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Quota flexibility in multi-species fisheries

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Keywords

Quota regulation, Flexibility, Costly targeting, Over-quota discarding

Disciplines

Agricultural and Resource Economics | Economics

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JEL Classification: Q2
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1 Introduction

We evaluate the bioeconomic performance of a cross-species flexibility (CSF) provision in a multi-species fishery that is managed with individual fishing quotas (IFQs). An important goal of CSF is to reduce over-quota discards which have been conjectured to arise in quota-managed fisheries as fishermen have difficulty matching random harvests with quota holdings (Copes, 1986; Sanchirico et al., 2006; Squires et al., 1998; Woods et al., 2015). The problem may be a particularly acute when catches and quotas must be aligned across multiple species (Squires et al., 1998). CSF provisions allow flexibility in landings whereby an unanticipated catch overage, i.e., a random harvest that exceeds a fisherman's quota holding, can be legally landed against the quota of another species. CSF provisions are used extensively in Icelandic fisheries and to varying degrees in New Zealand, Canadian, and U.S. fisheries.[1] The question of how effective CSF provisions are in reducing discards and in meeting other management goals is unresolved and the topic of this paper.

We present a model of a multi-product (multi-species) technology that captures unique elements of commercial fisheries. First and foremost, almost all commercial fisheries worldwide involve harvest of multiple fish species. Separate species cohabitate across spatially and temporally heterogeneous marine environments. Commercial fishermen employ vessel capital, labor, fuel, nets and hooks and bait to harvest fish. These inputs are aptly described as public factors of production allocated to harvest multiple fish species usually concurrently. Importantly, the technology is joint with production-cost complementarities linked to the ecological od individual species. Fishermen are however able to organize their operations, e.g., adjust gear types, select fine-grained fishing locations, depths, and times of the day and year that gear is set, bait and hook types, set trolling speeds, etc., to influence or *target*, albeit imperfectly, the mix of species intercepted and captured by their gear (Branch and Hilborn, 2008; see also Turner, 2005, Singh and Weninger, 2009). The implication of targeting ability is that the mix of harvested species now becomes an endogenous choice that will be based on the private incentives of fishermen. CSF provisions offer flexibility to land overfished species, but also allow directed targeting to increase fishermen's private fishing profits. CSF therefore alter the relationships between quota regulation and realized fishing mortality. We characterize this relationship under a generic CSF regulation and show how quota regulation are impacted and must be modified to meet management goals.

A first contribution of this paper is to fully characterize profit maximizing harvesting and discarding behavior under a quota regulation with CSF provisions. We show that privately optimal species-specific harvests and discards depend in complex ways on fish prices, operating expenses, multi-species stock conditions, specific-specific quotas, and the particular form of the CSF provision. Our results refine intuition first presented in Singh and Weninger (2009); over-quota discards occur when regulations raise the costs of matching harvests and quotas. This motive to discard will be present with or without randomness in the harvesting process.

A second contribution of this paper is an empirical analysis of discarding behavior in the Gulf of Mexico commercial reef fish fishery. We study harvesting and discard patterns over a period that spanned two distinct regulatory regimes: a command and control regulatory period where fleet harvests were controlled with trip-level landings constraints and seasonal closures, and a period where landings were controlled with IFQs, with CSF provisions. The discard patterns match predictions of our model, and illustrate stark effects, particularly discards choices, of the distinctly difference regulatory instruments. Not surprisingly, discards are

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[1] Sanchirico, et al., 2006 review mechanisms that are designed to help fishermen balance catches and quotas in fisheries throughout the world. Woods et al., 2015a, 2015b describe and evaluate the Icelandic program which includes an elaborate system whereby a subset of species quota can be exchanged at rates determined by previous year's landings prices. The analysis in woods et al., 2015a is primarily descriptive of landings patterns in Icelandic fisheries. Woods et al, 2015b includes simulations to illustrate the potential (negative) impacts of CSF on fishery outcomes. Woods et al., 2015b focus on revenue maximizing utilization of the specific CSF provisions in the Icelandic system.

largest under per-trip landings limits. What has been predicted in theoretical work (Singh and Weninger, 2015) but not shown empirically based on actual discard data from commercial fisheries is that discards effectively fall to zero under the IFQ regulation.

In a decentralized regulatory environment, and under information-constrained regulatory environments, CSF provisions will be exploited to address fishermen's private profit maximizing objectives. This misalignment of incentives can result in unintended consequences for regulators. A third contribution of our paper is to characterize second best quota management policies under CSF. We consider a planners problem of selecting a sequence of species-specific quotas to maximize the present discounted value of resource rents generated from a multiple species fishery. For this problem the planner first solves for the privately optimal harvest and discard choices of regulated fishermen under the quota regulation with CSF. We assume the regulator announces quotas under uncertainty over the true stock conditions that will prevail during the harvest season. The setting in intended to capture constraints operation in real work quota-managed fisheries.

This paper studies cross-species flexibility in the exploitation of a renewable natural resource. A literature examining *temporal* flexibility in cap-and-trade pollution emissions regulations has emphasized the advantage of allowing firms the option to bank or borrow permits over time. In stochastic production environments temporal flexibility can enable polluting firms to plan production and pollution abatement to take advantage of unanticipated economic or environmental conditions (see Yates and Cronshaw, 2001; Innes, 2003; Leard, 2013).[2] CSF can have a similar benefit, e.g., fishermen may exploit flexibility to land more of a more abundant species' stock, which can raise short term profits relative to the no-flexibility case. The timing and mix of individual species' harvests, however, has crucial impacts for future stock abundance and long term resource sustainability. We show how CSF, if excessive, will lower fishery value by limiting the regulators control over current harvests and correspondingly, the regulators ability to manage individual stocks in a way that maximizes long term resource rent.

The rest of the paper is organized as follows. Section 2 introduces a model of a two-species fishery that is regulated with species-specific quotas and a CSF provision. We derive privately optimal harvesting and discarding behavior of regulated fishermen. We isolate conditions under which discarding fish at sea raises fishermen's profits, and the role of CSF provision in harvest and discard outcomes. Section 3 considers the long-term management problem of choosing quotas, under CSF provisions, to maximize the value of the fishery. We illustrate the tradeoff between long term rent losses caused by a loss of regulatory control when CSF provision are in place, and the short run gains from allowing flexibility to exploit favorable stock conditions in a stochastic harvesting environment. Section 4 presents empirical evidence of discard patterns predicted by our model using a unique data set from the Gulf of Mexico commercial commercial reef fish fishery. Section 5 concludes and summarises the policy implications of the paper.

2 The Model

This section presents a model of a two-species fishery that is exploited by a large number of identical fishermen. The fishery is regulated with species-specific IFQs with a cross-species flexibility (CSF) provision that we describe shortly.

The regulatory environment we envision suggests the following timing of actions and information structure: The fishery is managed over an infinite horizon that is separated into discrete regulatory cycles, which we take to be a single year. We simplify the model and divide each year into a harvest phase which is followed by a stock-growth phase. We assume the regulator sets quotas at the start of each regulatory cycle, just before harvesting operations get underway. Our model will include an information asymmetry wherein the regulator is uncer-

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[2] The timing of emissions is arguably a less important determinant of the social damages from pollution. For example, the damages from CO_2 emissions are depend on the total accumulated quantity rather than the flow of the pollutant any any particular time.

tain about the stock growth that during the growth phase and, therefore, select species-specific quotas under stock uncertainty. The nature of stock uncertainty is articulated below. After species-specific quotas are announced, harvesting operations begin. We assume that because fishermen are *on the water* constantly observing their catch relative to gear deployed, that they fully observe stock abundance. In sum, fishermen know the quotas, stock abundance, the factor input, output and quota trading prices and organize their harvesting operations accordingly to maximize private profits during the harvest phase. We first characterize optimal harvest and discard choices of a representative fishermen during the harvest phased (within a single regulatory cycle). The regulators problem of choosing quotas is considered in section 3.

We first introduce a costly targeting harvest technology and the CSF provision in a two-species fishery. Let $x \equiv \{x_1, x_2\}$ denote current stock abundance, which is assumed fixed during the harvest phase.[3] We use $h \equiv \{h_1, h_2\}$, $l \equiv \{l_1, l_2\}$ and, $d \equiv \{d_1, d_2\}$ to denote the harvest, landings, and discards, respectively, of a representative fishermen.

The model employs a novel technology that features property of stock-dependent weak output disposability (Turner, 1995; Singh and Weninger, 2009). The two-species harvest set is defined as:

$$h \equiv \{h_1, h_2\} = \left\{ \begin{array}{c} \nu_1 \left(1 + \sin\left[\frac{a\pi}{2}\right]\right) x_1^{\mu} \\ \nu_2 \left(1 + \cos\left[\frac{a\pi}{2}\right]\right) x_2^{\mu} \end{array} \right\} z^{\gamma}. \tag{1}$$

where z denotes a scalar index of factor inputs employed; ν_1 and ν_2 are positive scale parameters, a is a parameter that defines the mix of the two species produced, μ is a non-negative parameter measuring the stock effect, i.e., that rate at which harvests change with stock size, and $\gamma \in (0, 1]$ measures the productivity of the factor input.

Fishermen can control the harvest through the choice of z and $a \in [-1, 2]$. The latter determines the point along the *boundary* of the output set, hereafter the harvest transformation frontier (HTF). It is easily checked that for $a \in [0, 1]$, the HTF exhibits the standard negative marginal rate of product transformation. For $a \in [-1, 0] \cap [1, 2]$, the marginal rate of product transformation is positive, which implies that a reduction in the harvest of one species is possible only if the harvest of the second species is also reduced. Note that

$$a = \left\{ \begin{array}{rl} -1 \Rightarrow & h \equiv \{0, \nu_2 x_2^{\mu} z^{\gamma}\} \\ 0 \Rightarrow & h \equiv \{\nu_1 x_1^{\mu} z^{\gamma}, 2\nu_2 x_2^{\mu} z^{\gamma}\} \\ 1 \Rightarrow & h \equiv \{2\nu_1 x_1^{\mu} z^{\gamma}, \nu_2 x_2^{\mu} z^{\gamma}\} \\ 2 \Rightarrow & h \equiv \{\nu_1 x_1^{\mu} z^{\gamma}, 0\} \end{array} \right.$$

In an unregulated environment a fisherman's optimal (profit maximizing) choice of a will lie between 0 and 1, i.e., the negatively-sloped segment of the HTF. For future use, we define

$$h_{i\,\min}(z) \equiv \nu_i x_i^{\mu} z^{\gamma} \text{ and } h_{i\,\max}(z) \equiv 2\nu_i x_i^{\mu} z^{\gamma}$$

Clearly, for any z, a fisherman will choose $h_i(z) \in [h_{i\,\min}(z), h_{i\,\max}(z)]$.

Figure 1 illustrates the HTF corresponding to three input levels, with $z' < z'' < z'''$. Stock abundance in the figure is such that the mix of two species stocks, i.e., $\frac{x_1}{x_2} \approx 1$. Observed first that the marginal rate of product transformation is negative for harvest vectors interior to rays $0A$ and $0C$ and is positive for harvest vectors outside of this region. Under the technology in 1, inputs are required to search or target a particular species and/or avoid intercepting the other species. If stocks are roughly equally abundant, a harvest vector of equal proportion, $\frac{h_1}{h_2} \approx 1$, will require fewest such targeting actions and therefore yield larger quantities of harvested fish.

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[3] This simplifying assumption avoids the need to account for harvest phase stock depletion. The analysis and results are unaffected qualitatively.

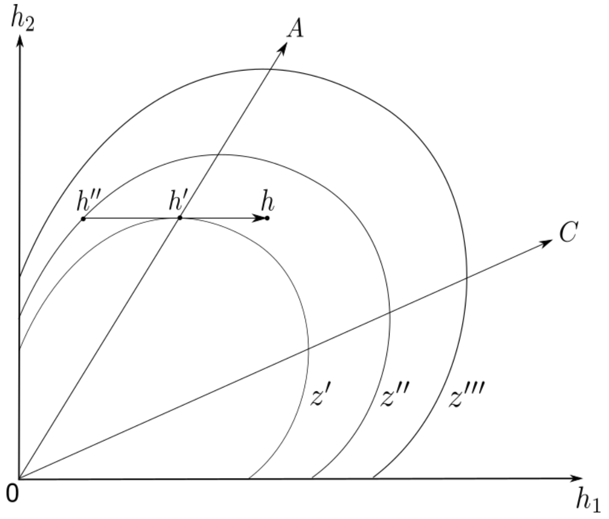

Figure 1: WOD Harvest Set.

In contrast, suppose a harvest vector with a larger share of species 2 is chosen, e.g., h'' in figure 1. In this case some of z' is spent searching for concentrations of the species 2 stock and/or avoid intercepting the species 1 stock. It is in this sense that our technology exhibits costly stock-dependent targeting of individual species.[4]

Figure 1 shows three harvest vectors h'', h' and h. h'' is located in the discard region, h' is on the boundary and h lines within a no discard region of the harvest space. The three vectors produce the same quantity h_2, and increasing quantities of h_1. For the reasons discussed above, h' can be harvested with a smaller input allocation than h''. The cost of harvesting h' is therefore larger than the cost of harvesting h''. The implication is that the harvest cost function dual to 1 exhibits regions for which the marginal cost of harvesting an individual species is negative (see Singh and Weninger, 2009). Along the ray from h'' to h' in the figure, costs decline as h_1 is increased (holding h_2 fixed).

2.1 The fisherman's problem

A representative fisherman begins the harvest phase with species-specific quotas, $\{q_1, q_2\}$. We assume the CSF provision allows for a fraction α of species 1 quota to be used to land species 2 fish and vice versa.[5] The fisherman's profit maximization problem is:

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[4] Empirical evidence in support of our technological assumptions is provided in section 4 below. Branch and Hilborn (2008) provide additional evidence of commercial fishermen's ability to control the mix of harvested species. See Singh and Weninger, 2009 for further discussion of costly targeting technologies in multispecies commercial fisheries.

[5] Alternate forms for CSF provision are easily formulated but add few additional insights. For example, the amount of species i quota used to land species j fish could differ for each i. Alternatively, the rate at which species-specific quota can be exchanged for other species quota may differ from unity as in Icelandic quota management program (see Woods et al., 2015a).

$$\begin{aligned} \max_{\{h_i,l_i\}} \Pi &= p_1 l_1 + p_2 l_2 - wz; \\ \text{s.t.} & \\ l_1 &\leq h_1;\ l_2 \leq h_2; \\ l_1 &\leq q_1 + \alpha q_2;\ l_2 \ \leq \ q_2 + \alpha q_1; \\ l_1 + l_2 &\leq q_1 + q_2, \end{aligned}$$

where the h_i's follow from (1), p_i is the landings price for species i fish and w is the unit price of z.

Notice that in the absence of flexibility provision, i.e., $\alpha = 0$, the quota constraints reduce to $l_1 \leq q_1$ and $l_2 \leq q_2$; the third constraint, $l_1 + l_2 \leq q_1 + q_2$ is then redundant.

The Lagrangian for the above problem is:

$$\begin{aligned} \mathcal{L} &= p_1 l_1 + p_2 l_2 - wz & (2) \\ &+ \lambda (q_1 + q_2 - l_1 - l_2) & (3) \\ &+ \omega_1 (q_1 + \alpha q_2 - l_1) + \omega_2 (q_2 + \alpha q_1 - l_2) & (4) \\ &+ \upsilon_1 (h_1 - l_1) + \upsilon_2 (h_2 - l_2), & (5) \end{aligned}$$

where λ, ω_i, and υ_i are Lagrange multipliers. Necessary conditions for optimal h_i, l_i and d_i include:

$$\begin{aligned} l_i &\geq 0;\ \ p_i - \lambda - \omega_i - \upsilon_i \leq 0;\ \ l_i\,(p_i - \lambda - \omega_i - \upsilon_i) = 0, & (6a) \\ \lambda &\geq 0;\ \ \lambda (q_1 + q_2 - l_1 - l_2) = 0, & (6b) \\ \omega_i &\geq 0;\ \ \omega_1 (q_1 + \alpha q_2 - l_1) = 0;\ \ \omega_2 (q_2 + \alpha q_1 - l_2) = 0, & (6c) \\ \upsilon_i &\geq 0;\ \ \upsilon_i (h_i - l_i) = 0. & (6d) \end{aligned}$$

Equation (6a) is the complementary slackness condition for landings. The multipliers λ and ω_i denote shadow prices for the aggregate and species-specific quota constraints, respectively, and υ_i is the shadow price of species i harvest. Notice that constraints in equation (6c) cannot both bind together since in this case the aggregate constraint (6b) would not be met. Therefore, either ω_1 or ω_2 or both are zero.

The optimal choice of a follows,

$$a^* = \frac{2}{\pi} \tan^{-1} \left[\frac{\upsilon_1}{\upsilon_2} \frac{\nu_1}{\nu_2} \left(\frac{x_1}{x_2} \right)^{\mu} \right], \tag{7}$$

and the optimal input choice is given by

$$wz^* = \gamma (\upsilon_1 h_1 + \upsilon_2 h_2). \tag{8}$$

Notice that υ_i is non-negative with strictly positive value only if $l_i = h_i$, i.e., there are no discards for species i. Suppose $\upsilon_1 = 0$, then $a^* = 0$. In this case, the optimal input choice is determined by its marginal contribution to harvest of species 2; marginal harvest of h_1 has no value since it discarded anyway. Symmetrically, when $\upsilon_2 = 0$ and $a^* = 1$, marginal harvest of h_2 is discarded and the input choice equates its unit cost with its marginal revenue from the harvest of species 1.

We next identify privately optimal harvests, landings and discards consistent with the necessary conditions (6a)-(6d), and solutions (7) and (8). In what follows, we will hold stock conditions and prices fixed and study optimal choices for alternative $\{q_1, q_2\} \in \Re^2_+$. We partition quota space into regions based on constraints that bind and constraints that are slack.

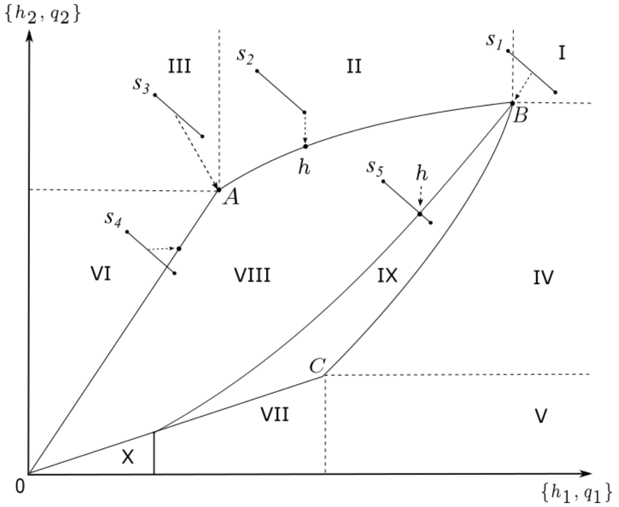

Figure 2: Constrained Harvesting Behavior.

These regions are depicted graphically in figure 2. To help fix ideas, and without loss of generality, we will assume $p_1 \geq p_2$.

As in figure 1, notice that the rays $0A$ and $0C$ in figure 2 separate discard and no discard regions. Quota allocations in regions III and VI, for example, induce positive discards of species 1 fish. The reason is that fewer inputs are needed if more h_1 is harvested. In region VIII discards are zero. For the same reasons (but with species numbers reversed), species 2 discards are positive for $q \in$ V, VII and X.

The technology in (1) exhibits diminishing returns when $\gamma < 1$, which is assumed in the figure. The set of quotas that can be profitably harvested is bounded by a non-negative profit condition. The segments AB and CB in figure 2 delineate regions of the harvest/quota space for which the marginal profit of harvesting additional units at least one of the two species is exactly zero. Point B identifies the harvests/quota at which marginal profit for both species is simultaneously zero, i.e., the quota-unconstrained optimum.

While perhaps not immediately apparent, segments $0A$ and $0C$ are drawn symmetrically in $\Re^2_+$ whereas B includes a larger share of h_1. This is the result of our assumption $p_1 > p_2$. More generally, the boundary of the discard set is determined by the structure of harvesting costs and stock conditions; the landings mix and quota utilization is dictated by relative prices.

In the absence of flexibility, i.e., $\alpha = 0$, and in our two-species case, a quota constraint is a point in $\Re^2_+$ with legal landings $l_i \leq q_i$ for $i = 1, 2$. With $\alpha > 0$, the quota constraint is a *line* segment with northwest coordinate $\{(1-\alpha)\, q_1, q_2 + \alpha q_1\}$ and southeast coordinate $\{q_1 + \alpha q_2, (1-\alpha)\, q_2\}$. Figure 2 shows several examples of such line segments, labeled $S_1, \ldots, S_5$. We hereafter refer to quota constraint under a CSF provision as a flexible quota constraint, or FQC.

Finally, it should be noted that regions I-X shift in $\Re^2_+$ with changes in factor input prices, output prices, stock conditions, and under a different structural properties of the technology in (1). Section 4 below investigates these relationships empirically.

We next summarize conditions within each region I-X in figure 2.

Aggregate constraint is slack ($\lambda = 0$):

From (6b), we see that with $\lambda = 0$, the sum of landings fall below the sum of quotas $l_1 + l_2 < q_1 + q_2$.

Region I: Neither species' constraint binds; no discards. Note that $\omega_1 = \omega_2 = 0$. Then $\upsilon_i = p_i$ and a^* and z^* follow from (7) and (8). Also $d_i = 0$ for both i. Then, $l_2 = h_2 < (1-\alpha)\,q_2$. For $q \in$ region I, profit maximizing harvest occurs are point B.

Region II: Species' 1 constraint binds; no discards. For $q \in$ region II, we have $p_1 > \omega_1 > 0$; $\omega_2 = 0$. Then $\upsilon_1 = p_1 - \omega_1 > 0$ and $\upsilon_2 = p_2$. Here, a^*, z^*, and ω_1 are jointly determined from $l_1 = h_1 = q_1 + \alpha q_2$ and (7) and (8). Then, $l_2 = h_2 < (1-\alpha)\,q_2$.

In region II the q_2 constraint is slack due to the fact that marginal profit of additional harvests is zero, all else equal. If the price of species 2 fish were higher, the segment AB in figure 2 would shift vertically.

Region III: Species' 1 constraint binds; positive species 1 discards. In region III $p_1 = \omega_1 > 0$; $\omega_2 = 0$. Here, $\upsilon_1 = 0$, $a^* = 0$, $l_1 = q_1 + \alpha q_2 < h_{1\,\min}(z^*)$, where z^* solves

$$wz^* = \gamma p_2 h_{2\,\max}(z^*)\,.$$

Then, $l_2 = h_2 < (1-\alpha)\,q_2$.

In regions III the species 2 quota is slack while the species 1 quota binds, so tightly that profit maximization involves positive discards of species 1 fish. For all $q \in$ III, harvest occurs point A in figure 2. For example, consider the quota allocation segment S_3; harvest occurs at point A however we have $l_1 < h_1$.

Region IV: Species' 2 constraint binds; no discards. Now $p_2 > \omega_2 > 0$; $\omega_1 = 0$. Then $\upsilon_2 = p_2 - \omega_2$ and $\upsilon_1 = p_1$. Here, a^*, z^*, and ω_2 are jointly determined from $l_2 = h_2 = q_2 + \alpha q_1$ and (7) and (8). Then, $l_1 = h_1 < (1-\alpha)\,q_1$

Region IV is the mirror image of region II; now the q_1 constraint is slack due to the fact that marginal profit of additional harvests is zero, all else equal. If the price of species 1 fish were higher, the segment CB in figure 2 would shift horizontally to the right.

Region V: Species' 2 constraint binds; positive species 2 discards. In region V we have $p_2 = \omega_2 > 0$; $\omega_1 = 0$. Here, $\upsilon_2 = 0$, $a^* = 1$, $l_2 = q_2 + \alpha q_1 < h_{2\,\min}(z^*)$, where z^* solves

$$wz^* = \gamma p_1 h_{1\,\max}(z^*)\,;$$

Then, $l_1 = h_1 < (1-\alpha)\,q_1$.

Aggregate constraint binds ($\lambda > 0$):

We now consider regions for which $\lambda > 0$. Form the necessary condition 6b we have $l_1 + l_2 = q_1 + q_2$. Here quotas are *tight* and the marginal profit from harvesting more fish remain positive an d thus the aggregate quota binds. The question then becomes, toward which species is CSF exploited, and when will discarding raise profit?

Region VI: Species' 1 constraint binds; positive species 1 discards. In region VI, $\omega_1 > 0$ and $\lambda = p_1 - \omega_1 > 0$; $\omega_2 = 0$; $\upsilon_1 = 0$ and $\upsilon_2 = p_2 - p_1 + \omega_1 > 0$. Since $l_2 = h_2$ and $\upsilon_1 = 0$ and $a^* = 0$, z^* is determined by,[6]

$$h_{2\max}(z^*) = (1-\alpha) q_2;$$

$l_2 = (1-\alpha) q_2$ and $h_1 = h_{1\min}(z^*) > l_1 = q_1 + \alpha q_2$.

Region VII: Species' 2 constraint binds; positive species 2 discards. Note that $\omega_2 > 0$ and $\lambda = p_2 - \omega_2 > 0; \omega_1 = 0$; $\upsilon_2 = 0$ and $\upsilon_1 = p_1 - p_2 + \omega_2 > 0$. Since $l_1 = h_1$ and $\upsilon_2 = 0$ and $a^* = 1$, z^* is determined by[7]

$$h_{1\max}(z^*) = (1-\alpha) q_1;$$

$l_1 = (1-\alpha) q_1$ and $h_2 = h_{2\min}(z^*) > l_2 = q_2 + \alpha q_1$.

Region VIII: Species' 1 constraint binds; no discards. Here, $p_1 > \omega_1 > 0; \omega_2 = 0$; $\upsilon_1 = p_1 - \lambda - \omega_1 > 0$ and $\upsilon_2 = p_2 - \lambda > 0$. Thus,

$$(p_1 - \upsilon_1) - (p_2 - \upsilon_2) = \omega_1;$$

the multiplier ω_1, which is positive in region VIII, equals marginal profit from adjusting harvests away from species 2 toward species 1. The boundary that separates regions VIII and IX is determined by relative fish prices, with the size of region VIII increasing in p_1.

Also, $h_1 = l_1 = q_1 + \alpha q_2$ and $h_2 = l_2 = (1-\alpha) q_2$. The above conditions along with (7) and (8) determine $\{a, z, \upsilon_1, \upsilon_2, \omega_1\}$.

Region IX: Species' 2 constraint binds; no discards. Here, $p_2 > \omega_2 > 0$; $\omega_1 = 0$; $\upsilon_2 = p_2 - \lambda - \omega_2 > 0$ and $\upsilon_1 = p_1 - \lambda > 0$. Therefore,

$$(p_2 - \upsilon_2) - (p_1 - \upsilon_1) = \omega_2;$$

the multiplier ω_2, positive in region IX, equals marginal profit from adjusting harvests away from species 1 toward species 2. Also, $h_2 = l_2 = q_2 + \alpha q_1$ and $h_1 = l_1 = (1-\alpha) q_1$. The above conditions along with (7) and (8) determine $\{a, z, \upsilon_1, \upsilon_2, \omega_2\}$.

Region X: Species 1 constraint binds; positive species 2 discards. Up until now these partitions appear symmetric. This will indeed be the case if $p_1 = p_2$. However, if $p_1 > p_2$, and the aggregate constraint binds, $\lambda \geq p_2$ must hold for (6a-6d) to hold. When $\lambda = p_2$, $\upsilon_2 = \omega_2 = 0$. In this region, $\omega_1 \in [0, p_1 - p_2]$. Since $\upsilon_1 \geq 0$, $a^* = 1$, z^* is determined by[8]

$$h_{1\max}(z^*) = q_1 + \alpha q_2;$$

$l_1 = q_1 + \alpha q_2$ and $h_2 = h_{2\min}(z^*) > l_2 = (1-\alpha) q_2$.

It it is worth reiterating that region X exists solely due to unequal prices. It is easily seen how the regions are modified when $p_2 > p_1$.

It is instructive also to contrast outcomes in regions VII and X. Recall that profit maximization requires CSF be exploited toward the landing of the highest marginal profit species. With $\upsilon_2 = 0$ in both regions VII and X, this margin is tilted toward species 2 fish, since the marginal profit is species 2 price. However, if $p_1 > p_2$, as we have assumed in figure 2, and at

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[6] ω_1 is in turn obtained from $wz^* = \gamma(p_2 - p_1 + \omega_1) h_{2\max}(z^*)$;

[7] ω_1 is in turn obtained from $wz^* = \gamma(p_1 - p_2 + \omega_2) h_{1\max}(z^*)$;

[8] ω_1 is in turn obtained from $wz^* = \gamma(p_1 - p_2 - \omega_1) h_{1\max}(z^*)$.

particularly at low levels of h_1, that marginal profit of landing species 1 fish dominates that of species 2 even when $\upsilon_2 = 1$. Moving left to right, from region X to VII in the figure however, corresponds to increasing species 1 marginal costs. When marginal costs of species 1 harvests rise enough, the optimal quota allocation tips back in favor of species 2 fish, i.e., region VII.

2.2 Quotas, CSF and the operating region

We have the following results,

- If any portion of the FQC lies in the region I, the optimal landing choices are unconstrained and there are no discards.
- If the southeast endpoint of the FQC lies in either of the regions II, III, VI, VIII, and X, the optimal harvests, landings, and discards are determined.
- If the northwest endpoint of the FQC lies in either of the regions IV, V, VII, and IX, the optimal harvests, landings, and discards are determined.
- Notice that the adjacent regions VIII and IX are demarcated by the line segment $0B$. If the FQC crosses $0B$, the aggregate constraint binds but no individual species' constraints bind, i.e., $\omega_1 = \omega_2 = 0$. Harvests equal landings and there are no discards. Since $p_1/geqp_2$, we restrict $\lambda \leq p_2$ so that $\upsilon_i = p_i - \lambda > 0$. Then,

  $$\upsilon_1 - \upsilon_2 = p_1 - p_2.$$

  Also, $l_i = h_i$ implies,

  $$h_1 + h_2 = \bar{q} \equiv q_1 + q_2;$$

  the above two equations along with (7) and (8) determine $\{a, z, \upsilon_1, \upsilon_2\}$. The line segment $0c$ represents values of $\bar{q}$ such that $\lambda \in [0, p_2]$.
- If the FQC crosses segment $0C$ such that its northwest endpoint lies in region X but the southeast endpoint lies in region VII, the choices are determined by $\omega_1 = \omega_2 = \upsilon_2 = 0$ and $\upsilon_1 = (p_1 - p_2)$. Here, $a^* = 1$, and z^* are determined by

  $$wz^* = \gamma (p_1 - p_2) h_{1\max} (z^*),$$

  with $l_1 = h_1$ and $l_2 = \bar{q} - l_1 < h_{2\min} (z^*)$.

This completes the mapping from the quota regulation with CSF provisions to fishermen's privately optimal harvests, landings and discards. We now investigate the implications for addressing the broad management goal of maximizing the stream of resources generated in the fishery.

3 Flexibility and Fishery Rent

This section considers the regulator's problem of setting species-specific under stock uncertainty. Ideally, the regulator would control species-specific harvests to sustain long-term fishery value, while at the same time allow for some harvest flexibility across species to perhaps reduce over-quota discards or to allow fishermen to exploit favorable stock abundance shocks. We first develop sharp analytical insights under a simplified version of the our model to highlight these tradeoffs. Technical details, solution techniques, and the results from the fully dynamic model are presented below.

3.1 A fixed proportions harvest technology with symmetric shocks

Let the harvest technology be given by

$$\{h_1, h_2\} = \{x_1, x_2\} z^{\gamma} \tag{9}$$

where z is as above; $\{x_1, x_2\}$ are from the regulators perspective jointly distributed random variables. To further simplify the presentation and focus on quota regulations under stock randomness, it is assumed that $\{x_1, x_2\}$ are perfectly negatively correlated. To begin with, we assume that x_i takes two values $\{\varphi, 1-\varphi\}$ with equal probability; furthermore, when $x_1 = \varphi$, then $x_2 = 1-\varphi$, and vice versa.[9]

We let $\varphi > \frac{1}{2}$, i.e., for any input allocation one species' harvests will exceed the other species' harvest.

The regulator's benefit function The regulator of a fishery not only cares about current harvest profit, but also accounts for the *prospective* costs of current harvests for depleted future stocks. We assume the regulator perceives the fishery's value as

$$W \equiv \pi(h_1, h_2) - \frac{\kappa_1}{2} h_1^2 - \frac{\kappa_2}{2} h_2^2 \tag{10}$$

where

$$\pi(h_1, h_2) \equiv p_1 l_1 + p_2 l_2 - wz. \tag{11}$$

Again landings may fall below harvests if fishermen choose to discard fish at sea. We will focus on an IFQ equilibrium in which fishermen maximize (11) subject to landing constraints, $l_i \leq q_i$.

We first examine the role of flexibility in a symmetric environment: we let $\kappa_1 = \kappa_2 = \kappa$; also, $p_1 = p_2 = p$. We derive the first-best harvest outcomes, i.e., a case where harvesting operations are fully controlled by a single sole owner. We then determine whether these first best outcomes can be replicated under an IFQ equilibrium.

A caveat is in order for the assumed quadratic form for h_i for the objective function in (10). Current harvests reduce escapement, which may linearly or non-linearly impact next period's stocks. The latter in turn will be valued in terms of next period's fishery benefits/losses (see the details in the next Section). If one assumes that the stock growth function is linear in escapement, and that the next period's fishery value is concave in stocks, a convex cost in terms of current harvests is justified. A quadratic term is therefore consistent with these assumptions. Moreover, it also delivers a closed form solution for the results derived below, which significantly helps in understanding the trade-offs between flexibility and control.

Note that parameters κ_i weigh the prospective costs of current harvests. Arguably, these coefficients may depend on the current stock abundance. A higher stock abundance would reduce the prospective costs of current harvests and therefore lower κ_i. If the quota allocation choices are made after the stock growth is realized or after observing (x_1, x_2), a lower future cost *ceteris paribus* would call for a higher harvest. To be as close to the first-best scenario, the regulator would like to increase harvest of the higher abundance species. But the motive for a higher harvest of the higher stock abundance species already operates via the technology channel.[10] Having κ_i as stock growth shock-contingent, in addition, will only strengthen

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[9] These assumptions imply means, variances and correlation coefficient, respectively, equal to

$$E(x_i) = \frac{1}{2};\ \sigma_{x_i}^2 = \left(\varphi - \frac{1}{2}\right)^2;\ \rho_{x_i x_j} = -1.$$

[10] Arguably, this may be the main first-order channel.

the flexibility versus control results that we derive. Nonetheless, this generalization would add clutter to algebra below without yielding additional insights. Therefore, we keep κ_i as deterministically constant.

In what follows, we use a tilde ($\tilde{}$) and an asterisk (*) to denote, respectively, values of *endogenous* variables obtained under a sole-owner control and under IFQ equilibrium.

3.2 A social planning problem

The owner chooses harvests after observing stocks to maximize (10) subject to (9). Irrespective of whether $x_i = \varphi$ or $1-\varphi$, the problem can be stated as

$$p\ z^{\gamma} - wz - \frac{\kappa}{2}\left((1-\varphi)^2 + \varphi^2\right) z^{2\gamma} \tag{12}$$

To simplify the analysis further, let $\gamma = 0.5$. Then, the optimal input choice, irrespective of stock realizations is given by

$$\tilde{z} = \left(\frac{1}{2}\frac{p}{w + \frac{\kappa}{2}\left((1-\varphi)^2 + \varphi^2\right)}\right)^2 . \tag{13}$$

The optimal input allocation balances its marginal cost and marginal benefit. The term $\frac{\kappa}{2}\left((1-\varphi)^2 + \varphi^2\right)$ in the denominator reflects that the fishery owner, in addition to considering input cost w, accounts for the harvest impact on prospective future stocks.

From here, it is straightforward to compute harvest choices. For $x_i = \varphi$:

$$\begin{aligned} \tilde{h}_i &= \frac{1}{2}\frac{\varphi p}{w + \frac{\kappa}{2}\left((1-\varphi)^2 + \varphi^2\right)}; \\ \tilde{h}_{j\neq i} &= \frac{1}{2}\frac{(1-\varphi)\,p}{w + \frac{\kappa}{2}\left((1-\varphi)^2 + \varphi^2\right)} \end{aligned}$$

It is optimal to exploit the higher abundance of species i and harvest a relatively higher amount.

Note, however, that the value of the fishery is decreasing in the stock variance:

$$\tilde{W} = \frac{1}{4}\frac{p^2}{w + \frac{\kappa}{2}\left((1-\varphi)^2 + \varphi^2\right)},$$

since the denominator is decreasing in φ for all $\varphi > 2$. This is due to the convexity of prospective costs in current harvests.

3.3 A standard ITQ equilibrium

As noted the regulator must set quotas before observing random stock abundance. Since the two species are symmetric, quotas for both species are equal. Let $q = q_1 = q_2$ denote the quota choice. The optimal regulation problem is solved backwards. First, the regulator derives the harvest outcomes from a particular q. Assuming that both species' landing constraints bind, i.e., $l_i = q$, one of the species' harvest will exceed its landing and the overage will be discarded. For $x_i = \varphi$ and $x_{j \neq i} = 1 - \varphi$, we have

$$\begin{aligned} h_j^* &= (1-\varphi)(z^*)^{0.5} = q = l_j^* && \text{(14a)} \\ h_i^* &= \varphi (z^*)^{0.5} = \frac{\varphi}{1-\varphi} q > q = l_i^* && \text{(14b)} \end{aligned}$$

and the discard of species i :

$$d_i^* = \frac{2\varphi - 1}{1-\varphi} q > 0.$$

Given the fishermen's equilibrium choices (14a) and (14b), a regulator sets quotas $\{q^*, q^*\}$ to maximize the expected value $E_x\{W\}$, where W is as in (10). The problem can be stated as

$$\max_q \left\{ 2pq - w\left(\frac{q}{1-\varphi}\right)^2 - \frac{\kappa}{2}\left(1 + \left(\frac{\varphi}{1-\varphi}\right)^2\right) q^2 \right\}. \tag{15}$$

This readily obtains

$$q^* = \frac{p(1-\varphi)^2}{w + \frac{\kappa}{2}\left((1-\varphi)^2 + \varphi^2\right)}. \tag{16}$$

Then, following (14a), the input is

$$z^* = \left(\frac{p(1-\varphi)}{w + \frac{\kappa}{2}\left((1-\varphi)^2 + \varphi^2\right)} \right)^{\frac{1}{2}} < \tilde{z} = (2(1-\varphi))^{\frac{1}{2}} z^*$$

It follows that for the species i with $x_i = \varphi$,

$$h_i^* = \varphi \frac{p(1-\varphi)}{w + \frac{\kappa}{2}\left((1-\varphi)^2 + \varphi^2\right)},$$

A comparison with the sole owner's harvest choices shows

$$\frac{l_i^*}{\tilde{l}_i} \leq \frac{h_i^*}{\tilde{h}_i} = 2(1-\varphi) < 1, \text{ for } i = 1, 2.$$

The larger is the species-specific abundance gap, the smaller is the harvests of both species under an *optimal* IFQ regulation. Since the overage of the higher abundance species is discarded, the marginal benefits are decreasing in φ. An optimal regulation responds with reducing the quotas of both species.

Quota market prices We began by assuming that the landing constraints for both species bind. In equilibrium, this requires that quota market prices for both species, which we will denote as $\{r_1, r_2\}$, be positive. The species i with $x_i = \varphi$ is discarded at the margin, and therefore its quota price $r_i = p$. In equilibrium, the fishermen's optimal input choice solves

$$wz^* = \frac{1}{2}(p - r_j) h_j^*, \tag{17}$$

where species j has $\varepsilon_j = 1 - \varphi$. Its equilibrium quota price is

$$\begin{aligned} r_j &= p - \frac{2wq^*}{(1-\varphi)^2} \\ &= p\frac{\frac{\kappa}{2}\left((1-\varphi)^2 + \varphi^2\right) - w}{\frac{\kappa}{2}\left((1-\varphi)^2 + \varphi^2\right) + w}, \end{aligned} \tag{18}$$

where the last expression follows from (16). *If the regulator assigns a sufficient weight on the prospective costs of current harvests, i.e.,* $\frac{\kappa}{2} > \frac{w}{(1-\varphi)^2+\varphi^2}$ *, both species' quotas bind in an IFQ equilibrium.*[11]

3.4 An ITQ equilibrium with cross-species quota flexibility

To get closer to the socially *efficient* harvests and landings, a regulator would like to set quota rules in a manner that aligns species-specific harvests with respective abundance shocks as a sole owner will do. We now consider a regulation that allocates a common quota q for landing both species, but also allows for cross-species-flexibility (henceforth CSF). Specifically, the regulation permits using α % of the quota of any species towards landing the other. The landing constraint for either of the species becomes:

$$\hat{l}_i \leq (1+\alpha)\, q \text{ subject to } \hat{l}_i + \hat{l}_{j\neq i} \leq 2q,$$

where a $\hat{}$ over a variable differentiates it from its counterparts in a first-best and a standard IFQ equilibrium.

Suppose, at the time of harvest $\{x_1, x_2\} = \{\varphi, 1-\varphi\}$. Relative to the case with no flexibility, the fishermen can now better utilize both quotas by choosing

$$\left.\begin{array}{c} \hat{l}_1 = (1+\alpha)\, q \leq \hat{h}_1 = \frac{\varphi}{1-\varphi}(1-\alpha)\, q \\ \hat{l}_2 = (1-\alpha)\, q = \hat{h}_2 \end{array}\right\} \text{ if } \frac{1+\alpha}{1-\alpha} \leq \frac{\varphi}{1-\varphi} \tag{19}$$

or

$$\left.\begin{array}{c} \hat{l}_1 = 2\varphi q = \hat{h}_1 \\ \hat{l}_2 = 2(1-\varphi)\, q = \hat{h}_2 \end{array}\right\} \text{ if } \frac{1+\alpha}{1-\alpha} > \frac{\varphi}{1-\varphi} \tag{20}$$

Replicating the first best The latter condition (20) holds when $\alpha > 2\varphi - 1$. In this case, none of the species are discarded and the total quota is utilized without discards, i.e., $\hat{h}_1 + \hat{h}_2 = 2q$. Using (20) in (10), the regulator solves

$$\max_q \left\{2pq - w\,(2q)^2 - \frac{\kappa}{2}\left((1-\varphi)^2 + \varphi^2\right)(2q)^2\right\}$$

Clearly, by setting $\hat{q} = \frac{1}{2}\tilde{z}^{\frac{1}{2}}$, the regulator achieves the efficient outcome. This holds for all $\alpha \geq 2\varphi - 1$. A CSF provision over and above $2\varphi - 1$ is *slack*, because of the *fixed proportions'* harvest technology. For whichever species has higher abundance, i.e., φ, a fisherman can use $(2\varphi - 1)$ % of the other species quota in addition to harvest $2\varphi\hat{q}$. The other species' harvest makes of the rest $2(1-\varphi)\,\hat{q}$. The CSF provision obtains the first-best by aligning the ratio of the two equilibrium harvests at $\varphi/(1-\varphi)$, precisely what the technology commands.

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[11] Since $\min\left\{(1-\varphi)^2 + \varphi^2\right\} = \frac{1}{2}$, a sufficient condition is $\kappa > 4w$.

Suboptimal CSF For $\alpha < 2\varphi - 1$, discards of species 1 occurs

$$\hat{d}_1 = \left(\frac{\varphi}{1-\varphi} - \frac{1+\alpha}{1-\alpha}\right)(1-\alpha)\, q.$$

Using (19) in (10), the regulator's problem can be stated as

$$\max_q \left\{ 2pq - (1-\alpha)^2 \left[\begin{array}{c} w\left(\frac{1}{1-\varphi}\right)^2 \\ +\frac{\kappa}{2}\left(1 + \left(\frac{\varphi}{1-\varphi}\right)^2\right) \end{array} \right] q^2 \right\}.$$

The optimal quota allocation with CSF[12]

$$\hat{q} = \frac{q^*}{(1-\alpha)^2} \tag{21}$$

Let λ denote the multiplier on aggregate quota constraint that holds with equality: $\hat{l}_1 + \hat{l}_2 = \hat{q}_1 + \hat{q}_2$, and let ω_1 be the multiplier on species 1 landing constraint that also holds with equality: $\hat{l}_1 = (1+\alpha)\,\hat{q}$. Since species 1 is discarded at the margin, $r_1 = p = \lambda + \omega_1$ while $r_2 = \lambda + \alpha\omega_1 = p - (1-\alpha)\,\omega_1$. It can be shown that

$$r_2 = p - 2w\hat{q}\left(\frac{1-\alpha}{1-\varphi}\right)^2$$

These results are summarized in the following proposition:

Proposition 1. *A CSF provision of $\alpha \geq 2\varphi - 1$ replicates the sole owner outcome in an IFQ equilibrium. The quota allocation for any $\alpha \in [0,1]$ is given by*

$$\hat{q} = \begin{cases} \left(\frac{1-\varphi}{1-\alpha}\right)^2 \frac{p}{w+\frac{\kappa}{2}\left((1-\varphi)^2+\varphi^2\right)}, & \textit{for } \alpha < 2\varphi - 1 \\ \frac{1}{4}\frac{p}{w+\frac{\kappa}{2}\left((1-\varphi)^2+\varphi^2\right)} = \frac{1}{2}\tilde{z}^{\frac{1}{2}}, & \textit{for}\alpha \geq 2\varphi - 1 \end{cases}$$

The value of fishery can be expressed as

$$\hat{W} = \begin{cases} \frac{p^2}{w\left(\frac{1}{1-\varphi}\right)^2 + \frac{\kappa}{2}\left(1+\left(\frac{\varphi}{1-\varphi}\right)^2\right)} \frac{1}{(1-\alpha)^2} < \tilde{W}, & \textit{for } \alpha < 2\varphi - 1 \\ \tilde{W} = \frac{1}{4}\frac{p^2}{w+\frac{\kappa}{2}\left((1-\varphi)^2+\varphi^2\right)}, & \textit{for } \alpha \geq 2\varphi - 1 \end{cases}$$

Finally, for $\alpha > 2\varphi - 1$ the quota price of both species equals p, while for $\alpha < 2\varphi - 1$ is given by $r_i = p$ for the species i with $x_i = \varphi$, while for $j \neq i$, r_j remains fixed at its value given in (18).

Suppose a regulator is constrained to set $\alpha < 2\varphi - 1$. Then some of the harvest of the higher abundance species is discarded. As flexibility (α) rises, discards diminish and the regulator's marginal value of quotas rises. This induces the regulator to set a higher quota to increase fishery value. If regulator could choose α optimally, it will choose $\hat{\alpha} = 2\varphi - 1$. This perfectly

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[12] Notice that the above problem nests with (15) for $\alpha = 0$.

aligns fish landings with the harvests. By setting the total quota $\hat{q} = \frac{1}{2}\tilde{z}^{\frac{1}{2}}$, the regulator can implement first best harvests. In effect, $\hat{\alpha} \geq 2\varphi - 1$ completely *insures* the fishermen against stock abundance shocks and thereby allows the regulator to behave as a sole owner.

When $\alpha > 2\varphi + 1$, neither of the individual landing constraints bind. Both species' quotas are equally valuable at the time of harvest and so are their market prices. A somewhat surprising result is that the two quota prices are invariant to changes in α for $\alpha \in (0, 2\varphi - 1)$. For α in this range, the higher abundance species' quota price is equal to its market price, whereas for the lower abundance species its quota price depends on its contribution to the aggregate landing as well as its contribution to the landing of the higher abundance species. With a higher α, more of the lower species' quota can be used towards landing the higher abundance species, which raises its quota market value. But a higher α is also accompanied by a rise in $\hat{q}$, which relaxes the aggregate landing constraint and lowers the market value of the marginal quota. The two effects turn out to be exactly offsetting due to a fixed proportions harvest technology.

It is worth noting that the results stated in Proposition 1 continue to hold even when stock abundance take multiple/continuous values, as long as stocks are symmetric and negatively correlated. The CSF provision in this case will offer insurance against the most extreme stock conditions. If the realized stocks are less spread, the flexibility provision will be only partially utilized. However, this may not hold when the harvest technology allows for cross-species harvest substitution. The CSF provision in case of low-spread abundance may be overused relative to what a sole owner would desire. We turn to this question next.

3.5 An IFQ-CSF equilibrium with output substitution

While the preceding results help understand the role, and build a case, for CSF provisions, the assumption of a fixed output proportions' technology is restrictive and not supported empirically as we show in the next section. In general, for a given input allocation, fishermen can choose the mix of harvested species. We therefore generalize the results above to our more general costly targeting harvest technology, while maintaining our simplifying assumptions for random stock conditions:

$$h \equiv \{h_1, h_2\} = \left\{ \begin{array}{c} \nu_1 \ \varphi^{\mu} \left(1 + \sin\left[\frac{a\pi}{2}\right]\right), \\ \nu_2 \ (1-\varphi)^{\mu} \left(1 + \cos\left[\frac{a\pi}{2}\right]\right) \end{array} \right\} z^{\gamma}. \tag{22}$$

We keep with our symmetry assumptions for now, and consider the case with $\nu_1 = \nu_2 = \nu$.

Sole owner's choices A sole owner's optimal harvesting choices are now characterized by

$$\begin{aligned} w\tilde{z} &= \gamma\left[\left(p - \kappa\tilde{h}_1\right)\tilde{h}_1 + \left(p - \kappa\tilde{h}_2\right)\tilde{h}_2\right]; && \text{(23a)} \\ \tilde{a} &= \frac{2}{\pi}\tan^{-1}\left[\frac{p - \kappa\ \tilde{h}_1}{p - \kappa\ \tilde{h}_2}\left(\frac{\varphi}{1-\varphi}\right)^{\mu}\right]. && \text{(23b)} \end{aligned}$$

The first equation is standard: it equalizes the marginal input cost inclusive of its impact on prospective stocks, with its marginal revenue benefit. The second equation allows the fishermen to optimally choose a to substitute between the two species along the harvest possibilities frontier as displayed in figure 1. Equations (23a) and (23b) along with (22) uniquely solve for $\{\tilde{z}, \tilde{a}\}$ and thereby $\left\{\tilde{h}_1, \tilde{h}_2\right\}$ for any realization of φ. However, even with $\gamma = \frac{1}{2}$ and either $\mu = 1$ or $\frac{1}{2}$, it is no longer possible to obtain closed-form expressions. Therefore, we rely on numerical computations for further analyses.

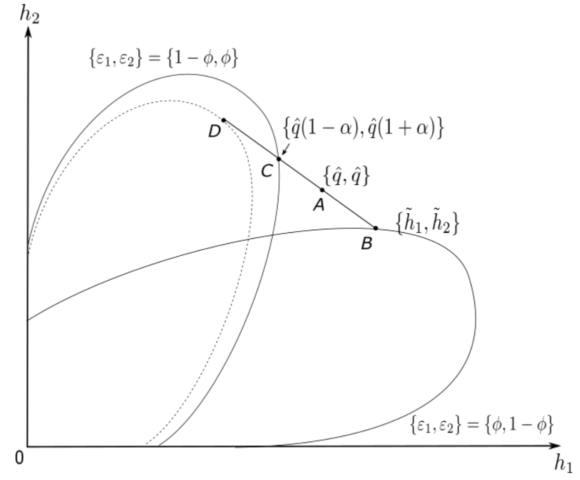

Figure 3: Cross-Species Flexibility and Stock Uncertainty.

An ITQ equilibrium with CSF Continue to assume for now that x_i takes values $\{\varphi, 1-\varphi\}$. Figure 3 displays the harvest frontier for the two possible stock realizations. Suppose the sole owner's state-contingent optimal harvest choices are at points C and B on the two possible frontiers.

Once again, with symmetry assumptions, the regulator sets equal quotas $\hat{q}$ for both species. Let the CSF provision allow α % cross-species quota use, i.e., the $\hat{l}_i \leq (1+\alpha)\,\hat{q}$. The details of how to compute an IFQ equilibrium for the general case are discussed in section 2 and for brevity are omitted here. For the simple two shock case in figure 3, the question we want to answer here is: How can a regulator optimally set $\{\hat{q}, \hat{\alpha}\}$ to achieve the preferred harvests? The answer is straightforward:

$$\hat{q} = \frac{\tilde{h}_1 + \tilde{h}_2}{2}; \hat{\alpha} = \frac{\tilde{h}_1 - \tilde{h}_2}{\tilde{h}_1 + \tilde{h}_2}$$

where $\tilde{h}_i$ relates to the case with $x_1 = \varphi$ at point B in figure 3.[13] It is easily checked in figure 3 that the full quota is landed, i.e., $\hat{l}_1 + \hat{l}_2 = 2\hat{q}$ for both stock realizations. Furthermore, for $x_i = \varphi$, $\hat{l}_i = (1+\alpha)\,\hat{q}$. A flexibility provision less than $\hat{\alpha}$ will either require a higher input allocation in equilibrium or will be accompanied by discards.[14] In either case, the equilibrium is *inefficient* relative to the sole-owner case.

But how about a flexibility provision that exceeds $\hat{\alpha}$ as defined above? Under a fixed proportions' technology, additional flexibility remains underutilized as stated in Proposition 1. However, with output substitutability additional flexibility will be exploited to obtain an identical harvest revenue ($2p\hat{q}$) at lower input employment, e.g., on a point such as D in figure 3 for $\{x_1, x_2\} = \{1-\varphi, \varphi\}$. The sole owner harvests are no longer implemented in the IFQ equilibrium and the value of the fishery will be lower.

To help understand the above argument, we conduct the following counterfactual thought experiment. Suppose the regulator allocates quotas after observing the shocks. For example, when $\{x_1, x_2\} = \{\varphi, 1-\varphi\}$, the regulator allocates $\{q_1, q_2\} = \left\{\tilde{h}_1, \tilde{h}_2\right\}$ at point B in figure 3, but also allows for a CSF of $\alpha = 10$ %.

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[13] Subscripts are symmetrically reversed for $x_2 = 1-\varphi$.

[14] Note that if $\alpha \neq \hat{\alpha}$, the regulator's quota allocation will be different than $\hat{q}$.

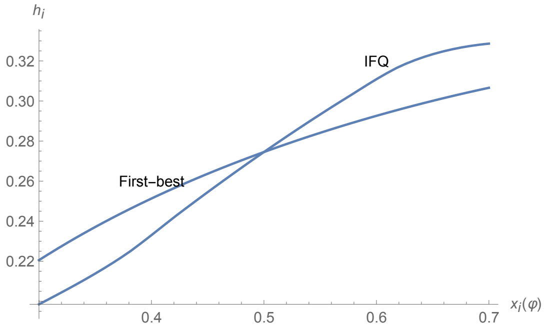

Figure 4: Harvests under First Best and IFQ Regulations.

Figure 4 presents the equilibrium harvest deviations under an IFQ equilibrium under this unwarranted flexibility provision. The parameter values assumed are $p = w = 1; \mu = 0.5; \gamma = 0.7; \kappa = 2.5$; φ is allowed to take 11 equally spaced values between $[\varphi_{\min}, \varphi_{\max}] = [0.3, 0.7]$. The schedules labelled as "IFQ" represent the market equilibrium outcomes. It is evident that when a species abundance is relatively higher, the market equilibrium incentivizes a higher harvest of this species relative to its socially optimal value.

Thus, increasing flexibility (α) beyond what is optimal may lead to overexploitation of higher abundance species and further decrease the fishery value. However, when the flexibility (α) reaches a sufficiently high value, no further incentive remains for overexploitation and the CSF is not fully utilized. Once again, from this point on, the fishery value stays constant with further increases in α.

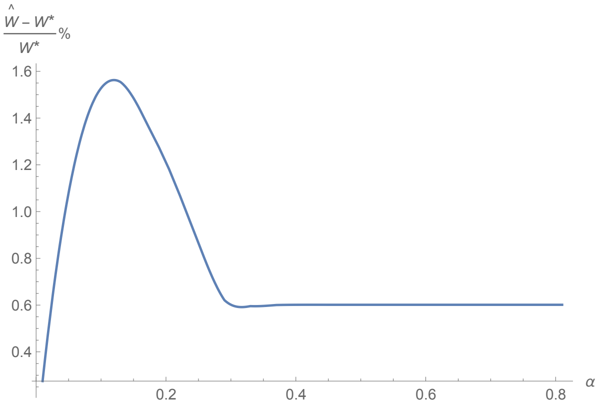

Figure 5: Flexibility and Fishery Rent.

Figure 5 displays the fishery value $\hat{W}$ under an IFQ regulation, as a function of CSF α.[15]

The key lesson to be drawn from this exercise is that in general there is a unique $\{\hat{\alpha}, \hat{q}\}$ that maximizes the fishery value in an IFQ regulation.

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[15] It bears emphasis that optimal $\hat{q}$ has the same shape as $\hat{W}$ above in response to changes in α. The response of $\hat{q}$ to α is not presented here to conserve space.

3.6 Asymmetric prices

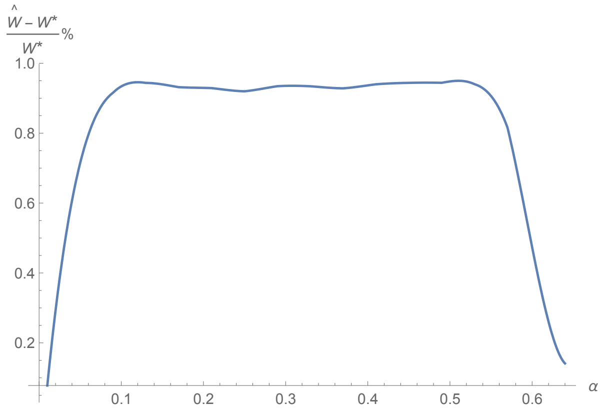

Figure 6: Flexibility and Fishery Rent: Asymmetric Prices.

We now turn to a fishery with price differences across species. To isolate the role of differential valuations, we let $\{p_1, p_2\} = \{1.5, 1\}$; the technology and random stock abundance remain as above. Figure 6 shows how welfare varies with α. The intuition behind $\hat{W}$ rising in α for small values is simple. Since flexibility insures against randomness in stock conditions, the rise in welfare for small values of α is consistent with the previous examples.

Figure 7 provide further intuition. A price differential across the two species tilts the harvest mix towards the higher-valued species. In general, a common CSF provision of α % is now used relatively more frequently to land higher priced species. This effect can be seen in panel (a) and (b) of figure 7.

The first best $\left\{\tilde{h}_1, \tilde{h}_2\right\}$ represent sole-owner's choices. A higher φ commands a higher $\tilde{h}_1$ and a lower $\tilde{h}_2$. Suppose the regulator assigns these stock-contingent harvest levels as quotas after observing x_i's and, in addition, allows for a flexibility $\alpha = 0.1$. Even when species 2 stock is relatively high (low φ), the CSF provision is used to harvest species 1. When the two species were equally valued, deviations from the first best is symmetric across both species (see figure 5).

Panel (c) and (d) of figure 7 show the regulator's optimally quota choices $\{\hat{q}_1, \hat{q}_2\}$. The regulator understands that as CSF (α) rises, CSF will be used to land the higher value species 1. To offset, an optimal regulation reduces $\hat{q}_1$ and increases $\hat{q}_2$. This is what explains the flat portion in figure 6 above.

Contrast the regulator's optimal quota response to the CSF provisions under price asymmetry with the symmetric example. In the symmetric case, the two quotas are identical. When α is increased beyond its welfare maximizing value, quota adjustment requires an identical reduction in both species' quotas, which in turn lowers fishery value. With asymmetric prices, quota adjustments under higher α maintain the same fishery value for a range of α. However, when α becomes sufficiently large, the quota of the higher-valued species becomes so small (see panel (c)) that its utilization towards the lower-priced species, in case the high abundance species, does not provide adequate landing coverage for lower priced species. Therefore, a further increase in α lowers the value of fishery. This explains the decline in $\hat{W}$ for high values of α.

(a) Harvest: species 1

(b) Harvest: species 2

(c) Quota: species 1

(d) Quota: species 2

Figure 7: First Best vs. IFQ Equilibrium Outcomes.

4 Discarding in the GOM reef fish fishery

This section evaluates harvest and discard patterns in the Gulf of Mexico (GOM) commercial reef fish fishery. We first present evidence to support the technological assumptions implicit in our costly targeting technology. We evaluate and test the predictions of our model in section 2 against discards patterns observed in our data. Finally, we calibrate the costly targeting technology and further evaluate the role of CSF provisions and other regulations in the decision to discard fish at sea and in the general management of the GOM reef fish fishery.

4.1 Data and regulations

The Gulf of Mexico (GOM) commercial reef fish fishery is a complex of bottom-dwelling species consisting of red, black, yellowedge, gag, warsaw and other species of groupers, amberjacks, triggerfish, porgies, tilefish, and red, vermilion, and other snapper species. Vertical hook and lines and longline gear are the main gear types used. Our data are from 2005-14 commercial reef fish fishing seasons. In 2014, the the commercial fleet generated \$69.884 m. in revenue on 19.459 m. pounds across all reef fish species. In the same year, red and vermilion snapper, red grouper, and gag grouper accounted for \$47.473 m. (67.93%) of the revenue and 11.799 m. lbs. (60.64%) of total landings.

Our data period spans two contrasting regulatory approaches which were introduced for at different times for different reef fish species. Prior to 2007, annual commercial harvests of all species were controlled with an input-based regulation. Under this *controlled access* regime, annual harvests were constrained through a system of vessel licensing that capped the number of boats in the fishery, limits on per-trip landings, seasonal closures where all landings were prohibited, and various gear restrictions. The second regulatory regime utilized output controls in the form of a multi-species individual fishing quota (IFQ) regulation, with CSF provisions.

Red snapper was managed under controlled access during two years of our data period (2005-06) and was switched to IFQs in 2007. Prior to the switch to IFQs, commercial reef fish vessel operators held one of three types of red snapper endorsement permits: no endorsement; a class II endorsement; or a class I endorsement. The endorsement program capped the total pounds of red snapper that could be landed on each trip from port, during calendar periods in which the red snapper fishery was *open*. Landings are prohibited during red snapper closures. Closures were spaced throughout each year to avoid harvest gluts and low dockside prices. Class II and class I permit holders were allowed to land 200 and 2,000 pounds of red snapper per trip, respectively. Red snapper landings by non endorsement vessels were prohibited at all times. Hereafter we refer to red snapper permit holders as no endorsement, class II and class I boats.

Under the red snapper IFQ program, seasonal closures ended. It should be noted that the initial allocation of red snapper quota was gratis and based on historical catch records. The bulk of the quota was allocated to class 1 and 2 endorsement permit holders.

Groupers and tilefish species were managed under controlled access for 5 of our 10 data years (2005-09). Key regulations included closures and a trip limit regulation that capped landings of shallow water groupers including red, gag, black, yellowfin, and yellowmouth groupers, rock, red and speckled hind, scamp, and others. In 2005, the cap was set at 10,000 per trip until 50% of the annual species-group total allowable catch (TAC) was reached. The trip limit then dropped to 7,500 pounds and then to 0 when the full TAC was landed. From 2006-09 the cap was lowered to 6,000 pounds per trip, and 0 when the TAC was met.[16]

In 2010, the Grouper-Tilefish Individual Fishing Quota, hereafter GT-IFQ program was introduced. Quota was issued for five species or species groups: (1) red grouper; (2) gag grouper; (3) shallow water groupers, which included black grouper, scamp, yellowfin grouper and yellowmouth grouper; (4) deep-water groupers, which included snowy grouper, speckled hind, warsaw grouper, and yellowedge grouper; (5) tilefish, which included blueline tilefish, golden tilefish and goldface tilefish.

The GT-IFQ program allows for unlimited cross-species flexibility for the species included in the (3) shallow water groupers, (4) deepwater groupers and (5) tilefish aggregates. Operating rules included an additional but limited CSF provisions for red and gag grouper.[17] Under this provision, a maximum share of red and gag grouper quota is designated as *multi-use* quota. The quantity of multi-use quota varied by species and year as shown in table 1.

Year	Gag Multi-use	Red Multi-use
2010	8%	4%
2011	8	0
2012	8	0
2013	70	0
2014	47	0
2015	33	4.8

Table 1: Red and Gag Grouper Multi-Use Quota, 2010-15.

In 2010, 4% of a fisherman's red grouper quota could be used to land gag grouper and 8% of a fisherman's gag grouper quota could be used to land red grouper. During 2011-14, gag quota could be used to land red grouper, following the percentages in table 1, whereas the no red grouper multi-use quota was set to zero. The explanation is an unfavorable gag grouper stock assessment which prompted additional regulatory measures to reduce gag grouper harvests.

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[16] The gag fishery was closed from February 15 through March 14 apparently to protect gag during a period in which spawning behavior is concentrated.

[17] The program also includes a cross-seasonal flexibility provision whereby 10% of the last trip's harvest could be legally landed against a fisherman's following year quota allocation. The quantity of discards impacted by this provision is likely small.

In 2015, apparently after gag grouper stocks have shown signs of recovery, 33% of gag quota could be used to land red grouper and 4.8% of red grouper quota could be used to land gag grouper (SEDAR, 2014).

4.2 Discarding patterns

We merge trip-level logbook landings data with fishermen's trip discard records for major gear types used in the eastern region of the GOM reef fish fishery (east of the Mississippi delta).[18] Data include for each trip, the date of departure, the days the vessel spent at sea, the quantity of fish landed and discarded by species, the type and quantity of gear used on the trip, crew size, area fished, and fishing depth, among other factors.

The discard section of logbook reporting system asks fishermen to report species, number, average weight, the condition of discarded fish,[19] gear type, area and the depth at which the discards fish were caught. Fishermen are also asked to choose one of five reasons for which the fish was discarded: 1. Regulations - Not Legal size; 2. Regulations - Out of Season; 3. Regulations - Other; and 4. Market Conditions. Instructions to fishermen make a clear distinction between undersize discards and discards due to seasonal closures, landings limits and quota constraints. Hereafter we consider discards that are attributed to non-size-limit regulations (reasons 2 and 3), which we assume are discards due to closures and trip limits under controlled access regulation and insufficient quota under IFQs. An analysis of undersize discarding is reserved for future work.

Reef fish discards occur at sea in the absence of observer coverage. Fishermen report numbers and average weight of discarded fish by species when the vessel returns to port at the end of a 3-6 day trip. The accuracy of self-reported discard numbers and individual fish weights cannot be verified. Examination of the data indicate consistent patterns and reasonable values for the *numbers* of fish discarded. The data included some extreme (mostly high) reported values for average weights of discarded fish.[20] To reduce the effects of reporting anomalies, we replace self-reported average fish weights (for discarded fish) with species-specific average weights obtained from observer data collected by the Southeast Fisheries Science Center. We calculate species-specific average weights for fish below and above the legal length limit and replace fishermen's self-reported average weights with survey data averages.[21] We then calculate total discarded pounds by species using the reported discard numbers times average fish weights.

Our data contain 75,564 trips taken in the eastern region of the fishery from 2005-14.[22] We focus on hook and line gear types which include bandit, handline, trolling and bottom longline gear types. These gears accounted for 75,564 trips (98%) of trips taken, 93.00 % of

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[18] Bandit, handline and longline gear trips are examined in the region east of the Mississippi delta along the western Florida coast to the Florida Keys.

[19] A choice out of six discard conditions are offered: Dead All, Dead Majority, Alive All, Alive Majority, Kept, and Unable to Determine.

[20] Reef fish fishermen are instructed to report "the number of animals for each species discarded" and "the estimated average individual weight in whole pounds for each species discarded." The outliers are concentrated in the average fish weight section. For example, values of 1,500 pounds for red snapper, 1,003 pounds for vermilion snapper and 300 pounds for red grouper are clearly out of bounds. One explanation is that these reported values are the result of a misreading of the instructions, e.g., total discarded pounds were entered rather than average weight per discarded fish.

[21] We match survey weights to fish lengths using the reported discard reason. For example, if the discard reason was "NOT legal size", an average weight of below-legal-length fish from the survey data is used. If the reported discard reason is due to a regulatory constraint, average weight for fish longer than the minimum length limit is used.

[22] We drop 3,532 trips that landed primarily shark species (75% or more of total trip landings), and 202 trips with incomplete vessel and gear deployment data.

total landed pounds, and 96.81 % of revenues during 2005-14. The analysis that follows will, in some cases require discard data information only, in which our data contain 17,568 complete observations. When the analysis require both discard and cost information, we utilize the 10,107 observations that report discard and have complete trip expense information.[23]

4.3 Red snapper discarding

		No Endorsement				Class II Vessels				Class I Vessels			
Year	TAC	N	h_i	$\frac{d_i}{h_i}$	$\frac{h_i}{\sum h_j}$	N	h_i	$\frac{d_i}{h_i}$	$\frac{h_i}{\sum h_j}$	N	h_i	$\frac{d_i}{h_i}$	$\frac{h_i}{\sum h_j}$
2005	4.19	199	115.68	0.22	0.24	203	190.81	0.12	0.49	76	783.20	0.15	0.68
2006	4.19	235	137.34	0.22	0.37	163	157.59	0.19	0.41	32	670.39	0.13	0.60
2007	2.76	152	242.98	0.14	0.30	254	342.52	0.07	0.46	133	1,176.62	0.12	0.59
2008	2.30	524	259.76	0.04	0.33	401	368.01	0.03	0.57	323	804.25	0.03	0.53
2009	2.30	339	385.54	0.04	0.45	273	585.58	0.03	0.66	157	1,309.75	0.00	0.58
2010	2.82	411	430.19	0.03	0.51	293	454.01	0.04	0.53	250	1,335.82	0.01	0.65
2011	3.26	626	497.75	0.09	0.32	380	600.43	0.04	0.48	226	1,264.35	0.00	0.51
2012	3.51	608	685.86	0.07	0.66	327	406.21	0.06	0.44	226	1,090.62	0.02	0.50
2013	4.13	600	849.80	0.02	0.62	382	377.02	0.01	0.42	150	2,209.47	0.00	0.70
2014	5.05	508	552.56	0.01	0.48	226	248.70	0.03	0.44	212	1,815.33	0.00	0.75

Table 2: Red Snapper harvest/discard activity, 2005-14. TAC is total allowable catch reported in millions of pounds; N indicates the number of trips reporting positive red snapper harvest; h_i denotes the average pounds harvested per trip; $\frac{h_i}{\sum h_j}$ is the landings-weighted average ratio of discarded to harvested pounds per trip; $\frac{h_i}{\sum h_j}$ is the landings-weighted average ratio of the harvested red snapper pounds to total harvested pounds per trip.

Table 2 reports 2005-14 harvest and discard information, across three vessel types, for trips reporting positive harvests of red snapper. We also report the red snapper commercial total allowable catch (TAC) in millions of pounds, the number of trips in the sample, the average harvested pounds per trip, a landings-weighted average of the ratio of discarded to harvested pounds, and the landings-weighted average red snapper harvest share, i.e., the trip red snapper harvest divided by the trip's total harvested pounds.

Observe first that the discard to harvest ratio $\frac{d_i}{h_i}$ varies systematically across vessel type and across years as quota constraints are lifted. The 10 year average value is 0.09 for no endorsement vessels, 0.06 for class II vessels and 0.05 for class I vessels. The discard-harvest ratio declines across years beginning in 2007, the first year that red snapper IFQ program. In 2007, trip limits were replaces with a seasonal landings limit; the sharp drop in the discard/harvest ratio under IFQ regulation is not surprising.

One interpretation of the result in table 2 is that class I vessels, who were allocated the largest shares of red snapper quota,[24] have organized their operation to fully exploit the economic incentives outlined in Singh and Weninger (2015).[25] On the other hand, table 2 shows

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[23] Of the 75,564 total eastern trip observations, 12,125 (16.0 %) recorded both discard and trip expense information. Trip observations with missing fuel expenses were dropped leaving 10,107 trips with complete discard and cost information. Appendix 7 reports descriptive statistics. Small differences in vessel characteristics and harvesting activity exist across the sample subsets and therefore the results that follow should not be directly extrapolated to the entire fishery.

[24] The initial red snapper allocation was based on landings history, which by virtue of the endorsement regulation, favored class I boats.

[25] Singh and Weninger (2015) show that discarding fish at sea due to insufficient quota is cost inefficient and will not be observed in a rational quota market trading equilibrium (in the absence of trading frictions).

evidence that adjustments to quota holdings and harvesting practices did no occur immediately in 2007. The average pounds of red snapper harvested per trip and the discard-harvest ratio for no endorsement and class II vessel types exhibit strong trends during 2007-12. The drop off in $\frac{d_i}{h_i}$ is immediate for class I boats.

The results in table 2 offer compelling evidence that reef fish fishermen control the mix of species harvested with their gear. The share of red snapper in the total trip pounds is considerably lower for no endorsement boats than for class II and class I boats in the early data years. The red snapper harvest share for no endorsement boats has increased during the IFQ regime, presumably as these vessel operators acquire red snapper quota.

Average harvested pounds per trip has increased since the 2007 switch to IFQ regulation. This pattern is also not surprising given that trip-level landings limits were dropped in 2007.

	Class II Vessels					Class I Vessels				
	N	h_i	d_i	$\frac{d_i}{h_i}$	$\frac{h_i}{\sum h_j}$	N	h_i	d_i	$\frac{d_i}{h_i}$	$\frac{h_i}{\sum h_j}$
Open (254 days)	263	205.99	40.66	0.21	0.42	77	997.08	199.04	0.15	0.48
Closed (476 days)	203	51.63	47.79	0.97	0.05	48	87.51	82.70	0.94	0.04

Table 3: Endorsement Vessel Harvest and Discards, 2005-06.

Closer examination of class I and class II vessel harvest and discards patterns during the controlled access regime offers further evidence of endogenous targeting. In 2005-06, the red snapper fishery was open (landings were permitted) on 254 days and closed on 476 days. Table 3 breaks down the simple average per trip harvests, discards, discard-harvest ratio, and harvest shares by endorsement class.

The results show notable and perhaps predictable patterns. Vessels harvested more red snapper when the fishery is open. During closures the sample mean value of the discard-harvest ratio is 0.97 for class II boats, and 0.94 for class I boats. During openings, the sample average discard-harvest ratio falls to 0.21 and 0.15 for class II and class I boats, respectively.

We also see stark differences in average red snapper harvest shares during open and closed periods. For class II boats, the average red snapper harvest share is 0.42 when red snapper is open and falls to 0.05 when red snapper is closed. Similarly, for class I boats; the average red snapper harvest share is 0.48 during open periods and 0.03 during closures.

4.4 Grouper discarding

Table 4 reports annual harvest and discard information for our sample observations that reported positive harvests of red and gag grouper. The table includes the commercial TAC[26] in millions of pounds, the percent of sample trips that reported positive discards, average harvested pounds per trip, the landings-weighted average of the discard-harvest ratio, and the landings-weighted average of the per-trip species-specific harvest share.

Average per-trip harvested pounds of red grouper show considerable variability across years, with a fairly sharp increase beginning in 2011; the second full year of the GT-IFQ program. Average per-trip harvest of gag grouper is flat or declining during the 2010-14 GT-IFQ regime. Grouper species were not regulated with the same strict per-trip landings limits that were used for red snapper. The 6,000 pound per trip landings limit (all shallow water groupers) likely did not bind for most vessels on most trips.[27] Landings data indicate that a small fraction of trips, 28 of the total 7,153 (0.39%) in our sample landed 5,500 pounds of the 6,000 pound limit during 2005-09.

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[26] Note that a species-specific TAC for Gag began in 2010 with the introduction of IFQs. Prior to 2010, gag was included in a shallow-water grouper TAC which was set at 9.98 million pounds from 2005-09.

[27] Assessing the extent to which this landings constraint was binding is difficult because trips landing more than 6,000 pounds are not observed in our data.

	Red Grouper						Gag Grouper					
Year	TAC	N	$\%\ trips_{(d_i>0)}$	$h_i/trip$	$\frac{d_i}{h_i}$	$\frac{h_i}{\sum h_j}$	TAC	N	$\%\ trips_{(d_i>0)}$	$h_i/trip$	$\frac{d_i}{h_i}$	$\frac{h_i}{\sum h_j}$
2005	5.31	701	71.18	731.73	0.16	0.63	9.98	497	64.39	449.33	0.11	0.43
2006	5.31	589	77.08	992.15	0.24	0.79	9.98	432	53.47	308.96	0.13	0.39
2007	5.31	816	63.36	897.60	0.18	0.77	9.98	609	32.18	353.14	0.06	0.45
2008	5.31	1,441	9.16	558.70	0.01	0.71	9.98	1,079	4.36	260.44	0.00	0.46
2009	5.75	905	8.51	696.54	0.01	0.75	9.98	643	4.51	159.17	0.01	0.30
2010	5.75	876	6.62	684.99	0.01	0.76	1.41	711	4.92	129.50	0.00	0.19
2011	4.46	1,232	5.28	1,268.91	0.00	0.75	0.43	866	22.17	163.59	0.06	0.13
2012	5.37	1,166	3.09	1,199.20	0.00	0.72	0.54	887	16.35	220.82	0.05	0.18
2013	5.53	1,209	1.74	1,037.99	0.00	0.71	0.71	1,005	9.65	194.61	0.05	0.18
2014	5.63	1,0435	2.22	1,373.45	0.00	0.77	0.84	810	2.10	174.31	0.01	0.17

Table 4: Red Grouper and Gag Harvests and Discards, 2005-14. Columns report: TAC is denoted in millions of pounds; N is the number of sample trips reporting positive harvest of species i; $\%\ trips_{(d_i>0)}$ denotes the percentage of sample trips reporting positive discards; $h_i/trip$ is average pounds (all species) harvested per trip; $\frac{d_i}{h_i}$ is the landings-weighted average ratio of discarded to harvested pounds per trip; $\frac{h_i}{\sum h_j}$ is the landings-weighted average harvest share of species i in the trip harvest. Note that gag grouper was managed under an all shallow-water grouper TAC of 9.98 million pounds from 2005-09.

The percentage of trips recording positive red grouper discards, and the red grouper discard-harvest ratio begin to decline in 2007, the year that the red snapper IFQ program began. The discard-harvest ratio for red grouper remains only slightly above zero during the GT-IFQ regime. To understand the decline in discards in 2008-09 we look more closely at discard patterns within each year, particularly during periods when the grouper fisheries were open and when they were closed. In 2005-06, all species were managed with closures. Cross-referencing trip-level data with date-specific regulations finds periods during which grouper fisheries were closed while red snapper and other reef fish fisheries remained open. A combination of grouper closures and red snapper opening occurred on 61 days during 2005-06. Class I and class II reef fish fishermen who were permitted to land red snapper took trips during these grouper closures. Our data show that on the 49 trips that took place during the 61 days in 2005-06, the discard-harvest ratio for red grouper is exactly 1, i.e., 100% of the red grouper that was harvested was discarded at sea. The pattern is the same for gag grouper; the discard-harvest ratio was 0.97 in 2005 and 1 in 2006.

Red snapper closures ended in 2007 with the introduction of the IFQ regulation, but grouper closures continued through 2009. In 2007 the red grouper discard-harvest ratio is 0.21 during red grouper openings and 0.92 during red grouper closures. In 2008, the red grouper discard-harvest ratio is 0.03 during openings and 0.57 during closures, while in 2009, the discard-harvest ratio is 0.02 during openings and 0.70 during closures. Annual averages reported in table 4 mask this within-season pattern in part because the number of trips taken during grouper closures is small, particulary from 2007 on.

During the 2005-09 controlled access regime, regulators often closed the red grouper and gag grouper species fisheries concurrently. Note also that groupers accounted for roughly 40% of trip revenue during 2005-09 (red snapper accounted for roughly 11%). When multiple grouper species fisheries were closed, reef fish fishermen stayed in port, since roughly 40% of a typical trips' revenue was disallowed due to the closures. The small number of trips that were taken resulted in the low annual average discard-harvest ratio (table 4). When the red snapper IFQ program began, grouper discards declined dramatically. The reason is that the red snapper

IFQ regulation allowed fishermen to harvest red snapper any time during the year; class I and class II endorsement permit holders stopped fishing for red snapper during grouper closures, thus causing the sharp decline in the grouper discard-harvest ratio.

As with red snapper, red grouper discards during the GT-IFQ regime, 2010-14, are near zero. Gag grouper discards fall sharply under IFQ management but remain positive from 2011 through 2013. Notice that the gag grouper TAC was set at 1.41 m. pounds in the fist year of the GT-IFQ regulation. The gag TAC dropped to 0.43 m. pounds in 2011, was raised slightly to 0.54 m. pounds in 2012, and was raised again to 0.71 m. pounds in 2013. During these years, the red grouper TAC remained relatively high.

The analysis of section 2 shows that a particularly tight quota for one species and a liberal quota for another are precisely the conditions under which discarding fish at sea can lower factor input costs. The ratio of gag to red grouper TAC ranged between 0.10-0.13 during 2011-13. In other words, an average quota holder was required by regulation to harvest one pound of gag for every 10-13 pounds of red grouper.

Did CSF provision play a role in the higher 2010-13 gag grouper discards? The average dockside price for gag grouper landings ranged from \$4.55-\$4.98 during 2010-13; the price for red grouper ranged between \$3.23-\$3.59 during the same period. Let gag proxy for the higher priced species 1 in figure 2. TACs place the average quota constraint in the north-west region of the figure, i.e., regions II, III, VI and VIII. For quota allocations in regions III and VI, discarding gag is raises private fishing profits. We investigate whether this very skewed mix of harvests impacted discard incentives below.

Discard patterns for other reef fish species including vermilion snapper, other shallow water groupers, deep water groupers and tilefish are reported in appendix 7 (table 9). Discard patterns follow model predictions: discards for vermilion snapper which is an unregulated species are effectively zero throughout the data period. The deep water grouper average discard-harvest ratio declined from 2% in the first year of the GT-IFQ program to 0 % in 2013-14. The shallow water grouper and tilefish discard-harvest ratio has declined substantially during the GT-IFQ regime but has lingered in the 2-5% range. A possible explanation is the low TACs for these species; other shallow water grouper (tilefish) TACs have been set in the range of 0.42-0.52 (0.44-0.58) million pounds during the 2010-14.

4.5 Quota-constrained discards: regression analysis

This section examines discard patterns using regression analysis to isolate multiple factors which may influence the decision to discard fish at sea. We specify a linear probability model of a discard event; the dependent variable is set equal to 1 if on trip j some or all harvested species i fish is discarded and 0 otherwise. The explanatory variables fall into two categories: (1) regulations, and (2) controls for the fact that reef fish fishermen choose the spatial-temporal stock conditions and prices under which each fishing trip occurs.

The regression we conduct seek to isolate causes of at-sea discards, conditional on having taken a trip under the observed stock and economic conditions and on a positive harvest, i.e., if on a trip j $h_{ij} = 0$, d_{ij} is also 0. While the regression results we report inform the discard patterns predicted in section 2, we cannot interpret the measured effects as the causal impacts of regulation on discarding.

Our analysis must first address a limitation in our data wherein stock conditions are unobserved by the researcher.[28] Our data contain detailed information on the quantity of hooks, lines, and soak time that fishermen set on each trip. We follow the fisheries stock assessment literature to estimate stock abundance indices for red snapper, red grouper and gag grouper. The method of stock estimation relies on the assumption that harvest will be proportional to the quantity of gear allocated and the unobserved stock abundance(see SEDAR, 2014). Under

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[28] Missing variable bias caused by unobserved stock variables may be particulary acute in trip level analysis where stock conditions can vary substantially across time and space due to natural variation in the marine environment.

this assumption an index of stock abundance, referred to as catch per unit of *effort* (CPUE), obtains from observable data, i.e., harvest and allocated gear. We detailed information on the type and quantity of hooks and lines used on each trip, and the number of hours the gear is soaked to estimate the following:

$$CPUE_{i,j} = \frac{h_{i,j}}{E_j} = \Phi(S_j|\beta_S) + \beta_m M_j + \chi_{i,j}. \tag{24}$$

In the above, $h_{i,j}$ is the quantity of species i harvested on trip j, E_j is the quantity of gear allocated, referred to as effort in the stock assessment literature, on trip j. We measure effort as the number of hooks that are set times the hours the hooks were soaked on the trip (SEDAR, 2014). The term $\Phi(S_j|\beta_s)$ is a polynomial function of the spatial subregion and the date for trip j.[29]

The third term in (24), is a liner function of controls M_j thought to influence the configuration of effort, plus other unobserved factors that may impact the CPUE relationship. Elements of M_j also include a fisherman fixed effect (to capture time invariant unobserved effects), species-specific prices, the price of inputs, and regulations in place at the time of the trip, e.g., we use species-specific cumulative landings relative to the annual total allowable catch, and an indicator for fishery closures.

The residual $\chi_{i,j}$ in equation 24 will represent the component of the trip j CPUE that is unexplained by the model. Recall that $\Phi(S_j|\beta_S)$ includes the spatial and temporal trip location and M_j includes fishermen fixed effects, and the trip economic and regulatory conditions, all variables that known to the vessel operator at the time that trip j begins. The residual term can therefore be interpreted as an unanticipated component of $CPUE_{i,j}$, or under the assumptions above, the unanticipated stock abundance for species i on trip j. We exploit this interpretation of the CPUE residual χ_{ij} in our regressions.

To elaborate, if at-sea discards are caused by unanticipated quota overages then $\hat{\chi}_{i,j}$ should be positive correlated with discard events in our data. Moreover, CSF provisions allow fishermen to legally land over-quota harvest under another species' quota. The intent of CSF is precisely to reduced discard arising from an unanticipated harvest overage. This suggests an approach to test for the effectiveness of CSF provisions, i.e., if CSF provisions are working as regulators anticipate, the impact of $\hat{\chi}_{i,j}$ on discards will be less when multi-use quota is available. From table 1 for example, the effects of high abundance on red grouper discards should be less when gag grouper multi-use quota is relatively large. The same principle applies to gag discards, however, since red grouper multi-use quota was set a zero in most years, evidence of the effects of CSF is not possible.

Testing for over-quota discarding and the effects of CSF provisions requires accurate information on trip-specific quota holdings and/or information on the ability to acquire additional quota when catch overages occur. We do not observe quota holdings directly. Our data contain measures of quota scarcity. A first measure is the species-specific TAC. Because TACs are set annually, however, their effect on discards cannot be separated from other factors that vary annually. We construct a second quota scarcity measure as the proportion of the annual TAC that has been landed at the time that trip j is taken. This measure of *unfished quota* for species i on trip j is hereafter denoted $UFQ_{ij} \in [0, 1]$, and is interpreted as a measure if tightness of species i quota market.

Table 5 reports linear probability regression results for red snapper, red grouper and gag grouper discard events. We include trips taken during each species' IFQ regulatory regime that reported positive harvests of their respective species. Models include an indicator (dummy) variable 'Longline gear' to account for potential difference in discarding patterns relative to handline, bandit and troll gear types. A linear trend is included to capture unobserved time-varying changes in the incentive to discard fish, for example, adjustments in a fisherman's

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[29] Space delineations follow the GOM subregion designations 1-11. Time is composed of a within season (day of the year) component and a trend that spans the entire 2005-14 data period.

	Red Snapper			Red Grouper			Gag Grouper		
	Est.	Std. Err.	p-val.	Est.	Std. Err.	p-val.	Est.	Std. Err.	p-val.
Constant	-0.606	0.944	0.260	0.363	0.317	0.126	0.876	0.736	0.117
UFQ_{ij}	0.054	0.042	0.099	0.027	0.017	0.060	0.057	0.056	0.157
TAC_i	-0.063	0.042	0.065	0.002	0.018	0.454	-0.191	0.045	<0.001
$\hat{\chi}_{i,j}$	0.029	0.013	0.012	0.000	0.003	0.451	0.054	0.017	<0.001
$\hat{\chi}_{i,j}\times$CSF	–	–	–	-0.163	0.300	0.294	-0.049	0.036	0.085
Trend	-0.429	0.204	0.018	-0.046	0.118	0.347	-0.433	0.112	<0.001
$\hat{X}_{ij}$ red snap.	-0.106	0.325	0.372	0.211	0.107	0.025	-0.344	0.211	0.052
$\hat{X}_{ij}$ red group.	0.001	0.065	0.493	-0.005	0.024	0.411	0.060	0.039	0.062
$\hat{X}_{ij}$ gag group.	0.072	0.151	0.126	-0.088	0.058	0.065	0.099	0.075	0.093
Lonline gear	0.320	0.105	0.001	0.004	0.013	0.364	0.005	0.043	0.454
Landings price	0.004	0.057	0.474	0.008	0.013	0.269	0.062	0.040	0.061
Effort price	0.161	0.020	0.089	-0.039	0.035	0.136	-0.052	0.082	0.264
	N = 4,664; R^2 = 0.112			N = 3,928; R^2=0.015			N=3,083; R^2=0.090		

Table 5: Red Grouper and Gag Discard Model.

portfolio of quota holdings over time. The data are an unbalanced panel with repeat trip observations taken by 440 unique vessel operators. Table 5 reports robust standard errors that are clustered at the level of the individual vessel.

The results find that the discard probability increases with quota scarcity; coefficients on unfished quota, UFQ_{ij}, are positive, although statistically different from zero at conventional levels for red snapper and red grouper only. Coefficients on species' annual aggregate quota, TAC_i, are negative and statistically significant for red snapper and gag grouper; the coefficient estimate is statistically and literally equal to zero for red grouper.

The effect of unanticipated stock abundance is positive and statistically significant for red snapper and gag grouper (p-value are 0.012 and <0.001, respectively), suggesting evidence that discarding may increase with an unanticipated high trip catch rate. When we interact $\hat{\chi}_{i,j}$ with multi-use quota we find an expected negative effect, although the estimate is statistically insignificant for both red and gag grouper.

These findings should be interpreted with caution. Note first that the identification of CSF effects on discards is rather limited. Multi-use quota is used for red and gag grouper only. Furthermore, variation in the quantity of each species maximum multi-use quota, required to identify the effect under investigation is limited. The data contain variation in gag grouper multi-use quota and large maximum values in several years. The question is, were reef fish fishermen inclined to use gag quota to land red grouper over-quota harvests? Below we present evidence to suggest that CSF of this form likely was not utilized in the reef fish fishery.

The coefficient on the trend variable is negative for all species but statistically significant at conventional levels (p-value <0.001) for gag only. This finding is consist with discard patterns reported in table 4.

The coefficient estimates for the additional controls show no clear pattern and are not discussed further.

4.6 More on regulations and discarding

A full calibration of the costly targeting technology introduced in section 2 allows further investigation of the regulatory environment in the GOM reef fish fishery under the GT-IFQ with CSF provisions regulation. Our calibration involves two additional steps: (1) aggregation of factor inputs to form a composite input z, and (2) estimation of targeting technology in equation (1). The methods used to construct the input aggregate follows Squires (1987) and is discussed in appendix 7. We specify the following system of equations for estimation of the two-species costly targeting technology:

$$h_{1,j} = \overline{h}_{1,j} + e_{1,j} = \left(\nu_1 \left(1 + \sin\left[\frac{a_j \pi}{2}\right]\right) x_{1,j}^{\mu}\right) (\theta \overline{z}_j)^{\gamma_j} + e_{1,j} \tag{25}$$

$$h_{2,j} = \overline{h}_{2,j} + e_{2,j} = \left(\nu_2 \left(1 + \cos\left[\frac{a_j \pi}{2}\right]\right) x_{2,j}^{\mu}\right) (\theta \overline{z}_j)^{\gamma_j} + e_{2,j}. \tag{26}$$

The residual terms in (26), $e_{i,j}$ $i = 1, 2$, are assumed to represent deviations from the mean harvest functions, $\overline{h}_{i,j}$ for $i = 1, /2$. We assume $e_{i,j}$ are iid random terms with zero means. Each is the result of exogenous natural variation in unobserved stock abundance which is assumed uncorrelated with the spatial, temporal, economic and regulatory conditions that influence the configuration of the aggregate input and/or targeting choice a_j for the trip.

Observe that we have inserted the fitted aggregate input into equation (26). We must also account for the fact that the trip j input, $\overline{z}_j$, is a public factor of production used to harvest multiple reef fish species (in addition to $h_{1,j}$ and $h_{2,j}$). The term $\theta_j \in (0, 1]$ is specified as a function of the share of $h_{1,j}$ and $h_{2,j}$ in the total harvest of trip j. We assume θ_j follows:

$$\theta_j = \frac{exp(\beta_\theta \frac{\sum h_{-i,j}}{\sum h_{i,j}})}{1 + exp(\beta_\theta \frac{\sum h_{-i,j}}{\sum h_{i,j}})}, \tag{27}$$

where $\frac{\sum h_{j,-i}}{\sum h_{j,i}}$ is the share of all species harvested other than red and gag grouper. The parameter β_θ is a scale parameter reflecting the rate at which the public input $\overline{z}_j$ contributes to the harvest of other reef fish species.

Next we allow the trip j targeting parameter to vary with observed factors hypothesized to impact fishermen's targeting choices. a_j is specified as,

$$a_j = \frac{exp(\beta_a T_j)}{1 + exp(\beta_a T_j)}, \tag{28}$$

where T_j is a vector of pre-determined variables that impact the targeting decision on trip j. Elements of T_j includes prices and regulatory variables.

Generalized non-linear least squares is used to estimate the model parameters. Parameter estimates, standard errors and p-value for a two-sided test of the null hypothesis that the estimated parameter is equal to zero are reported in table 6. Again, our data include multiple observations on individual vessels. Heteroskedastic-consistent standard errors are reported.

Three model specifications are included. In model specification 1, the targeting parameter a_j is set to a constant. This case represents a *no targeting* scenario, e.g., where reef fish fishermen do not engage in directed harvesting of individual reef fish species but rather passively allocate factor inputs to the fishery to obtain an exogenously determined harvest a mix, e.g., a mix of species determined by stock conditions. The second and third specifications allow the targeting parameter to be impacted with regulations and prices.

A test of the restrictions in specification 1, that targeting is unaffected by prices and regulations, is rejected at conventional levels of significance (the F-statistic is 78.494 with 1% critical value, 2.04). This result is consistent with evidence of targeting behavior reported in tables 2, 3, and 4.

Estimates of the targeting technology parameters follow expectations. The red grouper scale parameter estimate is 4-5 time larger that gag counterpart reflecting the dominance of red grouper in the mix of harvested species in the GOM reef fish fishery. The estimate of the stock index coefficient μ is positive across the three model specifications. The input elasticity parameter γ ranges between 0.870-0.877 and is stable across specification. The magnitude of the estimate indicates diminishing returns to the aggregate input at the trip level.

Model specification 2 includes both measures of quota scarcity; specification 3 drops the measures of unfished quota, UFQ_{ij}, $i = 1, 2$.

		Model 1			Model 2			Model 3	
Parm.	Est.	Std. err.	p-val.	Est.	Std. err.	p-val.	Est.	Std. err.	p-val.
v_1	1.026	0.363	0.005	2.290	1.280	0.074	2.128	0.843	0.012
v_2	0.359	0.108	0.001	0.503	0.288	0.080	0.450	0.185	0.015
μ	0.247	0.053	< 0.001	0.167	0.056	0.003	0.148	0.052	0.004
γ	0.870	0.028	< 0.001	0.877	0.033	<0.001	0.876	0.031	<0.001
Targ. parameter: $a = \frac{exp(.)}{1+exp(.)}$									
Var.	Est.	Std. err.	p-val.	Est.	Std. err.	p-val.	Est.	Std. err.	p-val.
Constant	1.049	0.206	<0.001	-66.973	14.322	< 0.001	-64.572	9.709	<0.001
UFQ_{1j}	–	–	–	2.817	2.747	0.305	–	–	–
UFQ_{2j}	–	–	–	-0.319	2.663	0.905	–	–	–
TAC_1	–	–	–	1.165	0.311	< 0.001	1.458	0.298	<0.001
TAC_2	–	–	–	-3.331	1.486	0.025	-4.196	1.305	0.001
MUQ_2	–	–	–	-1.891	1.511	0.211	-1.910	1.108	0.085
p_1	–	–	–	1.321	0.869	0.128	1.153	0.730	0.115
p_2	–	–	–	-1.789	0.754	0.018	-1.761	0.648	0.007
$\hat{w}_j$	–	–	–	8.342	2.001	< 0.001	8.092	1.306	<0.001
Input allocation: $\theta = \frac{exp(.)}{1+exp(.)}$									
Var.	Est.	Std. err.	p-val.	Est.	Std. err.	p-val.	Est.	Std. err.	p-val.
Constant	-0.446	0.910	0.627	0.615	0.943	0.515	0.464	0.700	0.507
$S_{j,-i}$	2.625	0.726	<0.001	2.379	0.401	<0.001	2.484	0.328	<0.001
	SSE =1,422.642			SSE = 1,140.201			SSE = 1,140.130		

Table 6: Targeting Technology Calibration for Red and Gag Grouper.

4.6.1 Regulation and fisherman incentives in the GOM reef fish fishery

The parameters from specification 3 are used to investigate discarding incentives under the GT-IFQ regime. As noted above, during 2011-13, discard/harvest ratios ranged between 5 % and 6% for gag grouper, but fell to almost zero for all other major reef fish species (table 4). During this period, regulators reduced the gag grouper TAC sharply and unilaterally in response to stock assessment that showed declines in gag grouper abundance (see figure 9 on appendix 7). We set prices and CPUE stock indices to average values in our 2012 data. We then derive the optimal input allocation, targeting choice and species-specific discards over a range of quota values.

Recall that our data do not contain quota holdings at the fisherman, or trip level. Annual quota is delineated as share of annual TAC's. In 2012, the red grouper and gag TAC's were set at 5.37 m. and 0.54 m. pounds, respectively. An *average* quota owner therefore may have held species specific quotas in these same proportions. We do not observe quota trades and as noted, quotas bind at the seasonal level not at the trip level. By evaluating fishermen's incentives over a range of quota holdings can illustrate incentives operational at least for a subset of fishermen in 2012.

To facilitate comparisons with the analysis in figure 2 we hereafter designate gag grouper as species 1 and red grouper as species 2. Consistent with 2012 CSF regulations, we allow 8% of the gag quota to be used to land red grouper but do not allow any red grouper quota to be used to land gag grouper.

Figure 8 plots the Lagrange multipliers for individual species' landings constraints, $\omega_i, i = 1,\ 2$, the aggregate quota constraint multiplier λ, and the ratio of discards to harvests for species 1 fish, gag grouper. No positive discards of red grouper obtained for the quota levels considered in the baseline calibration. The range for gag quota, q_1, is $[0, 5]$; the range for red grouper quota, q_2, is set at $[5, 15]$.

The top panels show $\omega_i, i = 1,\ 2$ for different quota combinations. At low values for q_1, ω_1 is positive and hovers around \$3.50. When q_2 is small ω_2 is positive as required although

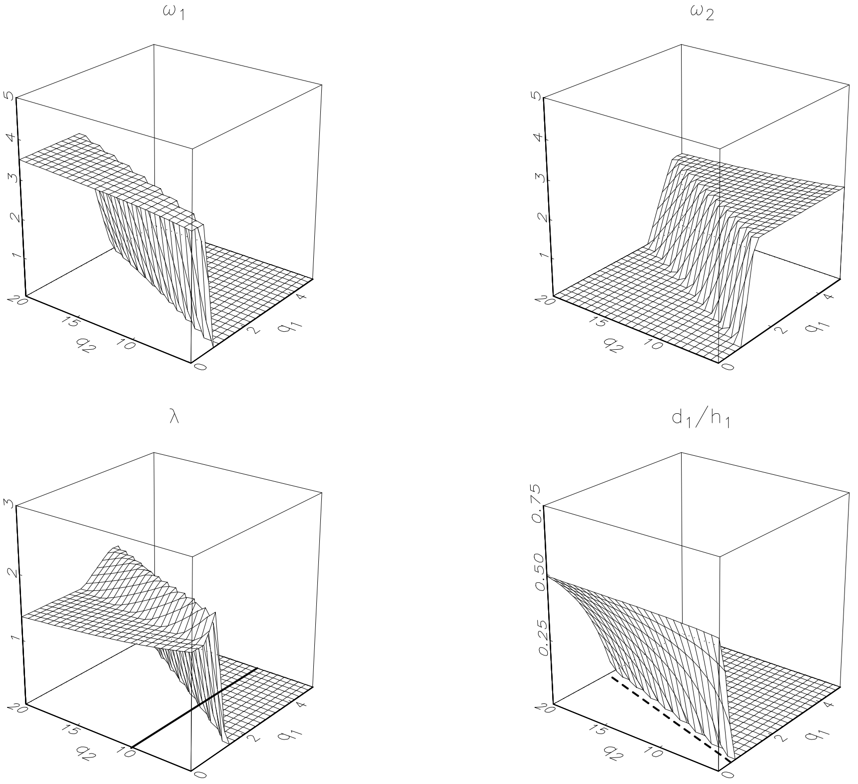

Figure 8: Quota-Constrained Harvests and Discards, 2012.

its value does not exceed \$2.50. The landings-weighted average prices for gag (species 1) and red grouper (species 2) in 2012 were \$4.87 and \$3.32, respectively. The fitted values for the constraint multipliers suggest that CSF, if available, would be used to land gag grouper. Given the regulatory objective of rebuilding gag stocks, it was apparently wise to set red grouper multi-use quota to zero.

The dashed line in figure 8 demarcates the skewed ratio of red to gag grouper quota: 5.37/0.54, or 9.94 pounds of red grouper per for pound of gag grouper. Observe that the ratio of red to gag TACs in 2012 places quotas in the positive discard zone VI of figure 2. Utilizing gag multi-use quota provision only skews the species mix further. From the top panels in figure 8 the option to utilize gag multi-use quota was likely rarely used.

The lower left panel shows the value of λ for different quota combinations. A useful exercise holds q_2 fixed at an intermediate level, say 10 units, and increases q_1 from 0 through 5 (along the solid line shown in the figure). As noted $(q_1, q_2) = (0, 10)$ falls in zone VI of figure 2 with $l_2 = q_2 = h_2$ and $l_1 = q_1 < h_1$. As q_1 increases, λ declines initially as the species 1 constraint is relaxed. λ then increases with q_1 entering zone VIII in figure 2. Here the marginal profit of additional harvest of both species is positive. The peak of the multiplier λ separates zone VIII and IX. In zone IX it is optimal to use gag multi-use quota to land red grouper. Zone IX is small. Holding $q_2 = 10$, further increases in q_1 cause the aggregate quota constraint to become slack, i.e., $lambda = 0$ for $q_1/ge3$, approximately.

The lower right panel in figure 8 suggests that tightening the gag TAC, while maintaining a relatively high red grouper TACs may have encouraged gag discards in 2012, perhaps delaying the gag stock recovery. The dashed line shown in the lower right hand panel delineates the 2012 ratio of gag to red grouper TAC, which lies in discard zone VI. Note that similar gag quota scarcity which persisted throughout 2011-13 may explain the higher discard/harvest ratios for gag grouper during these same years (table 4).

5 Conclusion

Cross-species quota flexibility (CSF) may play a role in reducing discards due to unanticipated over-quota discards. We find no evidence that such provisions reduced discards in the GOM commercial reef fish fishery. CSF on the other hand invites fishermen to target and land higher profit species against their flexible quota holdings. We characterize profit maximizing harvest and discard choices under a costly targeting technology in a quota-regulated fishery with a CSF provision. The analysis shows that harvest choices are impacted in complex ways by a flexibility provision; harvests, landings and discards vary with prices, stock conditions, the structure of the multi-species technology and the extent of flexibility allowed.

Our results highlight the main shortcoming of a CSF provision. Allowing fishermen flexibility to harvest their preferred mix of species constrains the regulators ability to control aggregate harvest and discard outcomes under decentralized management. CSF limits the ability of the regulator to steer the multi-species stock along a path that maximizes long term fishery value. A balance must be struck between the discard-reducing benefits of a CSF provision and the long term rent losses due to reduced control over stock abundance and growth.

We analyze a unique data set from the Gulf of Mexico commercial reef fish fishery. Evidence suggests that commercial reef fish fishermen adjusted harvesting operations to manage the mix of species that are harvested with their gear. The analysis finds that discarding was prevalent under the command and control regulation which limited, severely for some vessels, the quantity of individual species that could be legally landed on each trip. Discarding dropped sharply and after 3-4 years fell to zero under quota regulations. The role of CSF provision in the decline in discards could not be fully determined. Analysis of raw data, and trip-level analysis of discard events found no evidence that CSF played an important role in reducing over-quota discards. Calibration of our costly targeting model finds that the discards that did persist in the COM reef fish fishery were likely caused by regulations that set skewed annual landings limits for key reef fish species. Regulators who sought to rebuild gag stocks were wise to limit CSF in a way that limited additional gag grouper harvests and landings; our analysis suggests such flexibility, if offered, would have been directed at vulnerable gag grouper stocks.

A broader policy message that is strongly supported by our empirical results is that harvest/cost complementarity must be considered when setting annual total allowable catch limits in multiple-species fisheries, particulary when one or more stocks are threatened by overfishing. Evidence from the GOM reef fish fishery suggests that gag grouper stock rebuilding during 2011-14 were impacted by a decision to tightly constraint the gag grouper TAC in isolation, i.e., while concurrently maintaining relatively large red grouper and other reef fish species TAC's. Our results suggests the skewed TACs may have increased gag grouper discards. Allowing reef fish fishermen to land over-quota harvests of gag grouper under a CSF provision would have increased revenue, but would have also changed the mix of targeted and landed species across multiple species or species groups. Designing a stock rebuilding plan in a setting with costly individual species' targeting and competition and interdependent growth among competing species is a difficult problem and an important topic for future research.

Finally, this paper has focused on contemporaneous cross-species flexibility mechanisms in a setting where at-sea discards are unobserved by the regulator and therefore cannot be counted against fishermen's quota holdings. Targeting and discards and the role of flexibility will change with at-sea observability, raising new questions about the role of flexibility in addressing management goals. The implications of allowing flexibility in the temporal dimension, e.g., allowing fishermen to bank or borrow quota across seasons also raises new questions for policy design. Definitive answers to these policy questions is also reserved for future work.

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7 Appendix A

This appendix presents (1) Logbook data data descriptive statistics, (2) discard descriptive statistics for vermilion snapper, other shallow water groupers, deepwater groupers and tilefish, and (3) details and additional results from the construction of an aggregate input.

7.1 Logbook Data Descriptive Statistics.

The National Marine Fisheries Service logbook data reporting system collects trip-level landings by species and other information for all vessels licensed to harvest Gulf of Mexico reef fish, on all trips landing reef fish species. Our data contain 75,564 trip records taken during 2005-14 in the region of the Gulf east of the Mississippi delta.[30] On 57,996 (76.8%) of trips taken, operators were not required to report discards; discard information is available for the remaining 17,568 (23.3%) of trips. On 12,125 (16.0%) of eastern trips, operators were required to report both discard and trip expense information. Trip expense information is complete for 10,107 (13.4%) of the total trip records.

	(1) all trips	(2) w/out disc.	(3) w/disc.	(4) w/disc.&exp.	(5) w/disc.&exp.
Obs.	75,564	57,996	17,568	12,125	10,107
Days at sea	3.88	3.87	3.89	4.04	4.08
Crew size	2.34	2.33	2.38	2.44	2.46
Vess. Length	35.75	35.59	36.29	36.92	37.08
Total lbs./trip	1,470.27	1,424.55	1,621.23	1,776.77	1,850.56
Revenue/trip	4,611.50	4,464.53	5,096.70	5,555.23	5,847.80
			Revenue Shares		
Red Snap.	0.13	0.12	0.15	0.14	0.13
Verm. Snap.	0.08	0.07	0.12	0.15	0.08
Red Group.	0.28	0.29	0.24	0.24	0.28
Gag Group.	0.10	0.10	0.07	0.06	0.10
OSW Group.	0.03	0.03	0.03	0.03	0.03
DW Group.	0.03	0.03	0.02	0.02	0.03
Tilefish	0.01	0.01	0.01	0.01	0.01

Table 7: Logbook Data Subset Comparison. The table reports average values across five subsets of 2005-14 logbook trip records from the eastern GOM region. Column report sample averages for: (1) all trips; (2) trips with no discard information; (3) trips with discard information; (4) trips information on discards and expenses (but with incomplete fuel expenses) and; (5) trips with discard and complete trip expense information. Revenues are reported in $2014.

Table 7 reports mean values for trip days at sea, crew size, vessel lengths, landed pounds, revenue, and revenue shares for five data subdivisions. Trips recording discard and expense information are on average longer, with larger crew, are taken by longer vessels, harvest more pounds and collect higher revenues per trip. Difference across subsamples should be considered when extrapolating results in section 4 to the broader reef fish fleet and fishery.

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[30] Trips that harvested 75% of shark species were removed.

	Mean	Std.	5'th %	50'th %	95'th %
Days at sea	4.08	3.30	1.00	3.00	11.00
Crew size	2.46	1.08	1.00	2.00	4.00
Labor exp.	1,856.12	1,777.17	235.18	1,397.44	5,314.62
Fuel exp.	562.48	554.35	70.04	407.72	1,555.44
Oth. exp.	757.96	1,004.74	16.32	402.49	2,645.71
Capital exp.	99.76	135.30	12.57	63.12	294.14
Revenue	5,847.80	7,488.57	185.51	3,116.15	21,242.80
Harvested lbs.	2,034.87	2,417.63	76.00	1,244.00	7,026.11
			Cost Shares		
	Mean	Std.	5'th %	50'th %	95'th %
Labor	0.58	0.12	0.37	0.58	0.77
Fuel	0.20	0.10	0.08	0.18	0.38
Other	0.19	0.11	0.03	0.19	0.39
Capital	0.03	0.01	0.01	0.03	0.05

Table 8: **Trip Characteristics, Revenue, Landings and Expense Descriptive Statistics.** N = 10,107. Values are reported in \$2014.

7.2 Discard Descriptive Statistics: Other Reef Fish Species

	Vermilion Snapper			OSW Groupers				DW Grouper				Tilefish			
Year	N	*% trips* $(d_i{>}0)$	$\frac{d_i}{h_i}$	TAC	N	*% trips* $(d_i{>}0)$	$\frac{d_i}{h_i}$	TAC	N	*% trips* $(d_i{>}0)$	$\frac{d_i}{h_i}$	TAC	N	*% trips* $(d_i{>}0)$	$\frac{d_i}{h_i}$
2005	244	15.98	0.02	9.98	473	37.42	0.26	1.02	89	16.85	0.15	0.44	44	2.27	0.04
2006	186	21.51	0.01	9.98	348	26.15	0.18	1.02	79	16.46	0.17	0.44	46	2.17	0.10
2007	337	29.38	0.02	9.98	554	19.31	0.14	1.02	190	15.79	0.13	0.44	101	8.91	0.08
2008	808	5.32	0.00	9.98	1,068	23.31	0.14	1.02	192	19.79	0.12	0.44	65	3.08	0.02
2009	530	2.26	0.00	9.98	635	19.06	0.17	1.02	156	4.49	0.02	0.44	86	5.81	0.04
2010	621	4.83	0.00	0.41	624	16.03	0.13	1.02	208	5.77	0.02	0.44	115	14.78	0.06
2011	879	1.48	0.00	0.41	871	13.43	0.09	1.02	224	6.70	0.02	0.44	103	20.39	0.11
2012	894	0.22	0.00	0.50	864	7.99	0.05	1.12	235	4.26	0.01	0.58	120	11.67	0.04
2013	847	0.24	0.00	0.52	818	8.81	0.04	1.12	244	1.23	0.00	0.58	103	5.83	0.02
2014	693	0.72	0.00	0.52	673	11.14	0.03	1.11	251	3.19	0.00	0.58	133	14.29	0.04

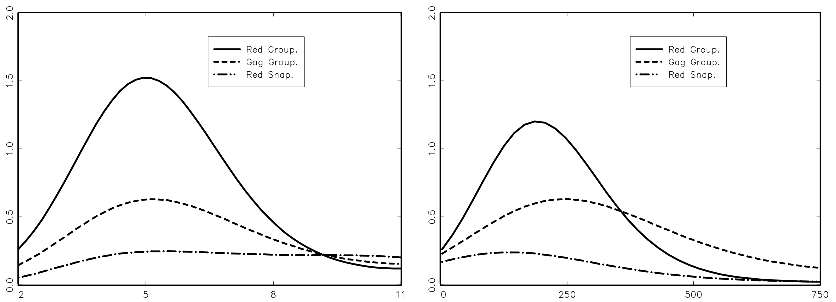
Table 9: Vermilion Snapper, Groupers-Tilefish Discards, 2005-14. TACs are reported in millions of pounds; N is the sample size; $\frac{d_i}{h_i}$ is the landings-weighted average ratio of discarded to harvested pounds.

7.3 CPUE index results

The fitted model in (24) is used to estimate species-specific CPUE at the spatial-temporal location of each trip in our data. This fitted value will proxy for stock abundance in equation (1).

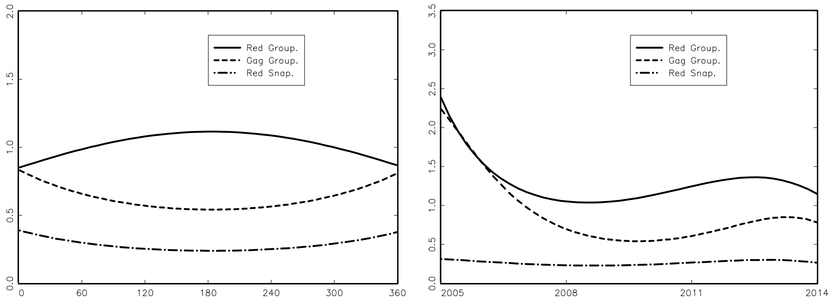
Figure 9 plots the fitted species-specific stock indices, CPUE, across GOM subregions, fishing depth, the day of the year and the cumulative day since January 1, 2005. Subregions are numbered from 1-11; subregion 1 begins at the Florida Keys. Subregions 2-7 extend northward along the west coast of Florida coast and subregions 8-11 extend eastward along the Florida panhandle through the Alabama and Mississippi Gulf coasts.

Panel (a) shows that peak CPUE for the three major species considered occurs in subregions 4-6 which are west of Tampa Florida. From panel (b) we see that CPUE peaks in depths ranging



(a) Region (s.e. to n.w.)

(b) Fishing Depth (ft.)



(c) Season (day of year)

(d) Year

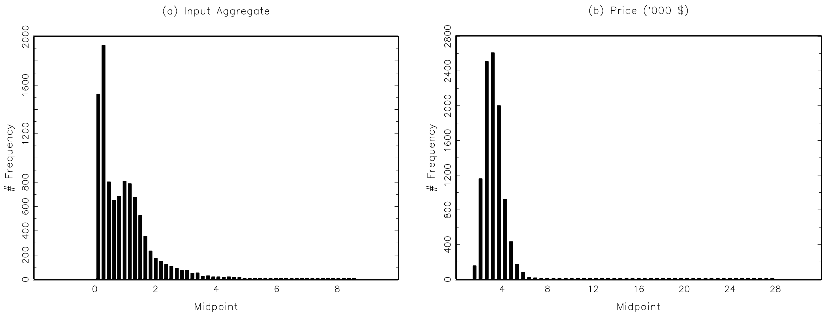
Figure 9: Red Grouper, Gag Grouper and Red Snapper Stock Abundance.

from 100-400 feet; red snapper CPUE peaks at shallower depths (150-200 feet). Gag grouper CPUE peaks in slightly deeper water than does red grouper. Panel (c) shows changes in seasonal CPUE. Patterns are consistent with gag grouper winter spawning aggregations. Red grouper CPUE peaks in mid-summer whereas red snapper CPUE shows no prevalent within season pattern. Panel (d) reports long-term changes in CPUE. The figure shows a sharp decline in the grouper CPUE during the early data years, 2005-08. The decline in gag grouper CPUE continues through 2010. The results indicate that red snapper CPUE has remained stable during the 2005-14 data period.

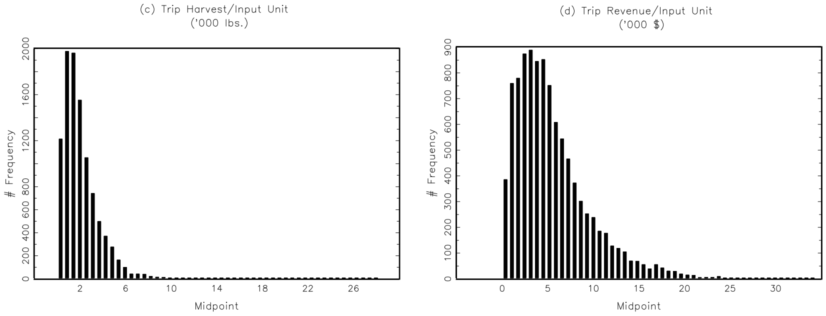
7.4 Input aggregation

We construct an input aggregate from four factor inputs, fuel, captain and crew labor, vessel capital services and miscellaneous expenses, following approach in Squires (1987). Note that consistent formation of an input aggregate requires an assumption of homothetic separability of the multiple-species harvesting technology. We maintain this assumption throughout. We estimate a system of 3 cost share equations (the miscellaneous expenses input cost share is dropped), with log input quantities as RHS regressors. Cost share equations are estimated with generalized least squares regression. The fitted parameters are then used to construct the empirical counterpart to the scalae input z from equation (1), which we summarize in figure 10.

Panels (a) and (b) in figure 10 are histograms of the input index and its implicit price (in \$2014) for all observations in our data with complete discard and trip expense information (N = 10,107). The input distribution shown in panel (a) is bimodal with the lower mode near zero and a second larger mode at roughly unity. A segment of the GOM commercial reef fish fleet consists of smaller vessel operations that take fewer and shorter trips than other more dedicated commercial fishermen.


(a) Input Aggregate

(b) Price ('000 $)


(c) Trip Harvest/Input Unit ('000 lbs.)

(d) Trip Revenue/Input Unit ('000 $)

Figure 10: Factor Input Aggregate.

Panels (c) and (d) show the distribution of harvested pounds and revenue per unit of the input aggregate across all trip observations. All panels show considerable variation in the trip-level data which is common in marine commercial fisheries.