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Rajesh Singh
Iowa State University, rsingh@iastate.edu

Quinn Weninger
Iowa State University, weninger@iastate.edu

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Rajesh Singh, Quinn Weninger

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Bio-economies of scope and the discard problem in multiple species fisheries

Rajesh Singh
Iowa State University

Quinn Weninger*
Iowa State University

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Abstract. This paper considers the problem of multi-species fisheries management when targeting individual species is costly and at-sea discards of fish by fishermen are unobserved by the regulator. Stock conditions, ecosystem interaction, technological specification, and relative prices under which at sea discards are acute are identified. A dynamic model is developed to balance ecological interdependencies among multiple fish species, and scope economies implicit in a costly targeting technology. Three regulatory regimes, species-specific harvest quotas, landing taxes, and revenue quotas, are contrasted against a hypothetical sole owner problem. An optimal plan under all regimes precludes discarding. For both very low and very high levels of targeting costs, first best welfare is close to that achieved through any of the regulatory regimes. In general, however, 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, discarding

*Correspondence: Quinn Weninger, Department of Economics, Iowa State University, Ames IA 50011 - 1040, USA; Phone: 515-294-8976; E-mail: weninger@iastate.edu

1. Introduction

Recent studies of the world's ocean fisheries identify a pattern of biological and economic decline. The list of problems include overfishing and serial stock depletion,[1] waste from discards of unwanted fish species,[2] and potentially irreversible alteration of ocean ecosystem function caused by excessive fishing pressure on high trophic-level species (Pauly et al. 1998).[3]

Management problems that arise due to the common property nature of fisheries' resources are well documented (Gordon, 1954; Munro, and Scott, 1996). Management difficulties have more recently been linked to a reliance on single-species management principles which ignore complex biological interactions found in real world fisheries.[4] A particular fallout of the single-species approach is the bycatch problem, i.e., unintended harvest, discard, and thus mortality of non-target fish species. FAO (2005) estimates that 8% of all harvested fish worldwide is discarded at sea. In US fisheries, discards of non-target species are estimated as high as 22% of total harvest (Harrington et al., 2005). In response to the perceived severity of the bycatch problem, the US National Oceanic and Atmospheric Administration's National Marine Fisheries Service has launched a National Bycatch Strategy 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).[5]

This paper demonstrates how economies of scope in fish harvesting create an incentive to discard fish under commonly practiced regulations that aim to address common pool problems in fisheries. We further show how scope economies alter optimal harvest policies and rent generation under such regulations.

The scope economies we consider characterize most if not all fisheries. Gear used to

[1] Food and Agricultural Organization (FAO) estimates that 25% of major fish stocks worldwide are overexploited, depleted or recovering from depletion; 52% are fully exploited, and 23% are under or moderately exploited (FAO, 2006). Serial stock depletion refers to a pattern of pushing farther and farther off shore to find undepleted fish stocks.

[2] 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; Harrington et al., 2005).

[3] The trophic level refers to the position that an organism occupies in a food chain. Pauly et al. (1998) raise concerns about the ecological impacts of a global trend that they call fishing down food webs, i.e., harvesting top predators first, and then turning sequentially to lower trophic level species.

[4] A growing view among fisheries scientists and marine ecologists is that a more holistic approach will improve the management of ocean fisheries resources (Brodziak and Link, 2002; Pikitch et al., 2004; Pew Oceans Commission, 2003; US Commission on Ocean Policy, 2004).

[5] 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 Bellman, 2006).

capture fish (e.g., nets, baited hooks, fish traps) regularly intercepts multiple fish species. The technology intrinsically embodies an economy of scope and produces a mix of species that depends on the absolute as well as the relative abundance of various species in the sea. Fishermen can target a particular species mix by employing different gear types at different locations, times of the year, times of the day, and depths.[6] However, targeting entails additional costs that fishermen, in general, will prefer to avoid.

In contrast to the above description of the harvesting technology, research on multiple species fisheries management has featured two extreme technological assumptions: cross-species cost independence (i.e., costless targeting of individual species) or, harvest in fixed-proportions to the relative abundance of stocks in the sea (i.e., no ability to target, or infinite targeting costs). These studies typically derive steady state harvest rules in competing species or predator and prey fisheries and show how harvest such policies 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. By definition, rebuilding plans can only be examined in dynamic frameworks.[7]

This paper extends the multiple-species bioeconomics literature in two directions. First, we dispense with the unrealistic extremes of technical independence or fixed-proportion catch across harvest of multiple species. Fishermen who target one of several fish species undertake costly actions to search out concentrations of the target species and/or take costly actions to avoid intercepting non-target species. Conversely, a strategy that involves no targeting efforts by the fisherman and therefore incurs no targeting costs will yield a particular harvest mix that will depend on the relative abundance of individual species stocks in the sea. To capture the unique form of scope economies in fisheries, we introduce a technology that links the harvest of multiple species to the composition of the in situ fish stock. In our framework, harvest costs rise as the fisherman's targeted harvest vector diverges from a no-target-cost harvest that is dictated by the relative abundance of stocks in the sea.[8] We allow for stock

[6] 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.

[7] 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.

[8] 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.

effects such that the resources required to harvest a unit of fish decline when stocks are more abundant. While "public" factors of production e.g., boats, gear, and labor create scope economies in the standard manner, the product mix in our technology is dictated by the relative abundance of the various species stocks.[9] It is this latter source of scope economies that is unique to fishing technologies.

Second, we numerically solve a *dynamic* multiple-species management problem in a model fishery that combines the above inter-species technological interactions with a Lotka-Volterra model of inter- and intraspecies ecological interaction (see 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 optimal harvest choices not only weigh current harvest returns against future stock benefits, but they also impinge on future scope economies through changes in relative stock abundance.

Important insights for the management of multiple species fisheries emerge. We show that at sea discards by fishermen arise when the individual-species harvest goal set by the regulator diverges sufficiently from the no-target-cost harvest mix. In such cases, fishermen can avoid targeting costs required to meet the regulator's harvest goal and simply discard any overages that cannot be legally landed.

We then study the problem of regulating the harvest of multiple fish species under a costly targeting technology. Three alternative regulatory schemes are examined, namely, tradable harvest rights in the form of 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. Quotas or landings taxes do not fully align divergent goals of autonomous fishermen and the regulator in the presence of unobserved discarding. As a result, these instruments do not achieve the first best outcome; we show how each regulatory instrument can achieve a "second best" management outcome.

We first identify harvest targets that are *implementable* when at sea discards are not observed. We employ a numerical dynamic optimization technique to compute the second best management policies by constraining the manager to choose from the set of implementable harvest targets only. Our results show that, in general, management constraints tend to be most pronounced, and thus the potential for discarding most severe, when the no-target-cost harvest mix and the regulator's preferred harvest mix diverge. Therefore, the second-best harvest policies trade off an ecologically desirable harvest, e.g., highest yield, against the

[9]Public factors, once acquired 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 management.

mix that minimizes targeting costs. The yield-target cost trade-off leads to harvest policies that substantially depart from conventional conservation principles, as demonstrated by our numerical results.

To understand this trade-off, consider for example a fishery with two competing species. Suppose one species has been overfished while the other is abundant. Ecological considerations, and conservation principles, suggest that to rebuild the depleted stock its harvest must be substantially reduced or stopped altogether, while to mitigate inter-species competition the harvest of the healthy stock must be increased. Our results show that a mismatch between harvest shares set by the regulator and the no-targeting-cost mix facing fishermen 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 regulator's harvest goal and the no-target-cost mix raises costs for fishermen introducing an incentive to intercept and discard the overfished species at sea.

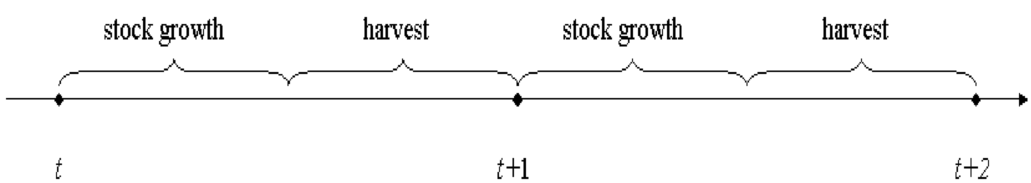
Optimal rebuilding may instead require only modest reduction in the harvest of depleted stock, which allows a higher harvest of the abundant species and reduced inter-species ecological competition. Thus, the depleted stock can be rebuilt by manipulating ecological interactions rather than through costly 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 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. 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, the latter being the case in which fishermen 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. While ranking the three, we show that landing taxes welfare dominate species-specific quotas while value-based quotas fare the worst.

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 incentives to discard under three alternative regulatory instruments. Solutions to the sole owner's problem as well as the constrained-management problem, along with their welfare rankings, are presented 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. Model

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. Stock abundance is assumed to be fixed during the harvesting phase, which allows us to treat the stock abundance simply as a constraint on 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 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 abundance requires extra efforts and is therefore costlier. Second, ecological interdependence among individual species 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. Harvest technology. Let $x \in R_+^m$ denote the stock of m species available at the beginning of an arbitrary harvest phase and let $z \in R_+^n$ denote an n-vector of inputs, for example, labor, capital, bait, and fuel, that is allocated to harvest. The harvest vector is denoted by $h \in R_+^m$.

The harvesting technology determines feasible combinations of inputs, outputs and stock levels. Let $H(z, x)$ denote a harvest possibilities set: $H(z, x) = \{h : z \text{ can harvest } h \text{ given } x\}$, where $h \in H(z, x)$ implies that, given stock abundance x, input z can intercept and land the vector $h = (h_1, h_2, ..., h_m)$. $H(z, x)$ is assumed to be closed, bounded, and nonempty for $z > 0$, $x > 0$. We assume further that $H(z, x) \supseteq H(\widetilde{z}, x)$ for $\widetilde{z} \geq z$ and $H(z, x) \supseteq H(z, \eta x)$ for $\eta \geq 1$; the harvest possibilities set does not contract with increased inputs or *proportional*

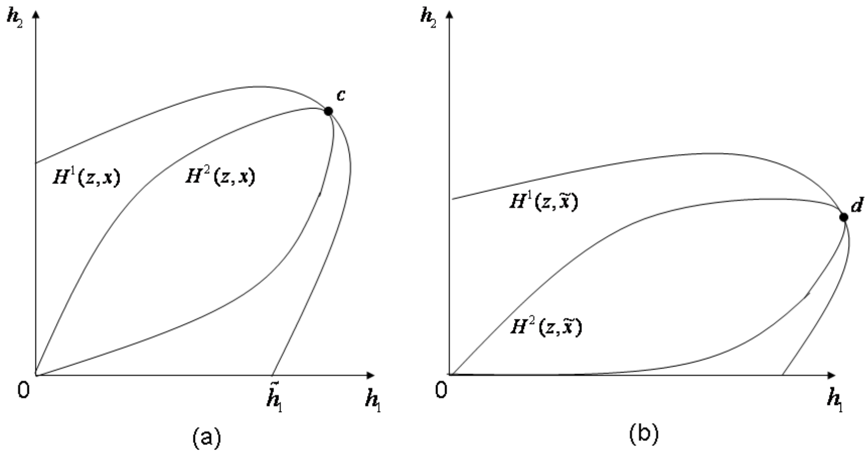


Figure 1: Multiple species harvest sets under cost targeting technologies.

increases in stock abundance. In future, for a given z and x, we denote $H(z, x)$ simply by H.

Multiple-species stock effects. For any given fishing technology and inputs employed, harvest possibilities in a multi-species fishery crucially depend on the composition of the available fish stock. Targeting a single species for example entails *costly avoidance* of other species. These costs in turn depend on the degree of targeting flexibility embedded in the technology. Turner (1995, 1997) recognized that costly targeting of individual fish species can be represented with a weak output disposability technology. Weak output disposability is often used to characterize technologies that produce both desirable and undesirable outputs, and for which disposal of the undesirable outputs utilizes valued factors of production (see Färe et al. (1994) for additional discussion). In the current context, weak output disposability reflects the fact that valued factors of production are utilized in preventing the fishing gear from intercepting non-target fish species. Figure 1 demonstrates this property for a two-species fishery example.

Panel (a) in Figure 1 depicts harvest sets for two example technologies, denoted by superscripts 1 and 2.[10] Harvest sets in panel (a) are conditional upon a common input bundle, z, and are conditional on common stock abundance, x. Stock abundance in panel

[10]Observe that, as the set of inputs and therefore the cost of production is fixed along the frontiers, the harvest possibilities curves essentially represent iso-cost curves. It should be noted that there is no reason to expect that, for a given input bundle, the harvest frontiers under technologies offering different flexibility will be tangential to one another (point c in panel (a), point d in panel (b)). The figure depicts special examples only for expositional convenience.

(b) differs and is discussed below. Each harvest set exhibits weak output disposability but varies in terms of the *flexibility* with which the mix of species can be adjusted by the fisherman.

Under technology 1, as exhibited by H^1, specialization, i.e., zero catch of one species and strictly positive catch of the other, is possible but costly. Since the input vector is fixed, the cost of targeting is reflected as foregone harvest. A fisherman who wishes to specialize in the harvest of 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, for example 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 fishing gear.

With technology 2, as exhibited by harvest set H^2, zero harvest of one species is possible only if the harvest of the other species is also zero; specialization is ruled out. Notice that targeting under technology 2 is generally more costly than under technology 1.

It is instructive to contrast the weak output disposability technology with fixed proportions and independent harvesting technology assumptions which dominate the multiple-species fishery literature. Under a *fixed-proportions* technology adjustments to the mix of harvested species is not possible. Assuming efficiency in production, this technology can be represented simply as point c in Figure 1. Under fixed proportions, the fishermen can adjust the scale of production only. At the other extreme, technological independence across harvested species, or a non joint-in-inputs technology, implies the existence of species-specific harvest functions, i.e., neither economies nor diseconomies of scope.

The single-species bioeconomics literature treats the fish stock as a normal production input; harvest is assumed 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 another), it is reasonable to expect that the mix of species intercepted by the fishing gear will positively depend on the composition of the stock (Mayo et al., 1981; Murawski, 1984). In what follows, we assume that targeting costs are lowest, in fact zero, when harvest shares are equal to stock shares. [11] More precisely, given stock abundance x, a harvest vector h with individual species shares $h_i / \sum_{i=1}^{m} h_i$ that are proportional to stock abundance shares, $x_i / \sum_{i=1}^{m} x_i$, is likely to require the fewest targeting inputs. On the other hand, more targeting inputs will

[11] This assumption is merely to simplify the analysis. In general, when a fishing strategy does not involve added targeting effort, its propensity to intercept species a more than species b will positively depend on a's abundance relative to b. See Appendix for details.

be required to harvest a mix of species that differs from the mix of individual species stocks. This suggests that the shape of the harvest possibilities set must depend on both absolute and relative abundance of the individual species stocks.

To further illustrate the implications of costly targeting, consider (h, x) such that $h_i / \sum_{i=1}^{m} h_i = x_i / \sum_{i=1}^{m} x_i$ for all i. Holding h fixed, consider an alternative stock vector $\widehat{x}$ where $\widehat{x}_1 > x_1$ and $\widehat{x}_j = x_j$ for $j = 2, 3, .., m$. It is conceivable that more targeting inputs will be required to harvest h since the fisherman must take measures to avoid the now more abundant species 1 fish. This suggests that, contrary to the assumption in the single-species literature, monotonicity between the harvest and the stock may not hold globally.

Returning to Figure 1, Panel (b) illustrates the hypothesized effect of an increase in the relative abundance of the species 1 stock. In our example, H^1, and H^2 in panel (b) are conditional on the common input bundle z (unchanged from panel (a)) but new stock abundance satisfying $\widetilde{x}_1/\widetilde{x}_2 > x_1/x_2$. For each harvest set, the feasible h_1 is increased relative to h_2 reflecting the increase in relative abundance of the species 1 stock. Lastly, we note that under a fixed-proportions technology, the harvest would be fixed at point d with the share of h_1 in the catch increased due again to the relative increase in the species 1 stock.

The discard set. If a fisherman chooses to discard fish at sea, *landed* fish 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%.[12] This second assumption simplifies the notation allowing us to equate the harvest with fishing mortality.

To characterize the incentive to discard fish at sea, we first define the *efficient* harvest set as

$$H^e = \{h \in H(z, x) : \widetilde{h} > h \;\Rightarrow\; \widetilde{h} \notin H(z, x)\}.$$

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.

Refer to the harvest set $H(z, x)$ in Figure 2. The efficient set H^e is shown as the segment bc. Elements of H^e satisfy the condition that the marginal rate of product transformation between any two species is non-positive. In contrast, for all other points along the boundary (or isoquant) of $H(z, x)$ that are not in H^e the rate of product transformation between two species is positive.

[12] 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.

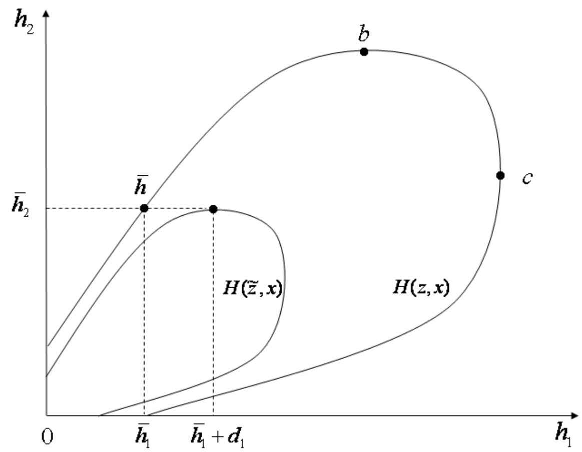


Figure 2: Discarding under weak output disposibility.

Assuming nonnegative prices for landed fish, profits can only decline if intercepted fish is discarded at sea. Then $h \in H^e$ is a necessary condition for profit maximization in the absence of any regulation. Under certain regulations, however, discarding fish at sea can increase private fishing profits. To see this, suppose that in response to conservation goals the fishery manager attempts to regulate catch at $\overline{h} = \left\{\overline{h}_1, \overline{h}_2\right\}$ 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. As shown in the figure, inputs that would otherwise be allocated to targeting activities can be saved by intercepting a mix of species that more closely mirrors the relative stock abundance. These input savings are exhausted at $\left\{\overline{h}_1 + d_1, \overline{h}_2\right\} \in H^e(\widetilde{z}, x)$, with $\widetilde{z} < z$.

Generalizing the above, we can define a discard set as the set of (regulated) harvest vectors for which fishermen can reduce harvesting costs by discarding fish at sea:

$$D(z, x) = \{h : h \in H(z, x),\ h \notin H^e(z, x)\}$$

Dual representation. Harvest technologies exhibiting weak output disposability cannot be represented with single-valued production or transformation functions (Diewert, 1973). To facilitate analysis of the dynamic management problem (Section 4) we adopt a dual representation of the costly targeting technology. We define the cost function as

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

where w denotes a n-vector of strictly positive fixed unit input prices. We assume that the cost function is non-decreasing and linearly homogeneous in w. It bears emphasis that the cost function is defined over intercepted fish (harvest), 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. Figure 2 for example shows that costs decline as h_1 is increased from $\{\overline{h}_1, \overline{h}_2\}$ to $\{\overline{h}_1 + d_1, \overline{h}_2\}$. The implication is that for $\overline{h} \in D(z, x)$ the marginal cost is negative for at least one harvested species. We can define the (dual) discard set as

$$D(w, x) = \{h : \partial c(w, h, x)/\partial h_i < 0 \text{ for some } i\}.$$

In future, we let $c_i \equiv \partial c/\partial h_i$. Inputs prices are assumed fixed, and to ease notation are hereafter suppressed.

The following cost function, which we utilize for our exercises in Section 5, captures the weak output disposability property in a two species fishery (a more general version of the following cost function appears in an appendix equation (7)):

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

This cost function leads to the following proposition.

Proposition 1. *Fix $h_1 = \bar{h}_1$. Then for any given $x_1, x_2 > 0$, there exists $\hat{h}_2 < \bar{h}_1 \frac{x_2}{x_1}$ such that for all $h_2 < \hat{h}_2$, $c_2 < 0$, i.e., the harvest vector $\left\{\bar{h}_1, h_2 < \hat{h}_2\right\}$ falls in the discard set.*

Proof. See Appendix 8.1. ■

Proposition 1 makes clear that any regulations that set harvests at $\left\{\bar{h}_1, \bar{h}_2\right\}$ with $\bar{h}_2 < \hat{h}_2$, will provide incentives to discard species 2 fish. Moreover, the threshold $\hat{h}_2$ depends on the permissible harvest for species 1 as well as the relative abundance of the two stocks. An observation of the cost function in (1) clarifies that the result stated in Proposition (1) holds symmetrically for both species.

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)). At the other extreme, as $\gamma_s \to \infty$, the cost function represents a fixed proportions technology.[13]

[13]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.

It bears emphasis that the above technological representation is introduced in terms of *aggregate* stock and harvest levels. Fisheries are typically exploited by many fishing firms. To simplify analysis and avoid introducing additional firm-level notation, we assume that there exists a *continuum* of identical fishermen uniformly distributed in $[0, 1]$, and each endowed with an identical harvesting technology. This allows us to consider the decision problem of a representative fisherman. Moreover, under this construct, per-fisherman and aggregate outcomes coincide in equilibrium.[14]

2.2. Stock growth. We assume the following Lotka-Volterra stock growth model:

$$x_i' = s_i' + r_i s_i' \left(1 - s_i' - \sum_{j \neq i} \alpha_{ij} s_j' \right), \quad i = 1, ..., m. \tag{2}$$

Recall that in our model the growth phase precedes the harvest phase. In the above expression $s_i' \equiv x_i - h_i$ denotes species i escapement at the end of the current harvest phase (equivalently, the beginning of the next period); x_i' denotes its stock abundance at the beginning of next period. The parameter r_i reflects the intrinsic growth 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. Implementable choices under alternative regulatory regimes

In this section, we study common regulations used to address inefficiencies in open access fisheries. 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, and therefore can not penalize discards at sea. Our goal is to identify cases under which the harvest levels chosen by fishermen diverge from the harvest goal selected by the manager.

We assume that the fishermen's objective is to maximize current period fishing profits. If the fishermen did not discard fish, landings and catch coincide and the manager can control catch through landings. However, with a harvesting technology that exhibits weak output disposability, catch and landings are not identical if the manager's landings' target falls in

[14] In general, if the technology is not CRTS a representative agent set up may not be appropriate and an additional entry condition may be required. However, if the mass of agents is exogenously fixed, as long as all the individuals make positive profits no one will exit. Indeed, with diminishing returns to scale, and in the absence of fixed costs, the profits are always positive and the equilibrium number of agents with free entry is infinite. If instead the number of fishermen is fixed at a large number, all of them will be active. Fixing the *mass* of these agents at unity essentially allows us to avoid differentiating between per unit and aggregate outcomes. The results will not change if instead the number of agents is fixed at a finite large number and the cost function is appropriately reparameterized.

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

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

where $p \in R^m$ denotes the vector of dockside prices for landed fish (vector conformability is assumed). It is worth noticing that the price of some species is allowed to be negative. These species will not be landed by fishermen; if caught, will be discarded. On the other hand, fixing a positive landing amount for such species is meaningless; such quotas will never be utilized. The following proposition summarizes the properties of a discarding equilibrium under this form of regulation.

Proposition 2. *(i) Under a species-specific quota regime, 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 $c_i^* \geq p_i$.*

Proof. See Appendix 8.2 ■

The intuition behind the result stated in Proposition 2 is simple. Since landings can not exceed the quota, discarding occurs if the profit maximizing harvest exceeds the landing quota. Conversely, if the harvest 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 harvest 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 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; the profit maximizing harvest equates marginal cost with the dockside price. In such cases the landing constraint is *slack.* However, if c_i evaluated at $\bar{l}_i$ is positive but below (or equal to) the species' dockside price, the quota is fully utilized. In such cases, 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 quota 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 $r_i \in [0, p_i], i = 1, ..., m$.*

$$r_i = \begin{cases} p_i - c_i^*, \text{ if } p_i \geq c_i^* \\ 0, \text{ if } p_i < c_i^* \end{cases}$$

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 harvest 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. Landing taxes. Under landing taxes, 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.[15] A representative fishermen then chooses landings and discards to maximize profits:

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

[15] 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.

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 ■

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 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 amount less than the optimum is negative. 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 under landing taxes. 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 quotas (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 dockside 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

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

This condition states that for any two species, the rate of product transformation, $-c_i(h,x)/c_j(h,x)$, 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.[16]

The implementable set under a value-based quota. A downside of a revenue quota regime, recognized by Turner (1995), is that the manager has limited control over the aggregate harvest in the multiple species 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*

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

3.4. The ranking of implementable sets. We have identified the set of harvest vectors that can be implemented under three regulatory regimes. It is useful to compare these implementable sets with a benchmark that a hypothetical sole owner of the fishery would face. Observe that a sole owner's implementable harvest set is constrained only by the available stock:

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

The following Lemma ranks the regimes in terms of the restrictions they impose on the implementable harvest sets.

[16] 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.

Lemma 1.

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

Proof. See Appendix 8.4. ■

The set of implementable harvests under the three regulatory regimes are illustrated graphically in Figure 3. The curve with the broken lines is a representative iso-cost curve (also a harvest possibilities frontier for a given input bundle), $c(h,x) = \bar{c}$, with stock levels $x_1 = x_2$ for the two species. The iso-cost curves in the example of the figure are homothetic (see (1)) and the points that demarcate elements of the efficient harvest set and harvests exhibiting positive marginal rates of product transformation fall along the rays $0-a$ and $0-b$. Observe that $\bar{c}_1 = 0$ along $0-a$ while $\bar{c}_2 = 0$ along $0-b$. Thus the discard region for species 1 lies to the left of $0-a$ (i.e., the triangular region $0-x_2-a$), while for species 2 the discard region lies to the right of $0-b$ (i.e., the triangular region $0-x_1-b$).

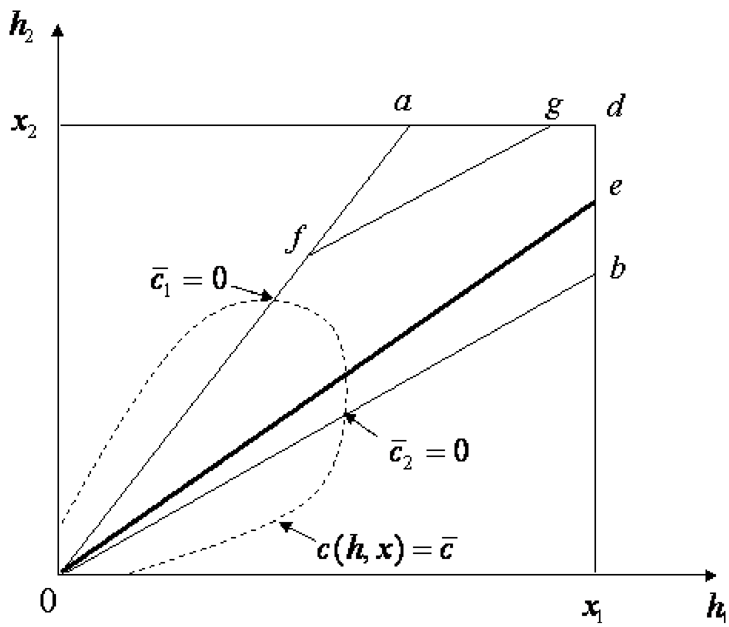


Figure 3: Implementable harvest sets

For the sole owner, the only constraint on implementable harvest choices is that they not exceed the available stock, i.e., $h_i \leq x_i$, for $i = 1,2$. Thus, the sole owner is able to implementable all harvests in the rectangle $0-x_2-d-x_1$. Under a landings tax and species-specific quota regulation, implementability is constrained further by the requirement that marginal costs be nonnegative. Thus, the landing tax implementable set shrinks to

$0-a-d-b-0$. Species-specific quotas face a further constraint that dockside prices must exceed marginal costs. To demonstrate, we assume that the dockside price of species 2 is low. Suppose $p_2 < c_2(h,x)$ in the region $a-g-f$, i.e., where h_2 is relatively high. The implication is that with a low species 2 price only harvests in the region $0-f-g-d-b-0$ can be implemented under a species-specific quota. Finally, under a revenue-based quota, implementable harvests must satisfy $c_1(h,x)/p_1 = c_2(h,x)/p_2 < 1$. With $p_2 < p_1$ minimizing the cost of attaining a revenue target requires $c_2(h,x) < c_1(h,x)$. For the case of equal stock abundance across the two species, fishermen will harvest a mix which satisfies $h_2 < h_1$. Homotheticity implies that the ratio of marginal costs is scale invariant and thus the implementable harvest set under a revenue-based quota is a ray such as $0-e$ in Figure 3.

By characterizing the implementable sets under the instruments of our interest, we have identified the constraints on optimal harvest choices in each period. The optimal harvest policy must additionally incorporate the dynamic biological aspects that stem from the stock growth model in (2). This is the task we undertake now.

4. OPTIMAL MANAGEMENT UNDER WEAK OUTPUT DISPOSABILITY

Our objective in this section is twofold: first, to study rules, i.e., species-specific quotas, taxes, revenue caps that maximize welfare within their respective regimes, and second, to compare them to the rules chosen by a hypothetical sole owner, or equivalently, the solution to the problem of a manager who can perfectly observe and control at-sea activities of the fishermen. The task of ranking regulatory instruments turns out to be easier and is shown below analytically. For computing constrained-optimal rules within each regulatory regime however we resort to numerical solutions, in which the sole-owner's harvest rules are used as the benchmark for understanding and evaluating each alternative.

In the absence of discarding and the problem of harvest slacks, as would be the case for a sole owner, the manager's harvest target can be implemented simply by setting landings at the optimal harvest levels. A manager may then wish to choose a harvest vector that falls in the discard set or implies a harvest slack, if such a choice adjusts the stock in a way that yields higher future returns. On the other hand, under the assumption that fishermen maximize *current period* profits, the impacts of discarding on future payoffs are not internalized.[17] The manager's harvest plan that is an element of the discard set will then lead to wasteful mortality of fish. The extent to which such divergent objectives of fishermen constrain the

[17] The assumption that fishermen are fully myopic is made to simplify the analysis. Arnason (1990) examines conservation incentives of individual fishermen operating in a rights-based fisheries management program.

manager's implementable aggregate harvests and reduce fishery value is of particular interest in what follows.

Below, we first study a sole-owner problem. Following the bioeconomics literature, the sole owner construct will provide a benchmark policy from which to assess the performance of our three regulatory instruments which remain subject to the hidden action problem, i.e., unobserved discarding.

4.1. The sole owner problem. At the beginning of the harvest phase, the owner observes the available stock x and selects current harvest h. The management 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 which, by equation (2), determines current stock abundance x. The control vector is $s' = x - h$, and β is the discount factor where $0 < \beta < 1$. The solution to this problem is an escapement policy or equivalently a harvest policy that specifies s' for all possible states s. The maximized value of the fishery for a given state s is $V(s)$.

Assuming an interior solution, the first order conditions with respect to the optimal harvests can be written as

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

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 the 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 (Clark, 1990; Flaaten, 1991)

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

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 $p_j - c'_j$ 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, or the *user cost* of the species i stock.

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. 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. Decentralized management. We now turn to the harvest policies that are implementable under decentralized management. Although the manager cannot observe and therefore cannot control at-sea fishing practices, he knows the decision rules of fishermen and is fully aware of the harvest and thus fishing mortality outcomes under various forms of regulation.

We know that the sole-owner can choose harvests within the discard set (although the catch is never discarded/wasted). Would the manager also not like to do so under decentralized management? Are there any future stock benefits that can accrue from such a harvest choice? The following proposition addresses these questions.

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 8.5. ■

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 is not 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 choice (which in this case equals landings) is what matters 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 assumed 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 regulatory 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. Directly follows from Lemma 1. ■

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.

From a policy perspective, the sole owner's problem can be implemented if monitors were placed on board and a system of penalties for discarding and/or rewards for targeting could induce fishermen to harvest their allocated quotas including elements of the discard set. Essentially then, monitoring will expand the harvest set to the sole owner's implementable set $\{h : h \leq x\}$. Suppose the cost of such monitoring is C_{obs}. Then, relative to any other regulatory regime with fisheries' value V^R, $R \in \{T, Q, V\}$, the monitored program can obtain $V^{SO} - C_{obs}$.

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. In this section, we use numerical methods to solve for the value function and the optimal management policies under alternative regulatory regimes; the optimal policy employed by the sole owner serve as a benchmark for all comparisons.[18] 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 two species that are 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; $p_2 = \frac{1}{3}p_1$. We suppose that due to the price differential, the high-price stock has been overfished while the low-price stock has been underfished relative to their respective steady states. The challenge for the manager is to restore each stock to its constrained-optimal steady state value.[19]

Figure 4 plots the sole owner policy (solid curves) and a second-best policy which is implementable under a species-specific quota regulation (dashed curves). From top to bottom, the panels in the figure show: (a) the stock of high-price species; (b) the stock of low-price species; (c) the harvest of high-price species; (d) the harvest of low-price species; and (e) the marginal costs for both species. Policies are shown for twenty four periods.

Consider first the stocks and harvests under the sole owner policy. The sole owner policy calls for aggressive investment in the high price stock. The initial harvest of the high-price species (panel (c)) is kept low, and the initial harvest of the low-price species (panel (d)) is set high. Note 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 when a stock is below its steady state value. Under a costly targeting technology,

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

[19] Note that because implementable harvests differ across regulatory regimes, steady states are in general specific to the regime that is in place.

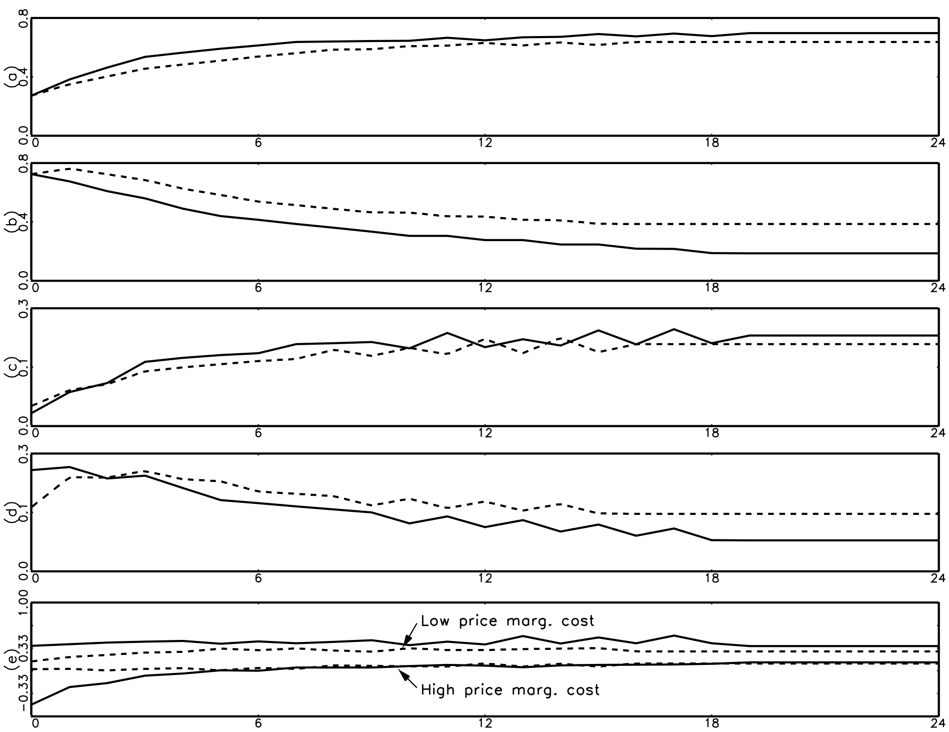

Figure 4: Sole owner versus species-specific quota regime: Panels are: (a) high-price stock; (b) low-price stock; (c) high-price harvest; (d) low-price harvest; (e) marginal harvest costs. Solid curves depict the sole owner policy. Dashed curves depict the species-specific quota policy. Parameter values are $r_1 = r_2 = 1$; $\alpha_1 = \alpha_2 = 0.35$; $p_1 = \$1$, $p_2 = \$1/3$; $\gamma_1 = \gamma_2 = 0.25$, and $\gamma_s = 50$.

the sole owner implicitly weighs the gains from setting catch shares that differ significantly from stock shares. More precisely, the date zero stock share for the high-price species is 0.272, whereas the catch share is 0.110 under the sole owner policy. Further reductions in the high-price species harvest (or further increases in the 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. This is because the costly targeting technology requires an alignment of harvest and stock shares to control targeting costs, which slows the transition to steady states.

The bottom panel of Figure 4 shows that the sole-owner marginal cost for the high-price species is negative during the first five production periods. That is, aggressive harvest of the low-price species with concurrent protection of the high-price species puts the sole owner's 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 results shown as the dashed curves in Figure 4. Under second best, 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 of \$1/3. 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 0.238 (stock share is 0.272). Maintaining similar harvest and stock shares keeps targeting costs low, as is required to avoid discarding.

We note that at the sole-owner steady state the low-price species marginal cost (\$0.39) exceeds the dockside price. The sole owner incurs losses at the margin 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 high- and low- price species are respectively below and above 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, further reduction in the low-price stock is also costly. The growth characteristics of competing fish species explains this result. As the low-price species' stock is reduced, less intraspecies competition increases 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 less inter-species competition, it is too costly to further reduce the low-priced stock.

Figure 5 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) (a) the stock of high-price species, (b) the stock of low-price species, (c) the harvest of high-price species, (d) the harvest of low-price species, (d) and the marginal costs for high- and low-price species.

The results show that while stocks and harvests under landings taxes follow a different transition 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

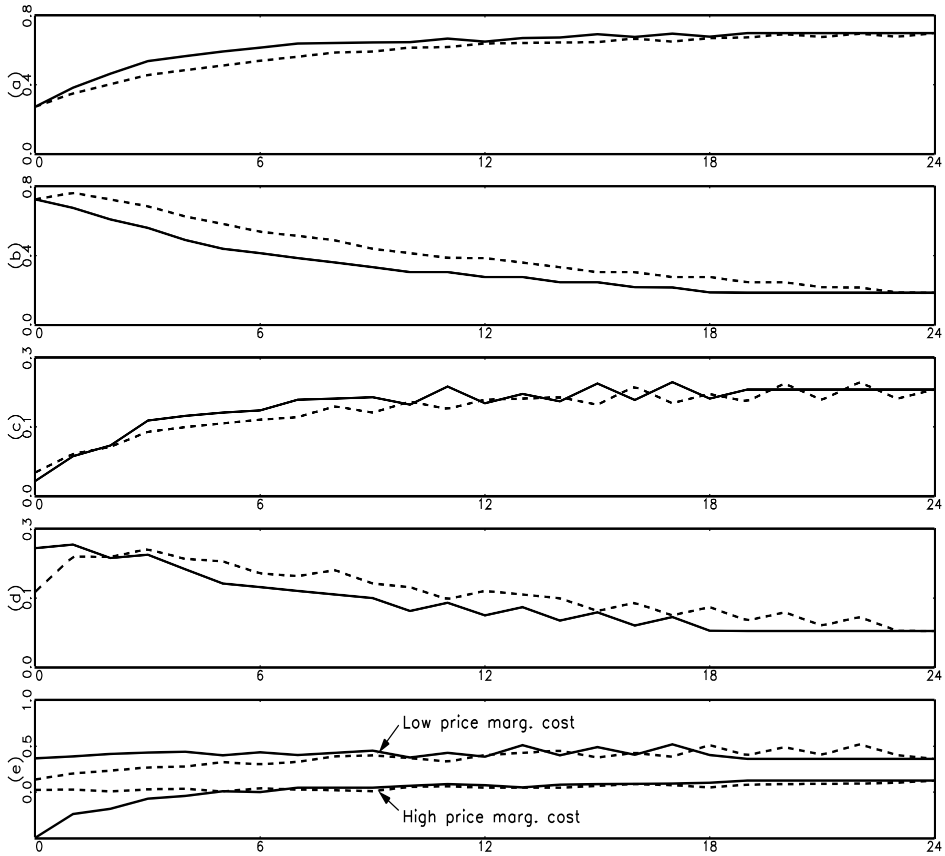

Figure 5: Sole Owner vs. Landings Tax Policy. Panels are: (a) high-price stock; (b) low-price stock; (c) high-price harvest; (d) low-price harvest; (e) marginal harvest costs. Solid curves depict the sole owner policy. Dashed curves depict the landing tax policy.

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.[20] 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 are 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 75% 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 346% of the sole owner level. Steady state harvests of the high- and low-price species are respectively 74.8% and 246.9% of their sole owner counterparts. The lack of control over individual species harvests and stocks reduces the value of the fishery considerably. Fishery

[20] A figure showing the value-based quota policy results adds few additional insights, and to save space is not included. The figure is available from the authors on request.

value under the value-based 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, 99.4% and 99.7% of the sole-owner value.

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. We assume that both stocks are initially below their respective steady state values, and thus stock rebuilding is called for.

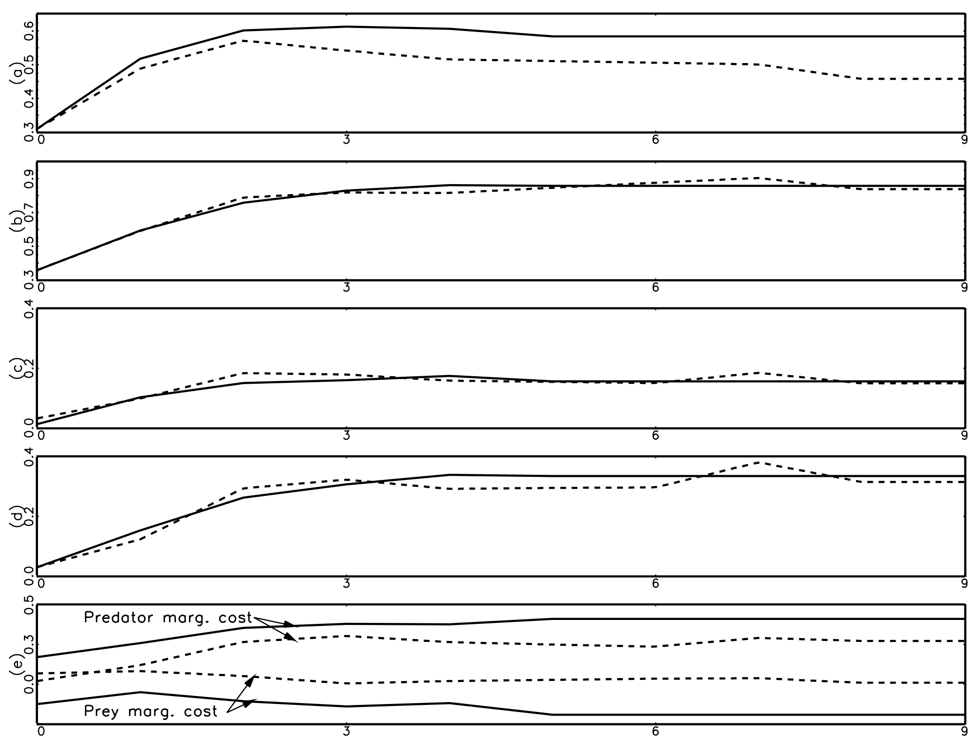

Figure 6: Sole Owner vs. alternative regulatory regimes in a predator-prey fishery. Parameter values in this example are: $r_1 = r_2 = 1$; $\alpha_1 = 0.4$, $\alpha_2 = -0.4$; $p_1 = p_2 = \$1$; $\gamma_1 = \gamma_2 = 0.25$; and $\gamma_s = 75$. Panels are: (a) prey stock; (b) predator stock; (c) prey harvest; (d) predator harvest; and (e) marginal harvest costs. Solid curves depict the sole owner policy. Dashed curves depict the landings tax and species-specific quota policies.

Figure 6 shows from top to bottom, (a) the prey stock, (b) the predator stock, (c) the prey harvest, (d) the predator harvest, and (e) the marginal costs. The solid curve depicts the sole owner policy and the dashed curve depicts both the species-specific and landings tax regimes. Dockside prices are set sufficiently high and harvests are low during the stock rebuilding phase. Thus there are no harvest slacks under the species-specific quota and thus the two second best policies coincide.

With a predator-prey fishery there is growth complementarity among the two species since a higher prey stock enhances growth of the predator. Both stocks are initially low, and their respective shadow prices are high, calling for aggressive investment in each stock, i.e., low initial harvest. With low initial stock abundance there is minimal intraspecies competition and high growth rates. Since the growth of the predator increases with the size of 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 catch share under decentralized management. 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 such harvests in the discard set during the approach to and at the steady state (see bottom panel). In contrast, the second-best policies are 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 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 7 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.[21] Consistent with Proposition 6, the percentage losses are largest under the value-based quota, followed by species-specific quotas, and then landings taxes.

At $\gamma_s = 0$, landing taxes and species-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 fishermen, i.e., dockside

[21] 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.

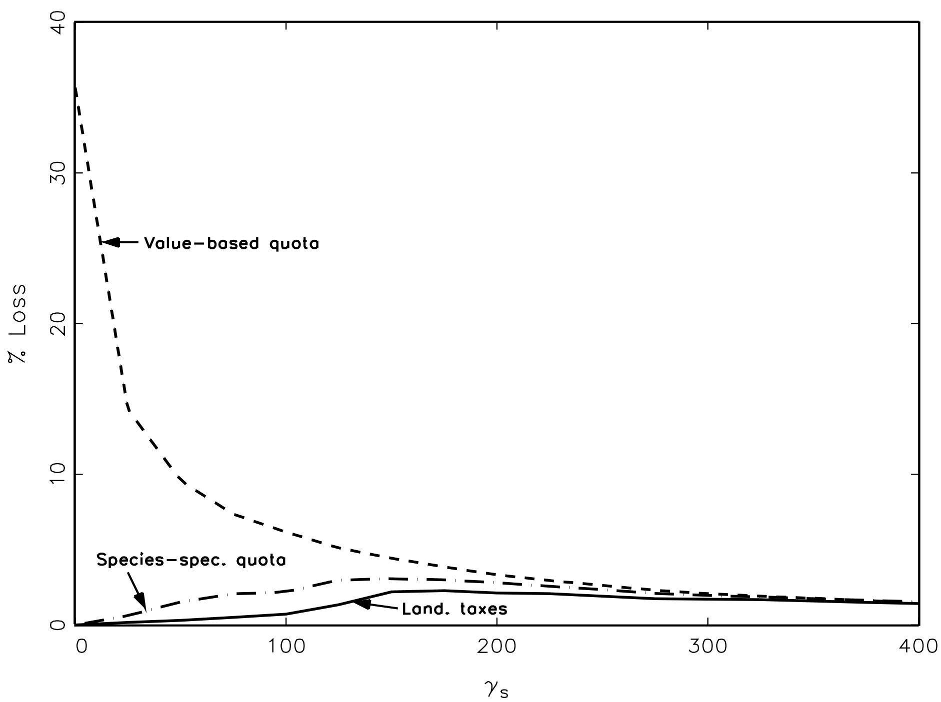

Figure 7: Lost fishery value due to unobservable at-sea discards. Parameter values are $r_1 = r_2 = 1$; $\alpha_1 = 0.4$; $\alpha_2 = -0.4$; $p_1 = \$1$, $p_2 = \$1/3$, $\gamma_1 = \gamma_2 = 0.25$.

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 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 poorly.[22]

Figure 7 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 technology. The ratio of 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

[22] 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.

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 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 implementable harvests. From the sole owner's perspective, when targeting costs are low, intertemporal ecological considerations dominate leading some preferred 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 type, bait, 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 a no-target-cost harvest mix implied by the composition 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 is aligned with 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 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.

The focus of this paper has been on harvesting and discards of fish species which have consumptive value. Incidental bycatch of sea birds, sea turtles, dolphins and other marine mammals poses a serious threat to the viability of commercial fisheries. Our model can be readily used to address the bycatch problem of species with non-consumptive values, and to study losses that arise when sea birds and mammals are killed during fishing operations. The insights gained in the preceding sections continue to apply.

We have only considered variable harvesting costs in the paper. In practice, fishermen do incur fixed costs in acquiring and maintaining fishing boats and accessories. In a dynamic set up, which is the case in our paper, including capital in the model and costly capital adjustment introduces an additional choice of optimal capital and an additional state variable. While this is an important aspect of optimal fisheries management, it complicates our analysis and we feel adds few additional insights to the discard problem and optimal management of multiple species fish stocks. It is our conjecture that having fixed capital will introduce policy persistence with respect to the level of optimal harvests (Singh et al., 2006). However, inter-species trade offs, and therefore discards, will remain very much at the core of the problem since variable costs will still depend on the relative stock abundance.

As a result, our qualitative results will continue to hold under fixed costs.

Another 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. This 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 (Brodziak and Link, 2002; 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 programs 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, 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.

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8. Appendix

The cost function in 1 is a special case of

$$c(h,x) = \left[1+\kappa \textstyle\sum_{i=1}^{m} \gamma_{s,i} \left[\theta_i - \chi_i(\varphi_i)\right]^2\right] \left[\textstyle\sum_{i=1}^{m} \dfrac{\gamma_i}{x_i} h_i^{\eta_i}\right], \tag{7}$$

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 $m=2$, $\kappa = \frac{1}{4}$, $\gamma_{s,1} = \gamma_{s,2} = \gamma_s$, and $\chi_i(\varphi_i) = \varphi_i$, 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 $\frac{x_2}{x_1} = \delta$. Let $r = \frac{h_2}{h_1}$. Then, after some algebra, it can be shown that

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

Notice that the second term is positive for all $r > 0$, whereas the first term is negative for all $r < \delta$, equal to zero for $r = \delta$, and positive for all $r > \delta$. Thus, for $r = 0$, i.e., $h_2 = 0$, the second term equals zero and $c_2 < 0$, whereas for $r = \delta$, $c_2 > 0$. Further, notice that the first term is monotonically increasing in r. Then , by continuity, there exists $\hat{r} < \delta$, such that $c_2 < 0$ for all $r < \hat{r}$. Equivalently, there exists $\hat{h}_2 < \bar{h}_1 \frac{x_2}{x_1}$ such that for $h_2 < \hat{h}_2$, $c_2 < 0$.

What is the sign of marginal costs for $r \in [\hat{r}, \delta]$? With our choice of parameters $\{\gamma_1, \gamma_2, \gamma_s, \eta\}$, we numerically find that the function is well behaved and the marginal cost crosses zero only once, in which case indeed $c_2 > 0$ for all $h_2 > \hat{h}_2$ (see Section 5 in the text).

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

$$p_i - c_i(l^*+d^*,x) - \lambda_i \leq 0, \text{ "}=\text{" if } l_i^* > 0; \quad \lambda_i\left(l_i^* - \bar{l}_i\right) = 0, \quad i = 1,...,m, \tag{8a}$$

$$-c_i(l^*+d^*,x) \leq 0, \quad d_i^* c_i(l^*+d^*,x) = 0, \quad i=1,...,m, \tag{8b}$$

$$l_i^* \leq \bar{l}_i, \quad i=1,...,m,\ d_i \geq 0 \quad i=1,...,m, \tag{8c}$$

First, suppose $d_i^* > 0$. Then equation (8b) requires $c_i^* = 0$. Then, from (8a), $\lambda_i \geq p_i$. If $p_i < 0$, $l_i^* = 0 \leq \bar{l}_i$ and $\lambda_i = 0 > p_i$. If $p_i = 0$, then $l_i^* \in \left[0, \bar{l}_i\right]$ and $\lambda_i = p_i = 0$;

here fishermen are indifferent between discarding all of the catch or landing the permissible amount. If $p_i > 0$, then $\lambda_i = p_i > c_i^* = 0$ and $l_i^* = \bar{l}_i$. Thus, whenever $l_i^* < \bar{l}_i$, $\lambda_i = 0$ and $p_i \leq c_i^*$.

Now, suppose $d_i^* = 0$.Then equation (8b) requires $c_i^* > 0$. If $p_i < 0$, $l_i^* = 0 \leq \bar{l}_i$, $\lambda_i = 0$, and from (8a) $p_i < c_i^*$. If $p_i = 0$, then $l_i^* > 0$ is not consistent with no discards, i.e., $c_i^* > 0$, because by reducing l_i profits can be increased. Finally, if $l_i^* = \bar{l}_i$, then $p_i > \lambda_i = p_i - c_i^* > 0$. Irrespective of whether discards occur or not, $l_i^* < \bar{l}_i$ if and only if $p_i \leq c_i^*$.

The implications for discarding are summarized in the vector λ. If $p_i < 0$, $\lambda_i = 0$. If $p_i \geq 0$, $\lambda_i \in [0, p_i]$

If quotas are traded in a lease market, it can be shown that the lease price of species i with $p_i > 0$ equals its equilibrium marginal profits:

$$r_i = \begin{cases} p_i - c_i^*, \text{ if } p_i \geq c_i^* \\ 0, \text{ if } p_i < c_i^* \end{cases}$$

Then, it follows from the above analysis that $r_i = \lambda_i$.

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

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

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

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 $c_i < 0$, can not be implemented by the manager since it will require $\hat{p}_i < 0$. But then $l_i^* = 0$ and then $d_i^* = h_i^*$.

8.4. Proof of Lemma 1. From Definitions 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.

8.5. 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 species-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 $h^*\left(x,\bar{l}\right) = l^*\left(x,\bar{l}\right) + u^*\left(x,\bar{l}\right)$. If $u_i^*\left(x,\bar{l}\right) > 0$, $d_i^*\left(x,\bar{l}\right) = u_i^*\left(x,\bar{l}\right)$, i.e., there is discarding of species i. On the other hand, if $u_i^*\left(x,\bar{l}\right) < 0$, $h_i^* \leq \bar{l}_i$, 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 fishermen's current period's decision rules into his own dynamic program, which can now be written as

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

where I_i is an indicator function that takes a value of 1 if $u_i^* \leq 0$; 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 $d_i^* = u_i^* > 0$. 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 $\bar{l}_i$ increase to h_i^* the manager can strictly increase $V(s)$ which contradicts (that it maximizes) the RHS while fishermen's harvest rules $h^* = h^*\left(x,\bar{l}\right) = h^*\left(x, h^*\right)$ are unaffected by this increase. Similarly, if $u_i^* < 0$, 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:

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

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