposability the manager can resolve the intertemporal externality problem by setting species-specific quotas. But such quotas may not be implementable now as the manager faces a hidden-action (unobservable discarding) problem.

Although the manager cannot observe and therefore cannot control at-sea fishing practices, he is assumed to be fully informed about the decision rules of fishermen. Therefore, while announcing harvest policies he is fully aware of the harvest outcomes that such policies will entail in the decentralized fishery. In terms of the choice of regulatory instruments, the manager can either rely on species-specific quotas, or landings taxes, or a value-based quota to implement the aggregate harvest goal. In either case, the manager then knows the implications of the announced policy on fishing mortality and landings at the port.

Will the manager ever choose policies that lead to discard or slacks? As for the value-based quota, whatever revenue cap the manager announces, discard does not occur in equilibrium and the revenue quota will be fully utilized as long as the announced cap is sufficiently small and the price to marginal cost ratio at full utilization does not fall below unity. In effect, the manager clearly knows the set of harvest levels that can be induced by capping fishermen's revenues.

For species-specific quotas or landing taxes the answer is not so obvious. We know that the sole-owner can choose harvest levels within the discard sets (although the catch is never discarded/wasted), then why would the manager also not like to do so? Clearly, the manager knows that such a choice will lead to wasteful discards. But, are there any future stock benefits that can accrue from such a choice?

Proposition 5. *An optimal policy belongs to the implementable sets described by Definitions 1 – 3: discarding is never a part of the optimal policy.*

Proof. See Appendix **??**. ■

To understand this result, first note that discarding is purely a deadweight social loss. Second, allowing discards does not bring any other current or future benefit: fishermen will discard exactly the amount dictated by their optimal decision rules contingent on the policy regime in place. Then why not just allow them to land all the fish? If the manager wants a higher mortality of particular species, possibly to enhance the growth of a competing species, he may as well permit the fishermen to land the same for sale at the port by appropriately designing quotas or landing taxes. If instead he wants to lower the mortality of a particular species by lowering its target harvest, he has to ensure that the target harvest for other species is chosen such that the full harvest vector not be an element of the discard set, i.e., that it be individually rational for the fishermen not to discard the species being protected.

Similarly, in the species-specific quota regime, it is pointless to announce too high a quota if it is never going to bind. Fishermen's actual harvest (which in this case equals landings) choice is what matters for the equilibrium and the manager may as well announce the same as the regulated quota.

Proposition 5 unambiguously informs us that the manager should restrict his choices to implementable sets as described by Definitions 1 – 3. Recall that the harvesting problem of the fishermen is static. The manager therefore only needs to incorporate the fishermen's current period decision rule into the dynamic program. The manager's problem then takes the following form:

$$V^R(s) = \max_{h \in I^R} \{ph - c(h, x(s)) + \beta \, V(x(s) - h\}, \tag{6}$$

where the superscript R in I^R denotes the regime, i.e., $R = Q, T$,or V.

Our next result on ranking alternative regulatory regimes directly follows from Definitions 1 - 3.

Proposition 6. *In terms of the value of the fishery, the regimes are ranked as*

$$V^{SO} \geq V^T \geq V^Q \geq V^V.$$

Proof. See Appendix 8.5. ■

The result directly follows from

$$I^V(x, p) \sqsubseteq I^Q(x, p) \sqsubseteq I^T(x) \sqsubseteq I^{SO}(x).$$

The intuition here is straightforward. Landing taxes offer more implementable harvest choices than do species-specific quotas. For example, under landing taxes the manager can induce a relatively larger harvest of a particular species through appropriate subsidies. Under a value-based quota regulation a single choice variable, the revenue cap, is used to control multiple harvests and stocks; it is more restrictive than multi-dimensional species-specific quotas.

At this stage, a question to ask is under what conditions, e.g., the nature of the biological interaction between fish species, the structure of the harvest technology, and relative prices for landed fish, will the differences in performance of the three forms of regulation be most pronounced. This is addressed in the next section.

5. Numerical results

Neither the sole owner problem (see equation (4)) nor the management problem under alternative regulatory regimes (see equation (6)) can be solved analytically. Therefore, in this section, we use numerical methods to solve for the value function and the optimal management policies under alternative regulatory regimes; the optimal policies employed by the sole owner serve as a benchmark for all comparisons.[11] The simulation exercises focus on the two-species case. Prices and parameter values are listed below.

In addition to current stock abundance, the key determinants of these policies are (a) relative dockside prices, (b) the nature of the ecological competition, and (c) the degree of technological complementarity between the two harvested species. Below, we focus on each of these factors in turn. Although the scenarios we consider are stylized examples of conditions encountered in actual fisheries, they allow us to highlight the main insights pertinent to the optimal management of multiple-species fisheries.

Competing species fishery with dockside price differential. We first examine harvest policies for a competing-species fishery. We assume that the two species are

[11] The numerical technique we use is value function iteration. The method is described in Judd (1998).

biologically symmetric, with common intrinsic growth rate and common competition parameters. The two species are assumed economically asymmetric with species 2 having a lower dockside price; $p_2 = 0.3p_1$. We assume that, due to the price differential, the high-price species has been overfished while the low-price species has been underfished relative to their respective steady states. The challenge for the manager is to restore each stock to its long run steady state.

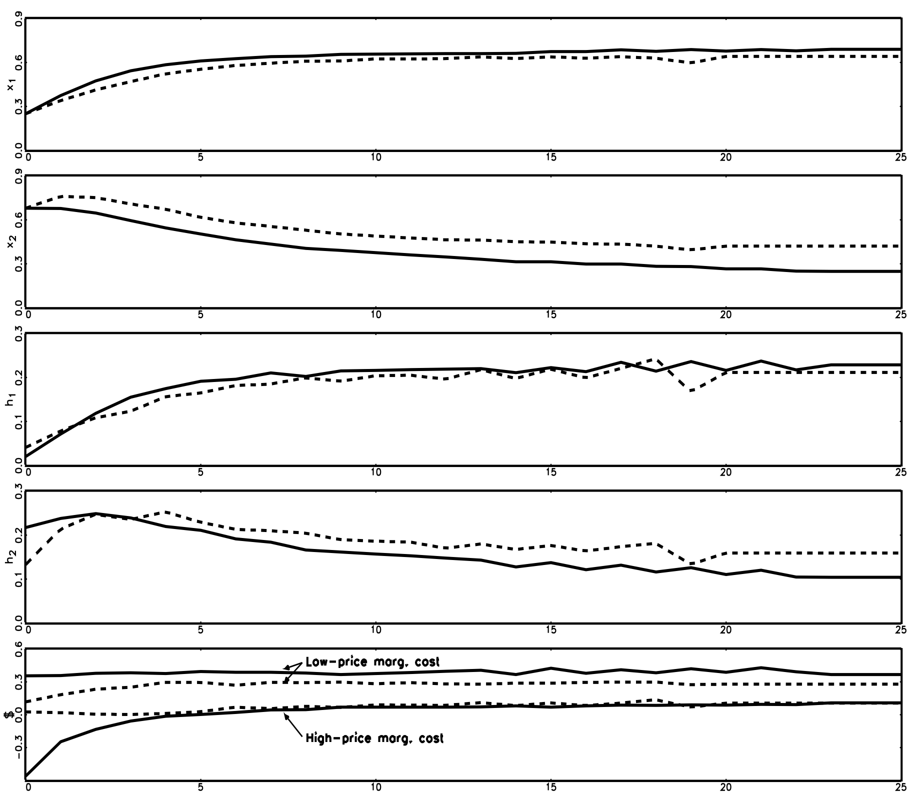


Figure 3: Sole owner versus species-specific quota regime: Solid curves depict the sole owner policy while dashed curves depict the species-specific quota policy. Panels are (top to bottom): high-price stock; low-price stock; high-price harvest; low-price harvest; marginal harvest costs both species combined. Parameter values are $r_1 = r_2 = 1$; $\alpha_1 = \alpha_2 = 0.3$; $p_1 = \$1$, $p_2 = \$0.3$; $\gamma_1 = \gamma_2 = 0.25$, and $\gamma_s = 50$.

Figure 3 plots the sole owner (solid curves) and a second-best policy which is implementable under a species-specific quota regulation (dotted curves). From top to bottom, the five panels in the figure show the stock of high-price species , the stock of low-price species, the harvest of high-price species, the harvest of low-price species, and the marginal costs for high- and low-price species combined. The policies are shown for twenty-five production periods.

Consider stocks and harvests under the sole owner policy. To move the stocks towards their respective steady states, the initial harvest of the high-price species is kept low, and the initial harvest of the low-price species is set high. Notice however that positive harvests of both species are maintained. This is in sharp contrast to a bang-bang approach to the steady state stock levels, which would call for zero harvests of the high-price species. The sole owner policy implicitly weighs the cost of setting catch shares that differ significantly from the stock shares. The date zero stock share for the high-price species is 0.269, whereas the catch share is 0.084. Further reductions in the high-price catch (or increased harvest of the low-price species) would move the stocks more rapidly toward their steady state values. The targeting costs that would be required to implement this strategy however outweigh the benefits. The costly targeting technology by requiring an alignment of harvest and stock shares slows down the transition to steady states.

The bottom panel of Figure 3 shows that for the sole-owner policy, the marginal cost for the low-price species is negative during the first six production periods. That is, an aggressive harvesting of the low-price species with concurrent protection of the high-price species puts the harvest vector in the discard set. It is clear that the sole-owner policy cannot be implemented under decentralized management.

This is demonstrated for the species-specific quota regime in Figure 3. Under species-specific quotas, harvests in the discard set and harvests that cause marginal costs to rise above the dockside price can not be implemented. The bottom panel shows that indeed the marginal costs for each species (dashed lines) are maintained at non-negative levels. Additionally, the low-price species marginal cost is maintained below its respective dockside price, \$0.30. These constraints on implementability impact the second best policy in predictable ways. First, harvest shares and stock shares are closer in magnitude than their sole owner counterparts; the first period harvest share for the high-price species is 0.231 (stock share is 0.269). Maintaining similar harvest and stock shares keeps the targeting costs low, as required to avoid discarding. Notice that at the sole-owner steady state the low-price species marginal cost exceeds the dockside price. The sole owner incurs losses at the dock in order to maintain the low-price stock at low levels. This reduces ecological competition and allows a slightly larger harvest of the high-price species along the transition path and at the steady state. Under species-specific quotas fishermen are unwilling to harvest larger quantities of the low-price species; ecological competition is maintained at a *costlier* level. As a result, the steady state stock level for the low- and high- price species are respectively above and below their sole-owner counterparts.

Finally, we see from the sole owner's optimality conditions in Section 4 that a price below marginal cost implies a negative shadow price for the fish stock; the presence of the low-price species depresses the value of the fishery. However, reducing the low-price stock too much is also costly. The growth characteristics of competing fish species explains this result. As the low-price species' stock is reduced, less intraspecies competition leads to a strong per-period growth. A low stock level and increased per-period harvest create a mismatch between the stock and harvest shares, a condition that raises targeting costs.

Thus, while the sole owner would prefer to reduce the low-price stock, it is too costly to do so.

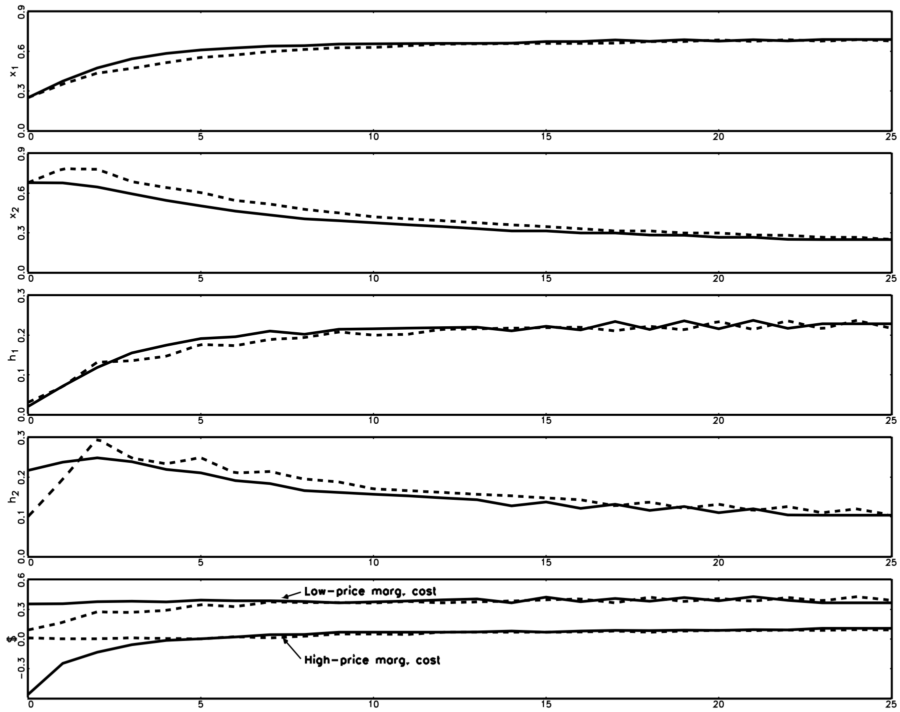


Figure 4: Sole Owner vs. Landings Tax Policy. Panels are (top to bottom): high-price stock; low-price stock; high-price harvest; low-price harvest; marginal harvest costs for both species combined. Solid curves depict the sole owner policy. Dashed curves depict the landing taxes policy.

Figure 4 depicts the sole owner policy (solid lines) and a policy that is implementable under landing tax regulations (dashed lines). As above the five panels in the figure are (from top to bottom) the stock of high-price species, the stock of low-price species, the harvest of high-price species, the harvest of low-price species, and the marginal costs for high- and low-price species combined.

The top two panels show that while stocks and harvests under landings taxes follow a different path, they reach the same steady state values as under the sole owner policy.

Unlike species-specific quotas, the regulator can subsidize the harvest of the low price species to reduce its stock and reduce ecological competition in the fishery. The regulator continues to face a constraint that harvests not be contained in the discard set. This affects harvest choices in the early periods when the stocks are farthest from their steady state values. The constraints on implementability slows the transition to the steady state stock levels.

Under a value-based quota regulation, our results show that the high-price species catch share is considerably larger than under the sole owner policy.[12] Recall that under a value-based quota fishermen's harvests are chosen to equate the ratio of marginal costs and prices, which in this example exceeds 3 to 1 in favor of the high-price species. Because fishermen focus their fishing effort on the high-price species, the high-price steady state stock under the value-based quota is 80% of the sole-owner value. Fishermen also harvest less of the low-price species under the value-based quota regulation; the low-price steady-state stock is 276% of the sole owner level. Steady state harvests of the high- and low-price species are respectively 78.5% and 186.5% of their sole owner counterparts. The lack of control over individual species reduces the value of the fishery considerably. Fishery value under the revenue quota (evaluated at the date zero stock levels) is 91.6% of the sole owner value. In comparison, fishery values under species-specific quota and landings tax regulations are, respectively, 99.0% and 99.3% of their sole-owner values.

Predator-prey fishery. Our second management scenario considers a predator-prey fishery. In this example, the two species are economically symmetric, with equal prices for both species and no harvest slacks. We assume that both stocks are initially below their respective steady state values, and thus stock rebuilding is called for.

[12] To save space, the related Figure is not included. It is available from authors on request.

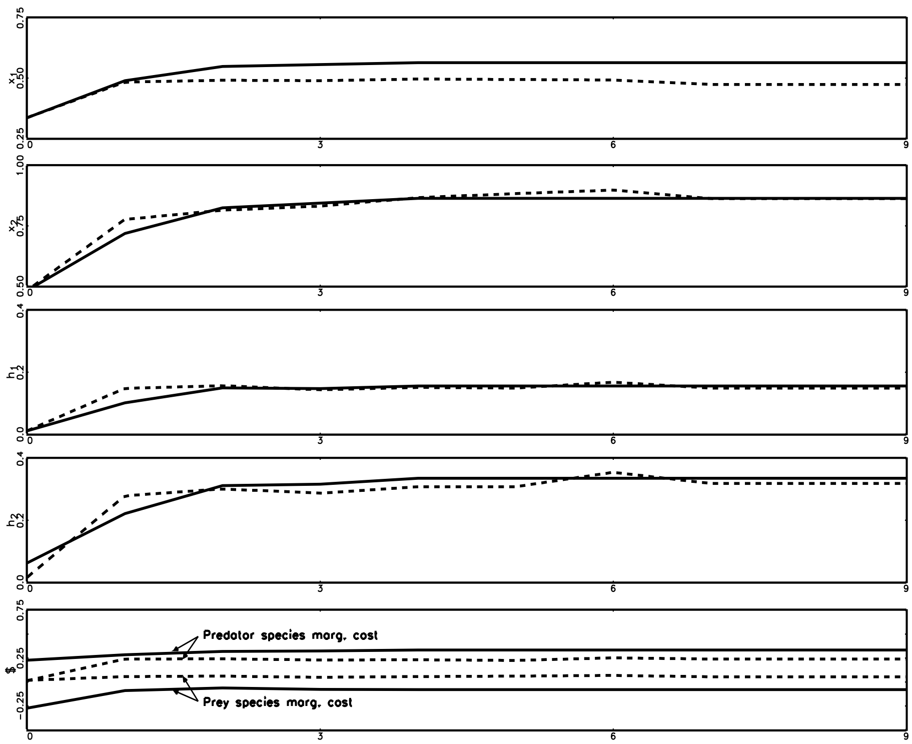


Figure 5: Sole Owner vs. alternative regulatory regimes in a predator-prey fishery. Parameter values in this example are: $r_1 = r_2 = 1$; $\alpha_1 = 0.4$, $\alpha_2 = -0.4$; $p_1 = p_2 = \$1$; $\gamma_1 = \gamma_2 = 0.25$; and $\gamma_s = 75$. Panels are (top to bottom): prey stock, predator stock, prey harvest, predator harvest, and marginal harvest costs for both species. Solid curves depict the sole owner policy. Dashed curves depict the species-specific quota policy.

Figure 5 shows from top to bottom, the prey stock, the predator stock, the prey harvest, the predator harvest, and the marginal cost for both combined. The solid curve depicts the sole owner policy and the dashed curve depicts both the species-specific and landings tax regimes. As the stock rebuilding requires low harvest levels, there are no slacks, and the two regimes coincide during transition.

With a predator-prey fishery there is growth complementarity among the two species since a higher prey stock enhances growth of the predator. We have assumed that initial stocks for both species are low relative to their steady state values. With both stocks initially low, the shadow prices for both are high, calling for aggressive investment in stocks, i.e., low initial harvest. With low initial abundance there is minimal intraspecies competition and high growth rates. As the predator growth increases with the prey stock, the incentive to invest in the prey stock is further strengthened. Notice that with rapid growth both stocks reach their steady state values by the sixth period.

Under the sole owner policy the prey stock (top panel) is maintained at a higher level than under the second best policy. Comparing catch and stock shares reveals that the sole owner catch share of the prey species is half or less of the regulated catch share. The bottom panel in the figure confirms that the difference between the two policies is due to the discarding constraint. Under the sole owner policy marginal harvesting costs are negative for the prey species indicating that such harvests are in the discard set during the approach to and at the steady state (see bottom panel). In contrast, the second-best policy is constrained to target harvests with only non-negative marginal costs. With the exception of the steady state prey species stock, which under the second best policy is 83.9% of the sole owner steady state value, the no-discarding constraint results in fairly small differences in the two policies. The value of the fishery under the second-best policy is 97.8% of the sole owner value.

Targeting costs and regulation. Here we investigate how the relative desirability of the three regulatory regimes vis-à-vis the sole owner's policies change when the targeting costs, as captured by the complementarity parameter γ_s in the harvesting technology (1), is varied. Over a range of $\gamma_s = 0$ to $\gamma_s = 400$ and under the three alternative regulatory regimes, Figure 6 below displays percentage losses in the value (relative to the sole-owner value) of a predator-prey fishery with a 3:1 dockside price differential in favor of the prey species.[13] Consistent with Proposition 6, the percentage losses are largest under the value-based quota, followed by species-specific quotas, and then landings taxes.

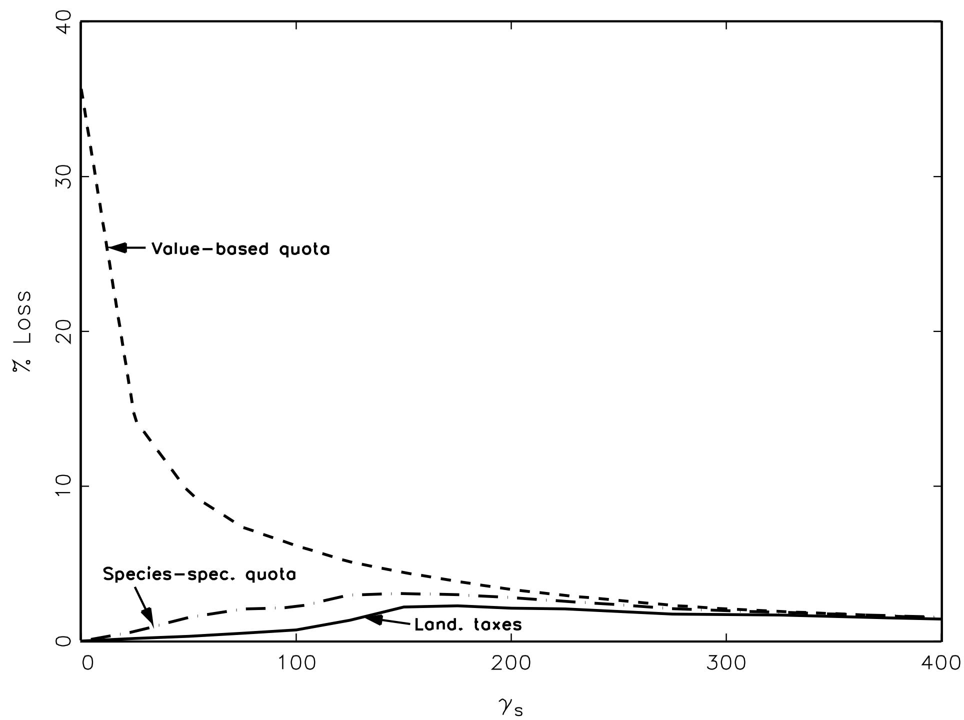


Figure 6: Lost fishery value due to unobservable at-sea discards. Parameter values for the panel (a) results are $r_1 = r_2 = 1$; $\alpha_1 = 0.4$; $\alpha_2 = -0.4$; $p_1 = \$1$, $p_2 = \$1/3$, $\gamma_1 = \gamma_2 = 0.25$.

At $\gamma_s = 0$, landing taxes and sector-specific quotas do as well as the sole owner policy. Observe that when $\gamma_s = 0$, the two harvests are technologically independent. Consequently, with strictly positive marginal costs for each species at any harvest level, discarding never occurs. In this case the sole owner plans can be implemented by landing taxes, or by species-specific quotas as long as the quotas are fully utilized by the

[13] Losses are calculated at the average of five escapement states: s_1 high and s_2 low; s_1 low and s_2 high; both escapement levels low, both high and both at intermediate levels. Losses in fishery value were similar when evaluated at other escapement states.

fishermen, i.e., dockside prices exceed marginal costs along the equilibrium path (which indeed is the case in our parametric example). While landing taxes and species-specific quotas can implement the vector of sole-owner's harvests, to do so with the value-based quota is not possible. Under the latter, any revenue quota leads to a vector of harvests that equalize the ratios of marginal costs to prices across all species. In general the implementable harvests are not what a sole-owner, who weights intertemporal ecological dynamics equally importantly, are likely to choose. Only in exceptional cases, e.g., a symmetric fishery with stocks level at their steady state values, the two may coincide. Thus for $\gamma_s = 0$, a value-based quota regime performs very poorly.[14]

Figure 6 shows that as γ_s gets sufficiently large, the percentage welfare losses relative to the sole owner fishery converge under each form of regulation, and decline toward zero . Intuitively, as $\gamma_s \to \infty$ targeting is not possible and harvest proportions are *fixed* by the technology. The ratio of the two harvests must equal the ratio of their respective stocks, since with any other *target* harvest ratio, the costs become infinite. The manager has no choice other than to set harvest shares equal to stock shares, irrespective of the regulatory regime that is in place. The same is true for the sole owner, who may however sometimes want to harvest quantities at which the species-specific quotas may not bind. This can be redressed through landing taxes. Similarly, as harvest proportions must equal stock proportions, sole owner quantities can now be implemented by a revenue cap, as long as it binds.

It is interesting to note that while landing taxes and species-specific quotas replicate

[14] We note that losses under a value-based quota in a fully symmetric fishery were much smaller (less than 0.35% of the sole owner fishery value). Intuitively, in a economically and biologically symmetric fishery the fishermen's choices roughly coincide with the management preferences. Most real world fisheries are however likely to be asymmetric and, therefore, losses under value-based quotas are also likely to be significant.

the first best under cross-species technological independence as well as a fixed harvest proportions technology, it is for the intermediate ranges of γ_s, i.e., costly targeting, that performance relative to the sole owner policy declines. In the current example, the percentage loss under landings taxes remains small for low values of γ_s, e.g., for γ_s between 0 and 100 losses are less than 1%. Due to harvest slacks, losses are higher under species-specific quotas than under landings taxes, although they do not exceed 3% of the sole owner value.

The non-monotonic variation of welfare losses under landing taxes and/or species-specific quotas with respect to γ_s can be explained as follows. First recall that an increase in γ_s expands the discard set, or equivalently, further constrains the regulator. From the sole owner's perspective, when targeting costs are low, intertemporal ecological considerations dominate leading some harvest choices to fall in the discard set. As γ_s increases the discard set expands and the sole-owner's harvests fall more often into this set. Thus as long as γ_s is not too high, increases in its value cause further divergence between the sole owner harvest policy and the second best policies under landing taxes and/or species-specific quotas. As a result, welfare losses under decentralized regulation increase. On the other hand, for high values of γ_s technological considerations dominate the sole owners' harvest choices since the cost of selecting a harvest bundle with shares that differ from stock shares is excessive. A further increase in γ_s reduces the likelihood that the sole owner's choices fall in the discard set. In other words, the sole owner's preferred harvests and the implementable harvests under regulatory regimes are more aligned.

6. Conclusion

This paper studies the management of a multiple species fishery under cross-species ecosystem interaction as well as cross-species technological interaction. Fishermen in practice adjust gear, bait used to capture fish, fishing times, and fishing locations to influence the mix of harvested fish species. We introduce a technology under which targeting of individual species is possible but costly, and for which costs rise as the mix of targeted species diverges from the mix of stocks in the sea. This representation captures economies of scope present in real world harvest technologies, and permits a novel characterization of the incentives to discard fish at sea in regulated multiple-species fisheries. We make a fair amount of analytical progress in ranking alternative regulatory regimes, namely, species-specific quotas, landing taxes, and value-based quotas. For studying optimal rules within each regulatory regime and comparing their performance to the harvest rule chosen by a sole owner, we solve related dynamic management problems using numerical methods.

A general conclusion from the analysis is that harvest policies should be chosen such that targeting costs implied under the regulated aggregate harvests are not too large. In our model, this requires that the share of the harvest of individual fish species mirrors the share of their respective stock abundance in the sea. Divergent catch and stock shares introduce an incentive for fishermen to discard fish and save resources that would otherwise be spent in sticking to the target. We identify ecological conditions (e.g., competing species versus predator-prey fisheries), and economic conditions (technology and relative prices) under which discarding imposes significant constraints on management choices. Second best management policies avoid the discarding problem through prudent choice of the target harvests. These policies balance ecological and technological interactions among competing fish species along the approach path to and at the steady state harvest and stock levels. The results provide important guidance for the management of real world fisheries for which stock rebuilding is often required, and in particular, when one or a few stocks are depleted while others are healthy.

An objection could be raised towards our assumption of perfect observability of fish stocks and fishing costs. If these factors are not observed, will our results, particularly the relative ranking of alternative regimes, continue to hold? Specifically, Turner (1997) shows that value-based quotas eliminate discards under unobservability of stocks and individual costs (technology). Our take is that even with unobservability of fundamentals, some market mechanisms can be exploited for the choice of appropriate regulatory regime. For example, suppose regulators who are implementing a species-specific quota regime have incomplete information about abundance and costs. Our results show that quota lease prices, which are typically observable, reveal vital information about discarding behavior and harvest slacks. One may be able to resolve the multiple-species management problem under unobservability of fundamentals through an appropriate mechanism design. The design of such a mechanism is a promising area for future research.

Our results contribute to a growing literature that acknowledges the importance of incorporating ecosystem (biological) interactions into the design of fisheries management policies. It has been suggested that the problem of overfishing and stock depletion in ocean fisheries may be addressed through an ecosystem-based management approach which explicitly accounts for complex interspecies interactions (Pikitch, et. al 2004; US Commission on Ocean Policy, 2004; Pew Oceans Commission, 2003). The results of this paper suggest that considering technological interactions among multiple fish species is equally important. Management policies that ignore technological interdependencies and the costs of targeting individual fish species within multiple-species fish complexes could aggravate discarding and reduce fishery value.

An increasingly popular approach for addressing discards in multiple-species fisheries is to penalize fishermen if they discard fish. These program are enforced with extremely costly on-board observer programs (NOAA, 2006). This paper shows that an alternative solution to the discarding problem is to select target harvest levels that are not contained in the *discard set*. In other words, with prudent choice of the harvest target, there will be no incentive to discard and no need for on-board monitoring. Our model can be used to weigh the costs and benefits of these two approaches. The benefit of on-board observers is that the set of implementable target harvests is expanded to include harvests in the discard set. This allows the manager to implement the sole owner harvest policy. The enhanced value of the fishery under the sole owner policy, less the added cost of placing observers on board fishing vessels, could be weighed against the value of the fishery managed under a second best harvest policy. Calibrating the model of this paper to an actual fishery would be a step forward in this direction.

7. References

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8. Appendix

The cost function in 1 is a special case of

$$c\left(h,x\right)=\left[1+\frac{1}{2}\sum_{i=1}^{m}\gamma_{s,i}\left(\theta_{i}-\varphi_{i}\right)^{2}\right]\left[\sum_{i=1}^{m}\frac{\gamma_{i}}{x_{i}}h_{i}^{\eta_{i}}\right], \quad (7)$$

where $\theta_i = h_i/(h_1 + ... + h_m)$ is the species i catch share, $\varphi_i = x_i/(x_1 + ... + x_m)$ is the species i stock share, $\gamma_{s,i}$ is the *specialization* cost parameter for species i. When $m = 2$ and $\gamma_{s,1} = \gamma_{s,2}$ the cost function in 7 simplifies to 1.

8.1. Proof of Proposition 1.

Without any loss of generality, fix $h_1 = \bar{h}_1 > 0$ and $\frac{x_2}{x_1} = m$. Let $r = \frac{h_2}{h_1}$. Then, after some algebra, it can be shown that

$$c_2=\frac{\partial c\left(h,x\right)}{\partial h_2}=\frac{\bar{h}_1^{\eta-1}}{x_1}\left[\begin{array}{c}-\left[\gamma_1+\frac{\gamma_2}{m}r^{\eta}\right]\gamma_s\left(\frac{1}{1+r}-\frac{1}{1+m}\right)\frac{1}{(1+r)^2}\\+\left[1+\frac{1}{2}\gamma_s\left(\frac{1}{1+r}-\frac{1}{1+m}\right)^2\right]\eta\gamma_2\frac{r^{\eta-1}}{m}\end{array}\right]$$

Notice that the second term is positive for all $r > 0$, whereas the first term is negative for all $r < m$, equal to zero for $r = m$, and positive for all $r > m$. Thus, for $r = 0$, i.e., $h_2 = 0$, the second term equals zero and $c_2 < 0$, whereas for $r = m$, $c_2 > 0$. By continuity, there exists $\hat{h}_2$ such that for all $r < \frac{\hat{h}_2}{\bar{h}_1}$, $c_2 < 0$. Similarly, there exists $\tilde{h}_2$ such that for all $h_2 > \tilde{h}_2$, $c_2 > 0$.

8.2. Proof of Proposition 2.

The Lagrangian for a representative fisherman's problem under species-specific quota regime is

$$\mathcal{L} = p \cdot l - c(l + d, x) - \lambda \cdot (l - \bar{l}),$$

where $\lambda \in R_+^m$ is a vector of Lagrange multipliers. Necessary conditions for optimal landings and discards, denoted l^* and d^*, respectively, are

$$\begin{aligned} p_i - c_i(l^* + d^*, x) - \lambda_i &= 0, \quad \lambda_i \left(l_i^* - \bar{l}_i\right) = 0, \quad i = 1, ..., m, & \text{(8a)} \\ -c_i(l^* + d^*, x) &\leq 0, \quad d_i c_i(l^* + d^*, x) = 0, \quad i = 1, ..., m, & \text{(8b)} \\ l_i^* &\leq \bar{l}_i, \quad i = 1, ..., m, \; d_i \geq 0 \quad i = 1, ..., m, & \text{(8c)} \end{aligned}$$

If $d_i > 0$, equation (8b) requires $c_i(l^* + d^*, x) = 0$. Then, from (8a), $\lambda_i = p_i \geq 0$ and $l_i^* = \bar{l}_i$. If $p_i = 0$, then $l_i^* \in \left[0, \bar{l}_i\right]$; here fishermen are indifferent between discarding all of the catch or landing the permissible amount. From (8a) it directly follows that if $l_i^* < \bar{l}_i$, $\lambda_i = 0$ and $p_i = c_i(l^* + d^*, x)$. Finally, if $l_i^* = \bar{l}_i, d_i = 0$,and from (8a) $p_i \geq c_i(l^* + d^*, x)$.

The implications for discarding are summarized in the vector λ. First, if for some $\bar{l}$, $\lambda_i = 0$, the landings constraint for species i does not bind. If $0 < \lambda_i < p_i$, the landings constraint for species i binds, and $d_i = 0$. If $\lambda_i = p_i$, $\bar{l}_i$ binds and d_i is likely to be positive (there will exist a particular $\bar{l}_i$ for which $mc_i(l^* + d^*, x) = 0$ and $d_i = 0$). Thus, $\lambda_i \in [0, p_i]$

If the quotas were traded in a lease market, it can be shown that the lease price of species i quota equals its equilibrium marginal profits. Under the representative agent construct, the equilibrium lease price will be

$$r_i = p_i - c_i^*.$$

But, from (8a), the RHS equals λ_i. Thus, $r_i = \lambda_i \in [0, p_i]$.

8.3. Proof of Proposition 3. Define $\hat{p} \equiv p - \tau$. The fisherman takes $\hat{p}$ as given. Under landings taxes the fishermen has no restriction on landing all of his catch h. The

Lagrangian for this problem is:

$$\mathcal{L} = \hat{p} \cdot l - c(l + d, x).$$

The first order necessary conditions are

$$\hat{p}_i - c_i(l^* + d^*, x) = 0, \quad i = 1, ..., m, \tag{9a}$$

$$-c_i(l^* + d^*, x) \leq 0, \quad \text{“} = \text{”} \text{ if } d_i^* > 0, \quad i = 1, ..., m. \tag{9b}$$

Thus, discard occurs if $c_i(l^* + d^*, x) = 0$. Notice further that any harvest target on the discard set, i.e., h such that $c_i(h, x) < 0$, can not be implemented by the manager since it will require $\hat{p}_i < 0$ i.e., $\tau_i \not> p_i$, which is not feasible. Why? If $\tau_i > p_i$, then $l_i^* = 0$ and then *effectively* $\hat{p}_i = 0$. In this case, $d_i^* \in [0, h_i^*]$.

8.4. Proof of Proposition 5. For the revenue-based quota the result is obvious. The manager is constrained to choose from the set described by Definition 3. For the other two cases it is useful to think of a two stage problem. Let us consider the sector-specific quota regime first. Given stock vector x, the manager announces a policy vector of permissible landings $\bar{l}$ that leads to fishermen's choice of harvest vector $h^*\left(x,\bar{l}\right) = h\left(x, h^*\right)$, where $h_i^* \leq \bar{l}_i$ for species with no discards and $h_i^* = \bar{l}_i + d_i^*$ for species with discard. What is the best $\bar{l}$ that the manager can choose? Let $h^*\left(x, \bar{l}\right) = l^*\left(x, \bar{l}\right) + z^*\left(x, \bar{l}\right)$. If $z_i^*\left(x, \bar{l}\right) > 0$, $d_i^*\left(x, \bar{l}\right) = z_i^*\left(x, \bar{l}\right)$, i.e., there is discarding of species i. On the other hand, if $z_i^*\left(x, \bar{l}\right) < 0$, $h_i^* \leq \bar{l}_i$, the quota of species i does not bind. Recall that the harvesting problem of the fishermen is static. The manager therefore only needs to incorporate their current period's decision rules into his own dynamic program, which can now be written as

$$\begin{aligned} V(x) &= \max_{\bar{l}}\{\sum_{i=1}^{m} p_i l_i^* \left(x, \bar{l}\right) + I_i z_i^* \left(x, \bar{l}\right) - c(h^* \left(x, \bar{l}\right), x) \\ &\quad + \beta\ V(G\left(x - h^* \left(x, \bar{l}\right)\right)\}. \end{aligned} \tag{10}$$

where I_i is an indicator function that takes a value of 1 if $z_i^* \leq 0$; otherwise $I_i = 0$. We show that $I_i = 1$ for all i. Suppose not, i.e. $\exists$ an $i \ni I_i = 0$. Then $d_i^* = z_i > 0$. Then the fishermen's decision rules imply that $d_i^* = h_i^* - \bar{l}_i$ and $l_i^* \left(x, \bar{l}_i\right) = \bar{l}_i$. An observation of (10) makes clear that by letting $\bar{l}_i$ to increase to h_i^* the manager can strictly increase $V(s)$ which contradicts (that it maximizes) the RHS while fishermen's harvest rules $h^* = h^* \left(x, \bar{l}\right) = h^*(x, h^*)$ are unaffected by this increase. Similarly, if $z_i < 0$, i.e., species i quota is slack, then by decreasing $\bar{l}_i$ to h_i^* for all $\bar{l}_i > h_i^*$, the fishermen's decision rules are unaffected, and the RHS of dynamic program remains unchanged.

A similar argument goes through for landing taxes. Let $h^*(x, \tau)$ denote the harvest decision rule of the fishermen. Then the dynamic program of the manager is:

$$\begin{aligned} V(x) &= \max_{\hat{p}}\{\sum_{i=1}^{m} p_i l_i^* (x, \hat{p}) - c(h^*(x, \hat{p}), x) \\ &\quad + \beta\ V(G(x - h^*(x, \hat{p})))\}; \\ \hat{p} &= p - \tau. \end{aligned}$$

We know from the fishermen's decision rules that $l_i^*(x,\ \hat{p} < 0) = l_i^*(x, 0) = 0$ and $d_i^*(x, \hat{p} < 0) = h_i^*(x, \hat{p} < 0) = h_i^*(x, 0) > 0$ if and only if $\tau_i > p_i$ since the effective dock-side price for fishermen is zero. By setting τ infinitesimally below p reverses fishermen's decision rules, i.e., $l_i^*(x,\ 0_+) = h_i^*(x, 0_+)$ and $d_i^*(x,\ 0_+) = 0$. Thus, allowing discards can not be optimal.

8.5. Proof of Proposition 6. From Lemma 1 and 2, it directly follows that $I^Q(x,p) \sqsubseteq I^T(x)$. Further, h in I^V implies that $h \notin D(x)$ (see Section 3.3). Moreover, I^V constrains $p_i \geq c_i$. These two together generate $I^Q(x,p)$. A further restriction under I^V is that $\frac{c_i}{p_i} = \frac{c_j}{p_j}$ for all i and j. Therefore, $I^V(x,p) \sqsubseteq I^Q(x) \sqsubseteq I^T(x) \sqsubseteq I^{SO}(x)$. The last of these relations is obvious.