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Discretion rather than rules in multiple-species fisheries

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Abstract

This paper evaluates the bioeconomic performance of individual fishing quota (IFQ) regulations in a multiple-species fishery. In our model, fisheries managers face uncertainty over the population sizes and growth characteristics of multiple cohabiting fish species'. Fishers control all aspects of harvest operations under full knowledge of the species-specific productivities of their fishing gear. We derive a rational equilibrium mapping from bioeconomic fundamentals and the IFQ regulation to the private profit maximizing mortality and rent outcomes that are implemented by fishers. Conditional on this mapping, we solve the second best problem of designing the regulation to maximize fishery value. Performance of a design that allows discretion over the mix of harvested species is contrasted against rules, via a discard ban. Both designs eliminate discards. Discretion diminishes information asymmetry between the manager and fishers and raises fishery value. Incorporating discretion into regulatory designs provides new prospects for improving fisheries management.

JEL Classification: Q2, L5

Keywords: Multiple species fishery, quota regulation, discretion, discard ban.

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1 Introduction

Individual fishing quotas (IFQs) have emerged as the predominant tool to address the tragedy of commons in fisheries. Owners of an IFQ hold a right to harvest a specified quantity of fish during a given calendar period, usually a year. Managers select the annual aggregate quotas, i.e., the sum of all IFQs issued, to meet management goals and monitor harvesting operations to prevent over-quota fishing. While management success would seem inevitable, in the assessments of many, IFQ regulations continue to under-perform. Choosing the aggregate quotas across multiple fish species that interact biologically and technologically in order to meet long term management goals remains a significant challenge.[1] A second problem is known as *implementation uncertainty*. Here, the species-specific mortalities and economic rent outcomes that are implemented by resource users do not match the mortality and rent outcomes that managers intended when the quotas were chosen (Branch and Hilborn, 2008; Fulton et al., 2011; Holland and HERRERA, 2009).

Both problems derive from the institutional features of fisheries. First, fish extraction processes are decentralized: a management authority, e.g., government agency, international commission, community organization, typically retains responsibility for choosing the aggregate quotas and designing and enforcing regulations. Autonomous resource users, hereafter fishers, control harvesting operations. It is therefore crucial that regulations provide incentives that *implement* mortality and rent outcome that are intended.

Second, selecting annual aggregate quotas is complicated by uncertainty over the true state of the bioeconomically-interdependent ecosystem that is under management. Formal stock assessments, which are rarely up to date and almost never available for all managed species, provide some information about the sizes and growth potentials of individual species stocks. Except in cases where very costly census methods, e.g., underwater cameras strapped to unmanned submarines, are deployed, fish *in situ* are unobservable.[2] Managers regularly choose annual quotas under uncertainty over true population sizes, their growth potentials, the nature of intra-species ecological interactions, among other factors.

[1] See for example, Batsleer et al. (2013); Briton et al. (2020); Hoff et al. (2010); Poos et al. (2010); Squires et al. (1998); Ulrich et al. (2008).

[2] In practice population size is inferred indirectly with the help of (untestable) ecological theory and indirect data sources, e.g., samples of sex and age distributions of a fish stock, past harvests, catch per unit of effort indices.

Yet as harvesting operations proceed, i.e., as nets, hooks and/or traps are deployed and retrieved from the water, fishers observe the productivity of their gear across the various species they pursue.[3] Gear productivity provides a signal about true stock abundances that is unavailable to managers when quotas are chosen (often well before harvesting operations begin although there are exceptions).[4] The question that is asked and answered in this paper is, can the IFQ regulation be modified to exploit information that is revealed to fishers in real time, as harvesting operations proceed, but is unavailable to managers when quotas are chosen? Our answer is a qualified yes; if managers are willing to grant discretion to resource users to respond to productivity signals they receive, and if specific bioeconomic conditions are met. We define these conditions formally below; in short, they are not overly restrictive.

We present a model of a decentralized, multiple-species fishery and contrast bioeconomic performance across competing IFQ-based regulatory designs. In our model, a manager chooses an aggregate annual quota for each fish species under uncertainty about its true population size and growth potential. Fishers then choose factor inputs and harvests to maximize their private single season profit, conditional on the regulation, technology constraints, the bioeconomic fundamentals in the fishery and, importantly, the realized gear productivities across species. The mapping from regulations to the outcomes that are implemented by fishers embeds rational ecological and economic equilibrium behavior under market clearing for the IFQs (Singh and Weninger, 2022).[5]

In our model, the manager attends to the resource user cost that captures tradeoffs between current and future resource extraction. A first best regulation would prescribe a gear-productivity-contingent harvest and factor input allocation plan that maximizes long term fishery value. We contrast bioeconomic performance in the second best setting of our model, with quotas chosen prior to the commencement of harvesting operations and before gear productivity is revealed.

We show how an IFQ regulation that grants fishers some discretion to adjust the mix of species that they can legally harvest will implement mortality and rent outcomes that are closer to the first best. We hereafter refer to this form of discretion as cross-species flexibility (CSF). An IFQ with CSF sets annual quotas for individual species but allows a specified portion the each quota to be used to land

[3]Catch per unit of gear deployed, or *catch per unit effort* indices, remain a core data element in stock assessment modeling (Hilborn and Walters, 2013).

[4]Managers of the British Columbia groundfish fishery regularly adjust groundfish quotas, mid season, in response to industry feedback regarding stock abundance and market conditions (Jonathan Gonzalez 2019, personal communication).

[5]Derivation of this mapping are often conditioned on *ad hoc* fisher behavior and restrictive assumptions for fishing technologies e.g. Ulrich et al. (2008, 2017); Briton et al. (2020, 2021).

other species. We derive bioeconomic conditions under which adding CSF to a standard IFQ design improves performance.[6]

Under CSF, short term gains in bioeconomic performance arise from the partial resolution of stock information asymmetry. Profit maximizing fishers allocate discretionary quota toward capture and landing of higher-profit species. Higher profits correlate with stock abundances. Thus, fisher-implemented mortality under CSF better aligns with mortality the manager would choose under full information about stock abundances. More generally, and relative to a standard IFQ design that does not allow discretion, CSF implements mortality outcomes that raise current use value, but not necessarily the long run total value of the resource. We show that across a range of bioeconomic fundamentals, long run fishery value is higher under moderate levels of fisher discretion.[7]

A second result, which is known in the literature, is that CSF reduces incentives to discard over-quota catch at sea, a problem that is considered severe in multiple-species fisheries (Sanchirico et al., 2006; Squires et al., 1998; Borges and Penas Lado, 2019). Discretion under CSF allows fishers to avoid costs that are otherwise required to precisely match harvests with quotas. Over-quota discarding reduces fishery value, i.e., the harvest costs that are expended to capture the fish are sunk, discarded fish generate no revenue at the dock, and due to low survival rates,[8] discards do not contribute to future abundance. CSF increases fishery value through this second channel as well.

Allowing too much discretion over the mix of harvested species can reduce fishery value. When fishers are granted discretion, the mortality outcomes that they implement respond to current profit motives only. Managers of course can foresee and incorporate this behavior into the regulatory design. However, differences between short- and long-term profits act to constrain the set of outcomes that can be implemented under second-best management. Excessive discretion, which we define formally, can

[6]CSF is used in IFQ-regulated fisheries throughout the world, although with explicit goal of reducing over-quota discards (Sanchirico et al., 2006). Over-quota discarding is considered problematic where catch and quotas must match across an array of harvested Squires et al. (1998); Borges and Penas Lado (2019). From 2010-15, the U.S. Gulf of Mexico Grouper-Tilefish IFQ program allowed between 8% - 70% of the aggregate gag grouper quota to be used to legally land red grouper, In 2010, 4% and in 2015, 4.8% of red grouper quota could be used to land gag grouper (Gulf of Mexico Fishery Management Council, 2008). Icelandic fisheries allow quotas to be used to land different species at specified quota exchange rates that are set in advance of each fishing season (Woods et al., 2016).

[7]This advantage shares features of a price-based regulation, but takes a different form. Weitzman (2002) shows how a landings tax instrument provides incentives to stop fishing when the true stock abundances in a single species fishery is drawn down to a particular threshold level. Price-based regulations provide an insurance against overexploitation of the stock. A quota regulation does not offer the same protections.

[8]Estimates of discard mortality that hover around 100% are common Suuronen (2005).

limit the managers' ability to steer mortality rates toward long-term value maximizing levels.[9] We show how IFQ regulations must be designed when, for example, prices paid for individual species differ, and derive the price differential at which the bioeconomic performance of an IFQ with CSF regulation declines. We derive similar results in the case where resource user costs differ across species.

We contrast bioeconomic performance of an IFQ with CSF design against: (i) a *standard IFQ* that is vulnerable to discarding (because discarding is allowed or unpreventable), and (ii) an IFQ regulation that counts the entire *catch*, i.e., all fish captured and retrieved to the deck of the boat, against available quota. This latter regulation is hereafter referred to as an IFQ with discard ban design. Our results show that under fairly general conditions, the outcomes of management interest that are implementable under an IFQ with CSF regulation mostly includes the set of outcomes that are implementable under an IFQ with discard ban. As a result, the bioeconomic performance (the expected value) of a fishery that is managed with an IFQ with CSF regulation almost always dominates.

The role of discretion as a means of reducing discards is not new (Borges and Lado, 2019; Woods et al., 2015). European Common Fisheries policy regulations allow what is termed inter-stock flexibility wherein up to 9% of a member state's target species quota can be used to harvest a non-target species, as long as the non-target stock is deemed to be within safe biological limits. While the Common Fisheries Policy offers discretion is also prohibits at-sea discarding of captured fish. The landings obligation, or discard ban policy requires, with few exceptions, that all captured fish be counted against quota and landed at port. What we add is a formal analysis of the discard-reducing effects of CSF and the long term tradeoff between discretion and rules-based behavioral control in multiple-species fisheries management.

Our paper contributes to the literature on fisheries management under uncertainty. Researchers have studied regulation under stock, price, cost and other uncertainties (Clark and Kirkwood, 1986; Weitzman, 2002; Hannesson and Kennedy, 2005; Reed, 1979; Sethi et al., 2005; Singh et al., 2006; Pizarro and Schwartz, 2021). Fewer studies have considered information asymmetry. An important exception is Weitzman (2002) who contrasts a tax against a quota regulatory instrument. Like in our

[9]Fisheries managers recognize that granting discretion over the mix of harvested species can result in excessive mortality of vulnerable fish stocks. Two conditions required under the EU Common Fisheries Policy are, "(a) that the stocks from which the catches are attributed to other stocks would be inside safe biological limits - to prevent the mechanism to result in higher catches of weak stocks and (b) that real catches by species would be recorded, to avoid catch data being misleading" (Borges and Penas Lado, 2019). To our knowledge, the role of CSF in exploiting asymmetric information about true stock abundances has not been previously recognized.

paper, the regulator is uncertain about the true abundance of the population while resource users observe and respond to the productivity of factor inputs during harvesting operations. Weitzman (2002) shows that the tax instrument provides an insurance against over-depletion of the uncertain fish stock. A quota regulatory instrument on the other hand can result in overfishing.[10] These results are derived in the context of the canonical single species fishery model.

Our paper expands the understanding of discretion or flexibility in the design of resource and environmental regulations. *Temporal* flexibility in cap-and-trade pollution emissions regulations has emphasized the advantages of banking or borrowing permits as a means of responding to unanticipated productivity shocks (Innes, 2003; Leard, 2013; Yates and Cronshaw, 2001). Studies of flexibility in quota regulated fisheries that include CSF are primarily descriptive (Woods et al., 2015,?). Simulation models have been used to evaluate outcomes and performance of quota regulations in multiple-species fisheries. Simulations rely on simplified and restrictive assumptions for fishing technologies (fixed output proportions) and fishing behaviors, e.g., behavior is *ad hoc* and/or follows naive updating rules, i.e., future behaviors track past behavior. Behavioral responses to prices of IFQs, changing bioeconomic conditions, and the regulations are typically ignored (e.g., Ulrich et al. (2017); Batsleer et al. (2013); Hoff et al. (2010); Poos et al. (2010).

The rest of the paper is organized as follows. The next section presents our model in the context of a two species fishery. Section 3 presents result under a multiple-species technology that exhibits fixed output proportions. This assumption, while restrictive, helps to fix ideas in a simple setting. Section 4 derives our main results under a technology that exhibits endogenous output substitutions, or endogenous *targeting* of individual fish species. This indisputable characteristic of multiple-species fishing behavior is central to the implementation uncertainty problem under regulatory discretion. Tradeoffs between short and long run management goals and an evaluation of IFQs with CSF and IFQs with a discard ban in meeting long term management goals is presented in section 5. Section 6 provides conclusions, a summary of the policy implications, and some directions for future research. Additional supporting material and proposition proofs are collected in an appendix.

[10] Hannesson and Kennedy (2005) extends the analysis to consider alternative sources of uncertainty, arguing that the manager must have detailed information about the fishing costa for the Weitzman (2002) results to hold.

2 Model

We consider a two-species fishery under a quantity-based regulation. Annual aggregate quotas, one for each species, are operationalized through a system of individual fishing quotas IFQs. The IFQ is a freely tradable permit to harvest and land a specified quantity of fish during the regulatory cycle, which we take to be a single year.

We use the term *harvests* to denote the quantity of fish that is captured by fishing gear and retrieved to the deck of a fishing vessel. *Landings* will refer to the quantities of fish that are transported from the fishing ground to a port for sale. The difference between the two, harvests minus landings, are discards.

The manager's objective is to design the regulation to maximize the long run value of the fishery. Our model is easily modified to consider alternate management goals such as maximization of sustainable physical yield. What is relevant for our results is that the regulator internalizes the effect of current mortality on future abundance and future profit. Fishers on the other hand are assumed to maximize profit earned during the current regulatory cycle.[11]

We simplify the manager's problem and assume existence of a fixed *resource user cost* parameters, one for each species, which informs the tradeoff as perceived by the regulator between current and future extraction of fish stocks. The manager is uncertain about the true species' stock abundances that cohabitate the fishing ground. We formalize these assumptions shortly.

The decentralized regulatory-extraction environment suggests the following timing of actions: the regulator announces species-specific quotas and, any accompanying provisions, under uncertainty about true stock abundances that will prevail during the regulatory cycle. Harvest operations then begin under full information about the relative productivity of gear across species.

To further simplify the model, we assume stock abundances are fixed during a harvesting phase of the regulatory cycle. Growth of the fish stock occurs after harvesting is completed and before the start of the subsequent regulatory cycle. There is no within-harvesting-phase depletion of the fish stock.[12] We use $x \equiv \{x_1, x_2\}$ to denote true stock abundances. We use $h \equiv \{h_1, h_2\}$, $l \equiv \{l_1, l_2\}$ and,

[11] Owners of IFQs in perpetuity, who may or may not be fishers, will surely care about future profit opportunities, which will be capitalized into the price of perpetual quota (Arnason, 1990). It is unlikely however that unilateral conservation efforts, which may increase shared fishery value, will dominate the short-term profit motive in an IFQ-regulated fishery. We feel the assumption of single-period profit maximization is reasonable.

[12] Incorporating harvests and stock growth concurrently complicates the model and adds few additional insights. Within-season harvesting and stock growth is considered in Singh and Weninger (2022).

$d \equiv \{d_1, d_2\}$ to denote the harvest, landings, and discards, respectively, of a representative fishing operation. The technology employs a scalar factor input z, which is purchased at constant unit price, w.[13]

To ease notation we assume that all discarded fish die. Harvests and fishing mortality are therefore synonymous.[14]

We assume there is a unit mass of fishers who conduct harvesting operations. We focus on the profit maximizing behavior of a representative fisher.

2.1 Management objectives and information

We write fishery value as perceived by the manager as,

$$W \equiv \Pi (h_1, h_2) - \frac{\kappa_1}{2} h_1^2 - \frac{\kappa_2}{2} h_2^2 \tag{1}$$

where

$$\Pi (h_1, h_2) \equiv p_1 h_1 + p_2 h_2 - wz. \tag{2}$$

p_i denotes the unit landings price for species i and κ_i are parameters that measure the manager's subjective user cost for the species i stock.

The management objective in equation (1) differs from the canonical dynamic fisheries management model and warrants comment. Appendix 7.1 explains equation (1) further and its relation to bioeconomic fishery management models.

Equation (1) exactly matches a class of management objective functions that maximize the present economic value of the fishery resource and are quadratic in harvests. Current period fishing mortality reduces escapement (post harvest-phase surviving fish), which may linearly or non-linearly impact subsequent period's stock abundances. Escapement is valued in terms of its contribution to the harvest benefits/costs over subsequent regulatory cycles. If one assumes that stock growth is linear in escape-

[13]Randomness in harvesting is often cited as a cause of over-quota discards (Squires et al., 1998). The law of large numbers and the ability of fishers to trade quotas (over an entire regulatory cycle) in response to unanticipated harvest shocks suggests that harvesting uncertainty is not important cause of over-quota discarding. Adding harvesting randomness to our model complicates the analysis while leaving the results unaffected, qualitatively.

[14]Including positive discard survival adds notation with few additional insights. Note that discard mortality rates approach 100% for some species and gear types (Suuronen, 2005).

ment, and that the next period's fishery value is concave in stocks, a convex in harvest specification is justified. Moreover, the quadratic form delivers analytical solutions that sharpen the presentation of trade-offs between discretion and rules in fisher-implemented mortality and rent outcomes.

Alternatively equation (1) will be valid for a management objective for which individual species inter-annual resource user cost are linear in current harvests. In our model the resource users costs take the form, $\kappa_i h_i$ for species i fish. What is important for our analysis and results is that the manager internalizes the cost of current harvest on future fishery value.[15]

The analysis that follows requires an explicit form for the beliefs of the fishery manager over possible true stock abundance realizations. In lieu of empirical evidence for specifying beliefs, we opt for specifications that facilitate the presentation of key results. We assume throughout that the manager believes true stock abundances are perfectly negatively correlated. As will become clear, a key channel through which regulations affect fishing outcomes is the relative profitability of harvests for each species, which derives from differences in individual species' abundance, among other factors. Positively correlated stock abundances by species are discussed informally in the concluding section 6.

Finally, the analysis in the next section maintains the assumption of a fixed output proportions technology. The fixed output proportions assumption expounds the role of IFQ regulations in fishing behavior and serves to introduce the features of alternate regulatory designs. The results under endogenous targeting are presented in section 4.

3 Regulation with fixed output proportions

This section assumes that, with equal probability, x_i takes one of two values, $\{\varphi, 1-\varphi\}$; hence, when $x_1 = \varphi$, $x_2 = 1-\varphi$, and vice versa. To build intuition, we first assume that $\varphi \in \left[\frac{1}{2}, 1\right]$ is a known constant.

We consider two provisions that are specific to the IFQ regulation. The first, and the main focus of our paper, is cross-species flexibility (CSF). This provision allows a specified portion of each species quota to be used to land the other species. The second provision is a discard ban. Under a discard ban,

[15] Interdependencies across multiple fish species may operate through three channels: (i) ecological dependence wherein the growth of the species i stock depends on other species stocks; (ii) complementarity/substitutability in consumer demand with attendant cross-species price effects, and (iii) cost interdependence under joint-in-inputs harvesting. Our model features cost interdependence only. The model can be extended to include other interdependencies, although doing so obscures insights for regulatory design. These extensions are therefore reserved for future work.

all *harvested* fish is counted against IFQs. Importantly, with the exception of the discard ban provision, at-sea discarding is either allowed or, because it is unobserved by the regulator, is unchecked. Thus under a *standard* IFQ regulation with or without CSF only the quantity of fish that is landed is counted against available IFQ. All regulations are fully enforced.

We will evaluate bioeconomic performance of competing regulations. This evaluation will assume that fishing profit, equal to the sum of landings revenues less total harvesting costs, is the single source of fishery value. We do not consider the costs of administering and/or enforcing any of the regulations we evaluate, although these costs are discussed in the concluding section.

Suppose multiple-species harvests are determined as,

$$h \equiv \begin{bmatrix} h_1 \\ h_2 \end{bmatrix} = \begin{bmatrix} c_1 x_1^{\mu_1} \\ c_2 x_2^{\mu_2} \end{bmatrix} z^{\gamma}; \tag{3}$$

c_1 and c_2 are scaling parameters (analogues to the catchability coefficient in Ulrich et al. (2008)); $\gamma < 1$ ensures harvests exhibit diminishing returns to inputs; $\mu_1 > 0, \mu_2 > 0$ imply harvests increase with stock abundances, a standard assumption. For analytical tractability and without *much* loss of generality, we assume $\gamma = \frac{1}{2}, c_1 = c_2 = 1, \mu_1 = \mu_2 = 1$ in the rest of this section.

For any input allocation, one species' harvests will exceed the other's (except when $\varphi = \frac{1}{2}$). When $\varphi = \frac{1}{2}$, species' stock abundances are equal and there is no uncertainty. In this regard, $\varphi = \frac{1}{2}$ represents certainty in stock abundances and we refer to it as such.

Consider a case with symmetric shadow prices where $\kappa_1 = \kappa_2 = \kappa$ is sufficiently large such that limits on current mortality of each species stocks is warranted to meet management goals.[16]

We next contrast equilibrium outcomes under the first best i.e., the outcome that would be implemented by a sole-owner of the fishery who controls harvesting operations in observation of realized true stock abundances. Results under the three regulatory forms discussed above follow. Appendix 7.3 derives all analytical results. We summarize the findings here.

[16] Appendix 7.4 derives the conditions that ensure binding quotas in a standard IFQ program.

First best

The first best is the mortality and resource rent outcome that would be implemented by a sole owner of the fishery who chooses z to maximizes value, equation (1), under the technology (3) and fully observed stock abundances, i.e., the first best harvests are stock abundance contingent.

Harvest of the higher abundance stock is $\varphi\sqrt{z}$ and harvest of the low abundance species is $(1-\varphi)\sqrt{z}$. Irrespective of realized abundances, the sole owner's optimization problem is:

$$\max_z \Big\{ \sum_i p_i x_i \sqrt{z} - wz - \frac{\kappa}{2}\left(\sum_i x_i^2\right) z \Big\}, \tag{4}$$

The harvest of the high and the low abundance stocks are given as (with $x_i \in \{\varphi, 1-\varphi\}$);

$$h_i = \frac{x_i}{2} \frac{\sum p_i x_i}{w + \frac{\kappa}{2}\left((1-\varphi)^2 + \varphi^2\right)}. \tag{5}$$

The solution balances marginal cost with marginal benefit. The denominator of (5) reflects that the sole owner, in addition to considering the marginal input cost w, accounts for the shadow price of the stock. Fishery value evaluated at the optimal harvests is

$$W = \frac{1}{4} \frac{\left(\sum p_i x_i\right)^2}{w + \frac{\kappa}{2}\left((1-\varphi)^2 + \varphi^2\right)}.$$

Thus, due to the convex in harvest objective function (equation 1), fishery value declines when stock abundance are more disparate.

There is no information asymmetry in the first best scenario. The solution approach is therefore straightforward. Outcomes under decentralized harvesting are solved in stages. First, for a given regulation, we derive fishers' privately optimal input choice. We then solve the regulation design problem by inserting fishers privately optimal behavior into the manager's objective function and solving for the quotas and, in the case of CSF, the flexibility parameter, that maximizes expected fishery value.

To simplify the analysis further, we impose an additional symmetry and assume that the two fish species have equal market value, i.e., $p_1 = p_2 = p$.[17] Details of the derivations that follow are presented

[17] Results with $p_1 \neq p_2$ are available on request.

in Appendix 7.3.

In what follows, an asterisk superscript will distinguish first best outcomes; superscripts S, F and DB, will distinguish outcomes under a standard IFQ, an IFQ with CSF, and an IFQ with a discard ban, respectively.

IFQ regulation

Consider the design of a standard IFQ regulation. Since in the current example, the two species are symmetric, quotas for each species will be equal. Denote the common quota as $q = q_1 = q_2$. Recall that κ_i's are assumed sufficiently large that the harvests of both species is profitable. Fishers will therefore land $l_i = q$ units of each species. The low abundance species' harvest will equal q, and the higher species harvest will be $\frac{\varphi}{1-\varphi}q$, of which q with be landed and $\frac{2\varphi-1}{1-\varphi}q$, will be discarded. The equilibrium input choice achieves full utilization of the low species' quota with $q = (1-\varphi)\sqrt{z}$, and therefore fishers will choose $z = (q/(1-\varphi))^2$.

Foreseeing these choices, the regulator maximizes fishery value by choosing $q = \arg\max_q \pi^S(q)$ with:

$$\pi^S(q) = 2pq - w\left(\frac{q}{1-\varphi}\right)^2 - \frac{\kappa}{2}\left(1 + \left(\frac{\varphi}{1-\varphi}\right)^2\right)q^2. \tag{6}$$

IFQ with discard ban

Suppose a discard ban is included with the standard IFQ regulation. Now fishing must stop when one species' quota binds. This occurs at $h_i = \varphi z^{\frac{1}{2}}$. Solving for z obtains $z = \left(\frac{q}{\varphi}\right)^2$, and thus $h_j = \frac{1-\varphi}{\varphi} z^{\frac{1}{2}}$. Regulators objective is then to choose $q = \arg\max_q \pi^{DB}(q)$ with:

$$\pi^{DB}(q) = p\frac{q}{\varphi} - w\left(\frac{q}{\varphi}\right)^2 - \frac{\kappa}{2}\left(1 + \left(\frac{1-\varphi}{\varphi}\right)^2\right)q^2. \tag{7}$$

IFQ with CSF

Consider next an IFQ with CSF regulation. This regulation allows fraction α of the quota of either species to be used to land the other species.[18] The landing constraint becomes:

$$l_i \leq (1+\alpha)\, q \text{ subject to } l_i + l_j \leq 2q,$$

The regulator's optimal choice of $\alpha \geq 2\varphi - 1$ ensures that neither species is discarded and the total quota is utilized, i.e., $h_1 + h_2 = 2q = \sqrt{z}$. Conditional on fishers' input choices, the regulator chooses $q = \arg\max_q \pi^F(q)$ with:

$$\pi^F(q) = 2pq - w\,(2q)^2 - \frac{\kappa}{2}\left((1-\varphi)^2 + \varphi^2\right)(2q)^2\,. \tag{8}$$

3.1 First-best *vis à vis* IFQ regulation

It is worth noting that all regulations that we consider will replicate the sole-owner's outcome when $\varphi = \frac{1}{2}$, i.e., the no stock uncertainty case. For example, a standard IFQ regulation simply sets $q = q^* = \frac{p}{4w+\kappa}$; a discard ban and CSF are trivially redundant.

For $\varphi > \frac{1}{2}$, comparison of the first best outcome with outcomes under the three regulatory regimes is summarized by the following proposition.

Proposition 1. *An IFQ with a discard ban and an IFQ with CSF of $\alpha = 2\varphi - 1$ replicates the first best fishing mortality and rent outcome ($W^F = W^{DB} = W^*$). An IFQ regulation obtains fishery value*

$$W^S = 4\,(1-\varphi)^2\, W^*,$$

where $W^* = \frac{1}{4}\frac{p^2}{w+\frac{\kappa}{2}\left((1-\varphi)^2+\varphi^2\right)}$, and $4\,(1-\varphi)^2 < 1$. Quotas under the three regulatory regimes rank as $q^{DB} > q^F > q^S$. Specifically:

$$q^{DB} = 2\varphi q^F = \frac{\varphi}{2\,(1-\varphi)^2}\, q^S,$$

[18] The choice of a common flexibility parameter in case of bioeconomically symmetric species is obvious. When species differ in terms of their bioeconomic characteristics a case arises for setting two flexibility parameters instead of one. In this case, the rate at which species-specific quota can be exchanged for other species quota differs from unity. See Woods et al. (2015) for an application in Icelandic fisheries. An analysis of this variation in design is reserved for future work.

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

Proof: See Appendix 7.3.

A corollary of the above is that for $\varphi > \frac{1}{2}$, quotas under an IFQ with or without CSF are declining in φ and therefore fall below the quota that corresponds to the first best harvest, $q^* = \frac{p}{4w+\kappa}$. Under a discard ban, in contrast, quotas rise with φ for all $\varphi \leq \sqrt{\frac{1}{2}+\frac{\kappa}{w}}$, and then decline to $\frac{p}{2w+\kappa}$ for $\varphi = 1$. These results are understood in the context of an example.

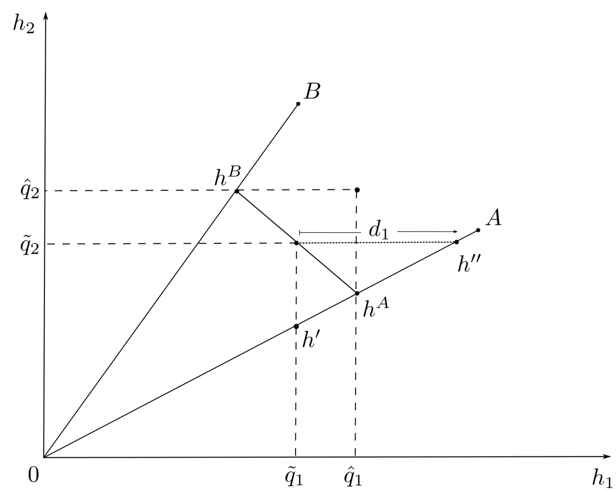


Figure 1: Quota setting under fixed output proportions and degenerate stock uncertainty.

Figure 1 depicts a fully symmetric fishery. The figure includes, as examples, two quota choices $\tilde{q}$ and $\hat{q}$; each has the same individual species quotas, as consistent with symmetry of the example. The harvest technology is fixed output proportions. The regulator believes two stock abundance realizations are possible.

How should quotas be chosen? If species 1 is the high abundance stock, harvests must lie along ray $0A$ in figure 1. If species 2 is the high abundance stock, harvests lie along ray $0B$ in figure 1.

Figure 1 shows, as examples, the first best harvest outcome at h^A if $x_1 = \varphi$ and at h^B if $x_2 = \varphi$. A sole owner can implement these outcomes directly. We next determine whether these harvest outcomes can be implemented with decentralized harvesting and asymmetric information about true stock abundance.

Suppose a standard IFQ is used to manage the fishery (no CSF and no discard ban) with the quota set at $\tilde{q}$. This regulation caps landings at $l_i \leq \tilde{q}_i$ for $i = 1, 2$. If realized abundance is $x_1 = \varphi$ with

$x_2 = 1 - \varphi$, species 1 harvests will exceed $\tilde{q}$ and the overquota catch will be discarded at sea. Discards of species 1 fish occur for harvests on segment $(h', h'']$ of $0A$. Since $h_1 > \tilde{q}$ must be discarded, the marginal revenue product of z is $\frac{1}{2}\left(p_j(1-\varphi)\right) z^{-\frac{1}{2}}$ once either species' quota binds. When fishing is profitable, as assumed, fishers will harvest at h'' and overquota discards of species 1 fish will equal d_1 as shown.

If species 2 is the higher abundance stock, the outcome is the mirror image of the one just described.

Figure 1 shows why the stock-contingent outcome (h^A, h^B) cannot be implemented under a standard IFQ design. If the species 1 stock is more abundant, there will be over-quota discards of species 1 fish and/or under-utilization of the species 2 quota, or both. If the species 2 stock is more abundant the outcome is the reverse. As noted above, discarding is biologically and economically inefficient in our model. Harvests that are subsequently discarded waste z and generate zero revenue. Discarded fish do not contribute to future abundance.

Consider an IFQ with CSF design, with quotas set at $\tilde{q}$. CSF allows αq units of species i quota to be used to the land species j fish. Legal landings lie on a line segment that has slope -1, e.g., connecting and including points (h^A, h^B) in figure 1. Flexibility afforded by CSF is precisely what is needed to implement the first best (stock-contingent) harvest outcome. If $x_1 = \varphi$ harvest is at h^A while if $x_2 = \varphi$ harvest is at h^B. There is no cost inefficiency and no discarded fish.

An IFQ with discard ban design also implements the first best outcome. Consider the quota at $\hat{q}$ in figure 1. The discard ban prohibits harvest beyond the point where the first species quota binds. If $x_1 = \varphi$, the quota constraint binds at h^A and a portion of species 2 quota is unused. If $x_2 = \varphi$, the harvest is at h^B and a portion of species 1 quota is unused. There is no cost inefficiency and no discards.

The results above follow from the assumption that φ is a known constant. We next show that neither CSF nor a discard ban will implement the first best outcome under a more general form of uncertainty.

3.2 Continuous abundance uncertainty

We now consider the case where φ is drawn from a continuous uniform distribution, $\varphi \sim U[\frac{1}{2}, \overline{\varphi}]$ with $\bar{\varphi} > \frac{1}{2}$. Since the regulator is free to choose $\alpha = 0$, an optimally designed IFQ with CSF will do at least as well as a standard IFQ. We therefore compare outcomes under an IFQ with CSF (F) and an

IFQ with discard ban (DB). Appendix 7.4 formally shows that an optimal CSF sets $\alpha = 2\bar{\varphi} - 1$. The quotas under the two alternatives are given by

$$q^{DB} = \arg\max_q E_\varphi \left\{ \pi^{DB}(q) \right\}; \;\; q^F = \arg\max_q E_\varphi \left\{ \pi^F(q) \right\}$$

where $\pi^{DB}(q)$ and $\pi^F(q)$ are as in (7) and (8), respectively.

We again contrast fisher-implemented outcomes to the first best (*) outcomes. Derivations of the results in this section appear in Appendix 7.4.

3.3 Discard ban *vis à vis* CSF

First best quota choices span a continuum of $\varphi-$contingent harvests and 'one-size-fits-all' quotas cannot replicate the first best. The expected fishery value under any regulation will therefore be below the first best, the difference arising due to stock uncertainty. Proposition 2 summarizes bioeconomic performance of alternate regulatory designs.

Proposition 2. *An IFQ with CSF set to $\alpha = 2\bar{\varphi} - 1$ will eliminate discards. The quotas under an IFQ regulation with discard ban are larger than under a IFQ with CSF regulation. Specifically,*

$$\begin{aligned} q^{DB} &= \frac{p}{2} \frac{E_\varphi \left\{ \frac{1}{\varphi} \right\}}{wE_\varphi \left\{ \frac{1}{\varphi^2} \right\} + \frac{\kappa}{2} E_\varphi \left\{ \frac{\varphi^2 + (1-\varphi^2)}{\varphi^2} \right\}} \\ > q^* &= \frac{p}{4w + \kappa} \\ > q^F &= \frac{p}{4} \frac{1}{w + \frac{\kappa}{2} E_\varphi \left\{ \varphi^2 + (1 - \varphi^2) \right\}}. \end{aligned}$$

For all $\bar{\varphi} < \hat{\varphi} \approx 0.728$

$$W^F > W^{DB}.$$

For all $\bar{\varphi} \in (\hat{\varphi}, 1]$:

$$W^F \gtreqless W^{DB} \Leftrightarrow \kappa \lesseqgtr \varkappa(\bar{\varphi}),$$

where $\varkappa(\bar{\varphi})$ *is a function over* $\bar{\varphi} \in (\hat{\varphi}, 1]$ *and*

$$\varkappa'(\cdot) < 0;\ \lim_{\bar{\varphi} \to \hat{\varphi}} \varkappa(\bar{\varphi}) = \infty;\ \varkappa(1) \simeq 0.7267.$$

Proof: See Appendix 7.4, for the expression $\hat{\varphi}$ and the function $\varkappa(\cdot)$ in explicit form.

While an IFQ-CSF regulation does better than DB for all $\bar{\varphi} < \hat{\varphi}$, irrespective of κ values, for $\bar{\varphi} > \hat{\varphi}$ states a discard ban does better if and only if κ is sufficiently high. Clearly, with $\kappa < 0.72$ such a situation never arises.

Evidently, q^F is declining in $\bar{\varphi}$, whereas q^{DB} first rises and then declines but stays above the first best harvest quantity $\frac{p}{4w+\kappa}$. Neither regulation will replicate the first best outcome. For example, when the realized $\varphi = \frac{1}{2}$, the sole-owner chooses $q^* = \frac{p}{4w+\kappa}$, whereas $q^{DB} > q^*$ while $q^F < q^*$.

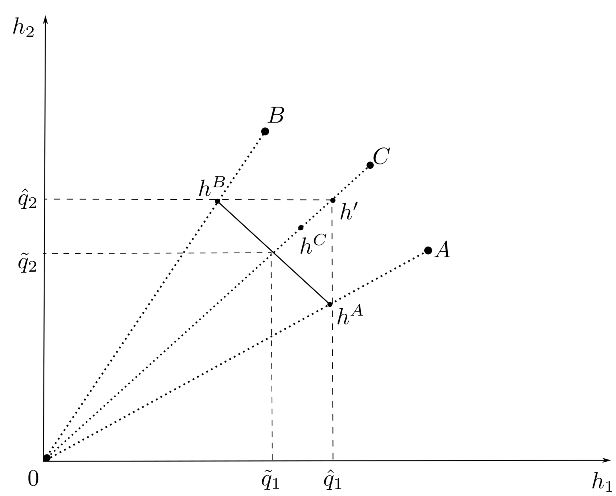


Figure 2: Fixed output proportions and continuous stock uncertainty.

Figure 2 presents an intuition for proposition 2. Referring to the figure, note that if x_1 is the largest stock, $\{x_1, x_2\} = \{\overline{\varphi}, 1 - \overline{\varphi}\}$, harvest outcomes lie along the ray $0A$. If x_2 is the high abundance stock harvests lie on ray $0B$. A third ray $0C$ shows the harvests if $\varphi = \frac{1}{2}$ under realized abundance, $x_1 = x_2 = \frac{1}{2}$. Recall that this section assumes φ is continuous. Abundance realizations spanning the entire cone $0AB$ are possible, but do not appear in the figure to reduce clutter. The three stock realizations depicted are sufficient to demonstrate the equilibrium outcomes under each regulation.

Figure 2 shows the first best harvest at h^A when $x_1 = \overline{\varphi}$, at h^B when $x_2 = \overline{\varphi}$ and at h^C when

$x_1 = x_2 = \frac{1}{2}$.[19] These outcomes cannot be implemented under a standard IFQ since discarding cannot be prevented. For example, a quota at $\tilde{q} = (\tilde{q}_1, \tilde{q}_2)$ will result in cost inefficiency, discards and under-utilization of one species quota.

Consider a quota equal to $\tilde{q} = (\tilde{q}_1, \tilde{q}_2)$ under an IFQ with CSF design. Following earlier logic, this regulation will implement h^A if $x_1 = \varphi$ and h^B if $x_2 = \varphi$. If $x_1 = x_2 = \frac{1}{2}$, the harvest outcome will lie on the ray $0C$ at $h_i = \tilde{q}_i < h_i^C$. The first best stock-contingent outcome thus cannot be implemented under a IFQ with CSF regulation.

Will a discard ban fare better? Consider quota $\hat{q} = (\hat{q}_1, \hat{q}_2)$ in figure 2. If $x_1 = \overline{\varphi}$, the harvest outcome is at h^A and some species 2 quota is unused. If $x_2 = \overline{\varphi}$ is realized, the harvest outcome will be h^B and a portion of species 1 quota unused. For stock realization $x_1 = x_2 = \frac{1}{2}$ harvest will be at $h' > h^C$. We see that an IFQ with discard ban also cannot implement the first best outcome.

Moreover, it is apparent that fine tuning the quota quantities does not solve the problem. For example, quotas could be increased under the IFQ-CSF design such that h^C is implemented if $x_1 = x_2 = \frac{1}{2}$ is realized. For all other abundance realizations, harvests will then exceed the first best quantity. Reducing quotas to $\tilde{q} = (\tilde{q}_1, \tilde{q}_2)$ and maintaining the discard ban will implement h^C only if $\varphi = \frac{1}{2}$ is realized. For all other realized abundances, $h_i < \tilde{q}_i$.

The example in 2 makes clear that first best, stock-contingent outcomes cannot be implementable under regulatory designs considered. It, however, suggests that CSF and discard ban provisions can *move* outcomes that are implemented by fishers closer to those that meet management goals. The next section assesses how close to the first best can the fisher-implemented outcomes be under an optimally configured second best regulation? The results demonstrate that CSF and DB provisions retain their relative rankings and their desirability vis-a-vis a standard IFQ.

4 Regulatory design with endogenous targeting

This section assumes fishers choose the scale and the scope (or mix) of species they harvest. We begin with a description of the fishing technology. We introduce a tractable analytical model that captures characteristics of the multiple-species fisheries that we deem requisite for analyses of IFQ regulatory

[19] Sections below formally derive stock contingent harvests that maximize the objective in (20)

designs and performance.[20] The section closes with a derivation of rational regulation-to-outcome mappings under alternate regulations.

General technology

Our general technology embeds three features of multiple-species fishing: (i) endogenous control over the mix of harvested species, (ii) an explicit positive link between the productivity of factor inputs in harvest of individual species and their respective stock abundances, and (iii) output substitutions capable of replicating targeting and discarding behaviors common in multiple-species fisheries that are regulated with IFQs.[21]

Let $H(z|x)$ denote the set of all vectors h that can be harvested and landed with factor input z under given stock abundances, x. Three examples of harvest sets for a two-species fishery appear in figure 3.

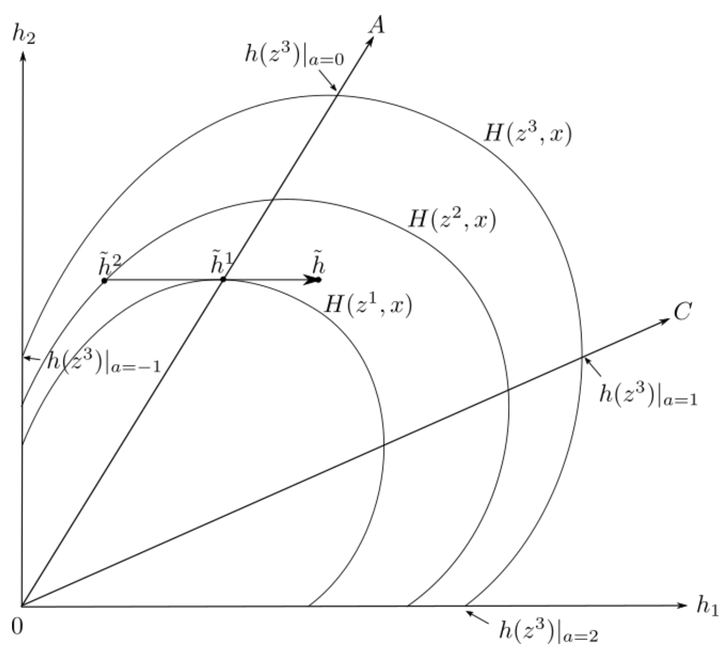


Figure 3: Multiple-Species Fishing Technology With Output Substitution. Harvest sets are conditional on input allocations $z^1 < z^2 < z^3$ and stock vector x, with $\frac{x_i}{x_j} \approx 1$.

The harvest sets in figure 3 assume increasing input quantities, $z^1 < z^2 < z^3$, under roughly equal

[20] A review of alternate representations of fishing technology and their limitations appears in Appendix 7.1.

[21] These features are emphasized elsewhere (Singh and Weninger, 2009, 2015; Turner, 1995, 1997; Scheld and Walden, 2018).

abundances of the two species stocks; $\frac{x_1}{x_2} = 1$.

The harvest sets in figure 3 illustrate costly targeting of individual species (Singh and Weninger, 2009). The costs materialize as factor inputs are *used up* when actions are taken to target a mix of species that differs from the mix of stock abundances in the water. Searching for and intercepting species i fish and/or avoiding intercepting species j fish expends fuel, perhaps requires use of specialized hooks and baits, fishing at certain times of the day on specific tides, or fishing only at a subset of available locations across the fishing ground. When targeting actions are taken, factor input z captures and transports back to port fewer fish than when no targeting such actions are taken. The absence of targeting actions, alternatively, reflects *acceptance* of a harvest mix that mirrors relative species' stock abundances. For $\frac{h_1}{h_2} \approx \frac{x_1}{x_2} = 1$, the feasible h takes its largest value.

For each $H(z|x)$ in figure 3, the marginal rate of product transformation (MRPT) is negative in the interior of a cone delineated by rays $0A$ and $0C$. MRPT is positive for h lying outside of this cone. Singh and Weninger (2009) refer to the exterior of this cone as the discard set. The terminology is understood by comparing costs at harvest vectors $\tilde{h}^2$, $\tilde{h}^1$ and $\tilde{h}$ in the figure. $\tilde{h}^2$ is in the discard set, $\tilde{h}^1$ lies on its boundary, on ray $0A$, and $\tilde{h}$ lies in a no discard region. The three vectors share a common harvest of species 2 fish and increasing harvest of species 1 fish. Species 1 harvests as large as $\tilde{h}^1$ are feasible with a smaller input allocation than z^2. Therefore, along the ray $\tilde{h}^2$ to $\tilde{h}^1$, input requirements are less and harvest costs decline with increased h_1. Input requirements and costs rise with h_1 as h_1 increases beyond $\tilde{h}^1$. Thus a quota regulation that attempts to implement a harvest $\tilde{h}^2$ provides an incentive to discard fish at sea. Costs savings arise from avoiding the costly actions that would otherwise be required to harvest a mix that includes a small share of species 1 fish.

We assume that fishers operate at boundary points of the harvest sets. The following correspondence offers a tractable analytical representation of the technology described above:

$$H(z,x) \equiv \begin{bmatrix} h_1 \\ h_2 \end{bmatrix} = \begin{bmatrix} c_1 \left(1 + \sin \frac{a\pi}{2}\right) x_1^{\mu} \\ c_2 \left(1 + \cos \frac{a\pi}{2}\right) x_2^{\mu} \end{bmatrix} z^{\gamma}. \tag{9}$$

c_1 and c_2 denote strictly positive scaling parameters. μ is the non-negative stock-harvest elasticity and $\gamma > 0$ is the input-harvest elasticity, measuring the percentage change in the harvest for a percent increase in z. The parameter a controls the mix of harvested species. Note that lowercase π in (9) denotes the mathematical constant $3.141\ldots$.

For $a \in [-1, 0] \cap [1, 2]$, the MRPT is positive, implying that, holding z fixed, a reduction (increase) in the harvest of species i is possible only with a reduction (increase) in the harvest of species $j \neq i$. It is easily checked that for $a \in [0, 1]$, the technology exhibits negative MRPT. It can be shown that in an unregulated fishery, the profit maximizing choice of a will conform to non-positive MRPT (Singh and Weninger, 2009).[22]

The following values of the targeting parameter are noteworthy:

$$a = \begin{cases} -1 & \Rightarrow h = [0,\ c_2 x_2^{\mu} z^{\gamma}]^T \\ 0 & \Rightarrow h = [c_1 x_1^{\mu} z^{\gamma},\ 2c_2 x_2^{\mu} z^{\gamma}]^T \\ 1 & \Rightarrow h = [2c_1 x_1^{\mu} z^{\gamma},\ c_2 x_2^{\mu} z^{\gamma}]^T \\ 2 & \Rightarrow h = [c_1 x_1^{\mu} z^{\gamma},\ 0]^T \end{cases} \tag{10}$$

where ^{T} denotes transposition. Figure 3 plots the corresponding harvests in equation (10) for input quantity z^3.

At $a = -1$ ($a = 2$) the harvest vector includes zero quantity of species 1 (2) fish. The technology thus allows for specialization in the harvest of one species, although at considerable cost, determined as foregone harvests of both species.[23]

When $a = 0$ the MRPT between species 1 and 2 is zero. Equivalently, at $a = 0$ the marginal cost of harvesting more h_1, conditional on maintaining h_2 constant, is zero. An increase in a tilts the harvest mix toward species 1. At $a = 0$ harvesting more h_1 utilizes factor inputs. Harvesting less h_2 saves factor inputs that would otherwise be utilized in avoiding species 2. At $a = 0$ these costs offset. By reverse reasoning, at $a = 1$ the MRPT between species 2 and species 1 is zero.

It is worth pointing out that $a \in [-1, 0)$ or $a \in (1, 2]$ arise under profit optimal targeting only if a discard ban is in place. Suppose discards are allowed by regulation. If at harvest vector h, MRPT > 0, more of each species can be harvested by adjusting a toward its midpoint value of one half. It is easy to see that if discarding is allowed, this adjustment to a will either increases revenue, lower cost, or both.

[22] Equation (9) embeds the fixed output proportions (equation (3)) as a special case. By fixing a to a value in $[0, 1]$, and setting $\mu = \gamma = 1$, the mix of harvested species becomes fixed and exogenously determined by x.

[23] Multiple-species fishing technologies may alternatively exhibit null-jointness in output/harvest, wherein a strictly positive harvest of species i is feasible only if the harvest of species $j \neq i$ is also strictly positive (see Scheld and Walden (2018)).

For future reference we define:

$$\underline{h}_i(z) \equiv c_i x_i^{\mu} z^{\gamma} \text{and } \overline{h}_i(z) \equiv 2c_i x_i^{\mu} z^{\gamma}.$$

The quantities above are, respectively, the minimum and maximum harvest of species i given z and for which the MRPT is non-positive. Referring to figure 3 with input z^3, for example, $\underline{h}_i(z)$ is shown at $h(z^3)|_{a=0}$, and $\overline{h}_i(z)$ at $h(z^3)|_{a=1}$. Notice that for any z, a profit maximizing fisher will choose $h_i(z) \in \left[\underline{h}_i(z), \overline{h}_i(z)\right]$ as we demonstrate below.

First best with endogenous targeting

As above we first characterize outcomes under the first best. Sole owner harvests are characterized by,

$$w\tilde{z} = \gamma \left[\left(p - \kappa \tilde{h}_1\right) \tilde{h}_1 + \left(p - \kappa \tilde{h}_2\right) \tilde{h}_2 \right]; \tag{11a}$$

$$\tilde{a} = \frac{2}{\pi} \tan^{-1} \left[\frac{p - \kappa\, \tilde{h}_1}{p - \kappa\, \tilde{h}_2} \left(\frac{\varphi}{1-\varphi} \right)^{\mu} \right]. \tag{11b}$$

Equation (11a) is standard: it equalizes the marginal input cost, inclusive of its impact on prospective stocks, with marginal revenue. The second equation determines the optimal choice of a. Equations (11a) and (11b) along with (9) 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. What follows therefore relies on numerical computations.

4.1 Outcomes under endogenous targeting and CSF

Consider a representative fisher's profit maximization problem. The input z and targeting action a is chosen to maximize own profits under given bioeconomic fundamentals and the regulation, e.g., aggregate quotas $\{q_1, q_2\}$ and CSF provision α, and the available technology. The problem formulation is:

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

The Lagrangian for this problem is:[24]

$$
\begin{gathered}
\mathcal{L} = p_1 l_1 + p_2 l_2 - wz + \lambda \left(q_1 + q_2 - l_1 - l_2\right) \\
+\omega_1 \left(q_1 + \alpha q_2 - l_1\right) + \omega_2 \left(q_2 + \alpha q_1 - l_2\right) \\
+\upsilon_1 \left(h_1 - l_1\right) + \upsilon_2 \left(h_2 - l_2\right),
\end{gathered} \tag{12}
$$

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

$$l_i \geq 0;\ \ p_i - \lambda - \omega_i - \upsilon_i \leq 0;\ \ l_i \left(p_i - \lambda - \omega_i - \upsilon_i\right) = 0, \tag{13a}$$

$$\lambda \geq 0;\ \ \lambda \left(q_1 + q_2 - l_1 - l_2\right) = 0, \tag{13b}$$

$$\omega_i \geq 0;\ \ \omega_1 \left(q_1 + \alpha q_2 - l_1\right) = 0;\ \ \omega_2 \left(q_2 + \alpha q_1 - l_2\right) = 0, \tag{13c}$$

$$\upsilon_i \geq 0;\ \ \upsilon_i \left(h_i - l_i\right) = 0. \tag{13d}$$

Equation (13a) is the complementary slackness condition for landings. λ and ω_i are multipliers for the aggregate and species-specific quota constraints, respectively, and υ_i is the multiplier for the species i harvest. Notice that the constraints in equation (13c) cannot both bind simultaneously since in this case the aggregate constraint (13b) would not be met. Therefore, either ω_1 or ω_2 or both are zero.

The optimal choice of a follows,

$$a = \frac{2}{\pi} \tan^{-1} \left[\frac{\upsilon_1}{\upsilon_2} \frac{c_1}{c_2} \left(\frac{x_1}{x_2} \right)^{\mu} \right], \tag{14}$$

[24] In the absence of a 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.

and the optimal input choice satisfies,

$$z = \frac{\gamma}{w} \left(\upsilon_1 h_1 + \upsilon_2 h_2 \right). \tag{15}$$

The multiplier υ_i is non-negative with strictly positive value only if $l_i = h_i$, i.e., $d_i = 0$. Suppose $\upsilon_1 = 0$, then $a = 0$. In this case, the optimal input choice is determined by its marginal contribution to the harvest of species 2; marginal harvest of h_1 has no value since it must be discarded. Symmetrically, when $\upsilon_2 = 0$ and $a = 1$, marginal harvest of h_2 is discarded and the input choice equates its unit cost to its marginal revenue product in the harvest of species 1.

We next describe fisher-implemented harvests, landings and discards that are consistent with necessary conditions (13a)-(13d), and solutions (14) and (15). In what follows, we hold stock abundances and prices fixed and present profit-maximizing outcomes across the full quota domain, $\{q_1, q_2\} \in \Re^2_+$. We partition this space into regions for which regulatory constraints bind and are slack. Regions are depicted graphically in figure 4. A formal derivation of our results is presented in appendix 7.4.

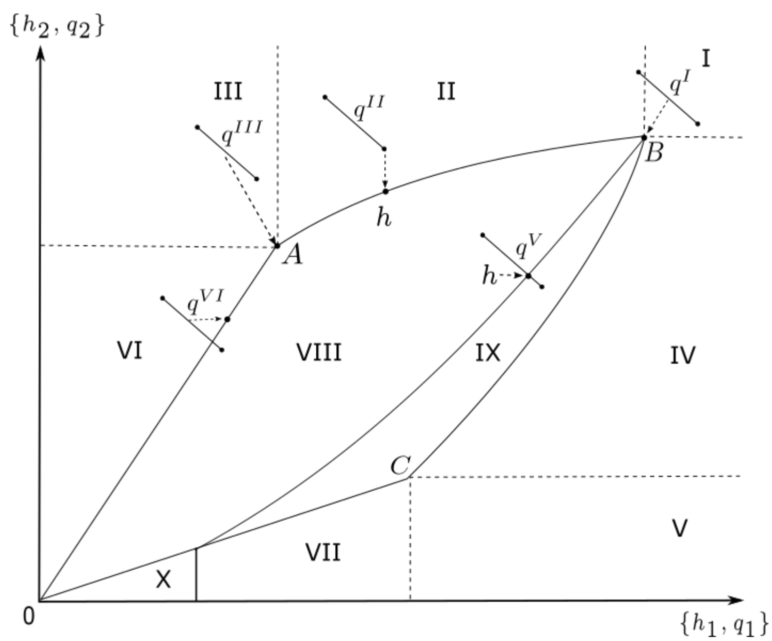


Figure 4: Quotas and Implemented Harvests Under CSF. Regions I-X distinguish quota vectors for which constraints (13a)-(13d) are either binding or are slack. Line segments $S_1 - S_5$ are landings vectors allowed under the regulation. Stock abundances are fixed and assumed equal across species. Prices satisfy $p_1 > p_2$.

To fix ideas, and without loss of generality, figure 4 assumes $p_1 \geq p_2$. Stock abundances are assumed equal across species.

Quotas in regions III and VI induce positive discards of species 1 fish. In these regions there is low q_1 relative to q_2 and since abundances are equal, targeting a species mix that matches the quota mix is costly, i.e., marginal cost for species 1 is negative at $h_1/h_2 = q_1/q_2$ and costs can be reduced by harvesting $h_1 > q_1$ and discarding the overage. For the same reasons but with species numbers reversed, species 2 discards are positive for quotas set in regions V, VII and X in figure 4.

Discards are zero for quotas set in region VIII. For such quotas, the MRPT is everywhere negative such that harvesting in excess of available quotas increases costs with revenue unchanged.

The technology in (9) exhibits diminishing returns when $\gamma < 1$, which is assumed in figure 4. Point B delineates the quota/harvest vector at which marginal profit is zero for both species simultaneously. Point B is the harvest vector that is implemented absent the regulation.

Segment AB in figure 4 delineates harvest combinations for which the marginal profit from additional h_2 conditional on h_1 is zero. Segment CB has a similar interpretation with species labels reversed.

While perhaps not immediately apparent, segments $0A$ and $0C$ are drawn symmetrically in $\Re^2_+$ whereas the harvest bundle at B includes a larger share of h_1. This result is explained by our assumption that abundances are equal while landing prices satisfy, $p_1 > p_2$. The result highlights a nonlinearity in the relationship between landings prices and implemented harvests. When one or both quota constraints are slack, the marginal profit of individual species harvests is determined by the landings price less the species' marginal harvest costs. When quotas bind, marginal profits are strictly positive and equal to quota lease prices. When quota prices are strictly positive, small changes in landings prices have no impact on input and harvest outcomes.

IFQ with CSF regulation is reflected in figure 4 as a set of legal landings. For a quota $q \in \Re^2_+$ space, the regulation takes the form of a line segment with northwest coordinate $\{(1-\alpha)\, q_1, q_2 + \alpha q_1\}$ and southeast coordinate $\{q_1 + \alpha q_2, (1-\alpha)\, q_2\}$. Some example quotas under a moderate value of α are shown to aid the discussion.

Consider quotas in region I and specifically q^I in figure 4. The set of legal landings spans regions I and II. Point B is the quota-unconstrained profit maximizing harvest and is legally implementable under q^I and flexibility $alpha$. It is easy to see that all quotas that span region I induce equilibrium harvest at point B.

Next consider q^{II} which lies entirely in region II. In region II, the marginal profit of species 2 *harvest* is negative; recall that line segment AB demarcates harvest vectors for which the marginal profit from additional h_2 conditional on $h_1 = q_1$ is zero. Marginal profit from additional species 1 harvest is positive in region II and therefore it is optimal for fishers to use CSF discretion to harvest and land species 1 fish. The profit-maximizing harvest lies on segment AB with $h_1 = q_1^{II} + \alpha q_2^{II}$ and $h_2 < (1-\alpha)q_2^{II}$.

Extending these insights obtains the following inferences for fishing behavior:

- If any portion of the CSF quota constraint lies in region I, the optimal landing choices are unconstrained and there are no discards.

- If the southeast endpoint of the CSF quota constraint lies in either of the regions II, III, VI, VIII, and X, the optimal harvests, landings, and discards are determined (as described above for q^{II}).

- If the northwest endpoint of the CSF quota constraint lies in either of the regions IV, V, VII, and IX, the optimal harvests, landings, and discards are determined (as described above for q^{II} but with species-labels reversed).

- Notice that adjacent regions VIII and IX share the boundary given by line segment $0B$. If the CSF constraint crosses $0B$, the aggregate constraint binds but no individual species' constraints bind, i.e., $\omega_1 = \omega_2 = 0$. Harvests are equal to landings with no discards. Since $p_1 \geq p_2$, 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 (14) and (15) determine $\{a, z, \upsilon_1, \upsilon_2\}$. Line segment $0C$ represents values of $\bar{q}$ such that $\lambda \in [0, p_2]$.

- If the CSF quota constraint 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

$$wz^* = \gamma (p_1 - p_2) \overline{h}_1 (z^*),$$

with $l_1 = h_1$ and $l_2 = \bar{q} - l_1 < \underline{h}_2 (z^*)$.

Under a discard ban, quotas are matched to harvested fish. Regulatory constraints reduce to $l_1 = h_1 \leq q_1$ and $l_2 = h_2 \leq q_2$. The Lagrangian for the fishers' profit maximization problem is:

$$\mathcal{L} = p_1 h_1 + p_2 h_2 - wz + r_1 (q_1 - h_1) + r_2 (q_2 - h_2) \tag{16}$$

where r_i denotes the Lagrange multiplier for species i quota. Substituting the technology in equation (9) gets

$$\mathcal{L} = \begin{bmatrix} (p_1 - r_1) \nu_1 (1 + \sin a\pi 2) x_1^{\mu} \\ (p_2 - r_2) \nu_2 (1 + \cos a\pi 2) x_2^{\mu} \end{bmatrix} z^{\gamma} - wz + r_1 q_1 + r_2 q_2.$$

The optimal choice of a follows,

$$a = \frac{2}{\pi} \tan^{-1} \left[\frac{p_1 - r_1}{p_2 - r_2} \frac{\upsilon_1}{\upsilon_2} \left(\frac{x_1}{x_2} \right)^{\mu} \right], \tag{17}$$

and the optimal input choice satisfies,

$$wz^* = \gamma ((p_1 - r_1) h_1 + (p_2 - r_2) h_2). \tag{18}$$

Finally, complementary slackness condition require:

$$r_i \geq 0; \;\; r_i (q_i - l_i) = 0.$$

There are four cases to consider which, as above, are define by constraints that bind and constraints that are slack. Figure 5 illustrates.

A first case is where neither quota binds, with $r_1 = r_2 = 0$. Equations (17) and (18) then determine

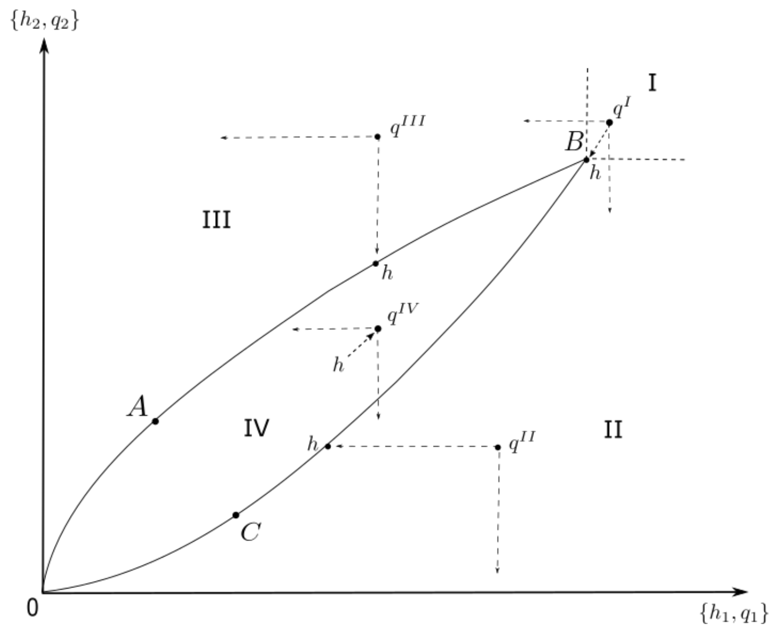


Figure 5: Quotas and Harvests Under a Discard Ban. Regions I-IV distinguish quota vectors for which quota constraints are binding or are slack. Stock abundances in the figure are fixed and assumed equal across species. Prices satisfy $p_1 = p_2$.

the joint bounds $\{\tilde{q}_1, \tilde{q}_2\}$ such that if $q_1 \geq \tilde{q}_1$ and $q_2 \geq \tilde{q}_2$, the harvest outcomes are $\{h_1, h_2\} = \{\tilde{q}_1, \tilde{q}_2\}$; quotas exceeding these thresholds will be unused.

Quotas in region I of figure 5 satisfy this criteria. It is easy to see that under a discard ban, all quotas in region I implement harvest at point B.

A second case is that quota for species 2 binds, while quota for species 1 is slack; $r_1 = 0, r_2 > 0$. Quotas in region II of figure 5 satisfy this criteria.

Consider the line segment 0CB which identifies the upper boundary of region II. Moving from point B toward point C, along $0CB$, the value of a declines from its no-targeting value, $\frac{2}{\pi}\tan^{-1}\left[\frac{p_1}{p_2}\frac{v_1}{v_2}\left(\frac{x_1}{x_2}\right)^{\mu}\right]$ to 1. For values of a in this range, we have $r_2 \in [0, p_2]$ with optimal (z, a) determined such that the MRPT remains non-positive. The implication is that quotas in region II for which the ratio $\frac{q_1}{q_2}$ is not too small facilitates multiple-species harvesting in the domain of the technology for which the MRPT is non-positive.

However, notice that $r_1 = 0$ in region II with a species 1 quota constraint that is slack, with $p_1 > 0$. There are quotas in region II for which fishers are willing to incur a marginal profit loss in the harvest of species 2 fish in order to the harvest more species 1 fish. The marginal loss derives from costly avoidance of species 2 fish. The result is $r_2 > p_2$ with $a \in (1, 2)$. Harvests along segment $0C$ in figure 5 satisfy this property.

A third case is that the species 1 quota binds while the species 2 quota is slack with, $r_2 = 0, r_1 > 0$. Quotas in region III in figure 5 satisfy the criteria. This case corresponds the one just described with species labels reversed. Moving from point B to A, the optimal a declines from its no-targeting value to $a = 0$ with the MRPT non-positive. At A the optimal a becomes negative and the MRPT positive.

For quotas in region III, implemented harvests utilize all of the relatively scarce species 1 quota with species 2 quota unused, e.g., at quota q^{III}, $h_1 = q_1^{III}$ and $h_2 < q_2^{III}$.

Case four includes quotas for which $r_1 > 0$ and $r_2 > 0$. Quota interior to $0CB$ and $0AB$ denoted as region IV satisfy the criteria. In region IV harvests implemented by fishers match quotas set by the regulator.

5 Regulatory performance with endogenous targeting: CSF vs. discard ban

This section evaluates the performance of the CSF and DB regulations.[25] We choose a set of fundamentals; prices, technology, random distribution of relative stock abundances, and resource users costs. We derive fishers' privately optimal behavior under these fundamentals and for each regulation. For CSF we solve for the fishers optimal choice of (z, a) for all $(q \in \Re^2_+, \alpha \in [0, 1])$ with quotas countered against landings, i.e., discards are allowed. For DB we derive fishers optimal choice of (z, a) for all $(q \in \Re^2_+)$ and with quotas counted against harvests, i.e., discards are banned. Conditional on fishers choices we solve the manager's problem of choosing regulations to maximize expected fishery value. Before presenting the results we demonstrate, graphically, an intuition for how the two regulatory approaches determine performance in the setting of our model.

Figure 6 considers a fully symmetric fishery example. The setting is one where the manager believes φ is continuous on the interval $(\frac{1}{2}, \bar{\varphi}]$. Thus, at one extreme the species 1 stock will be largest, $\{x_1, x_2\} = \{\varphi, 1 - \varphi\}$. This abundance realization is represented by the ray $0C$ in figure 6. At the

[25] A standard IFQ regulation is a special case of CSF with the flexibility parameter set to zero. Its performance is thus dominated by the CSF regulation.

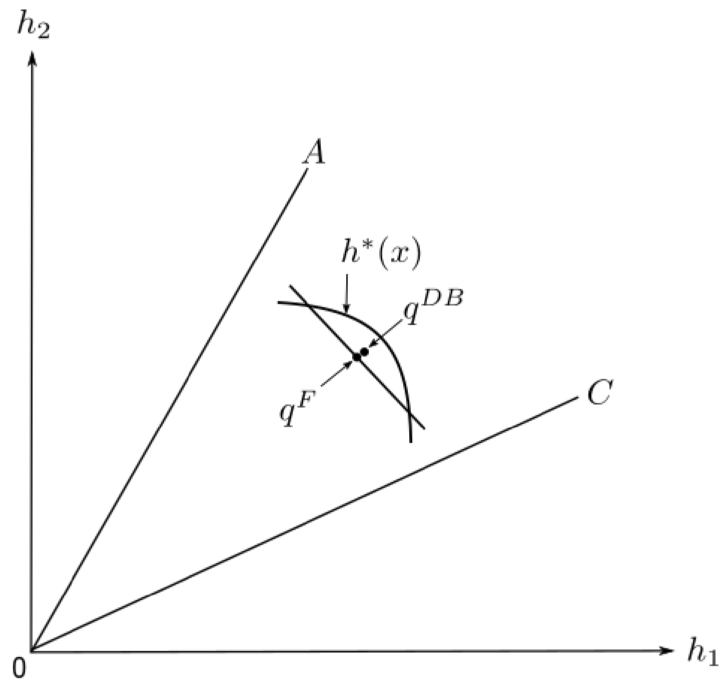


Figure 6: Regulatory performance under stock uncertainty: CSF vs. discard ban.

other extreme species' abundances are reversed with $x_2 = \bar{\varphi}$. This abundance realization is represented by the ray $0A$ in the figure.

Figure 6 plots the first-best, stock-contingent harvests shown as an arc of harvest vectors labelled $h^*(x)$. To understand the shape and location of $h^*(x)$, recall that the regulator internalizes the temporal resource user costs. First best harvests equate marginal profit to the resource user cost; $\nabla_{h_i}\Pi(h_1, h_2) = \kappa_i h_i$. The assumption in the figure, that $\kappa_1 = \kappa_2$, prescribes a harvest mix that is not too different. The first best harvest mix is less dissimilar than the realized stock abundance mix.

Figure 6 shows the implementable mortality under the CSF regulation as a familiar downward sloping line segment that intersects quota q^F. Proposition 2 makes clear that the CSF regulation cannot implement $h^*(x)$. The challenge is to choose (q^F, α) optimally, such that implemented and first best mortalities, weighted by the probabilities of the abundance realizations, maximizes fishery value. Under the second best design, implemented and first best mortalities do not perfectly align, but they come close due CSF allowed under the regulation.

The second best quota under a discard ban is shown at q^{DB} in figure 6. The design problem is as described above. The regulator chooses q^{DB} such that the implemented and first best mortality, weighted by the probabilities of the realized abundances, maximizes fishery value. The implemented harvest is at $h^{DB} = q^{DB}$ for all realizations of φ. It is easy to understand why, for the symmetric fishery example in figure 6, performance under a CSF regulation will exceed performance under a DB regulation.

Will CSF always outperform DB? Recall that an advantage of a DB design is that it can implement harvests that cannot be implemented under the CSF design. Harvests that lie in the CSF discard regions of figure 4 can be implemented under a DB regulation. Correspondingly, a DB regulation will outperform CSF across the set of bioeconomic fundamentals for which DB-implementable harvests yield high expected fishery value. We next characterize the bioeconomic fundamentals under which the two regulatory approaches perform best.

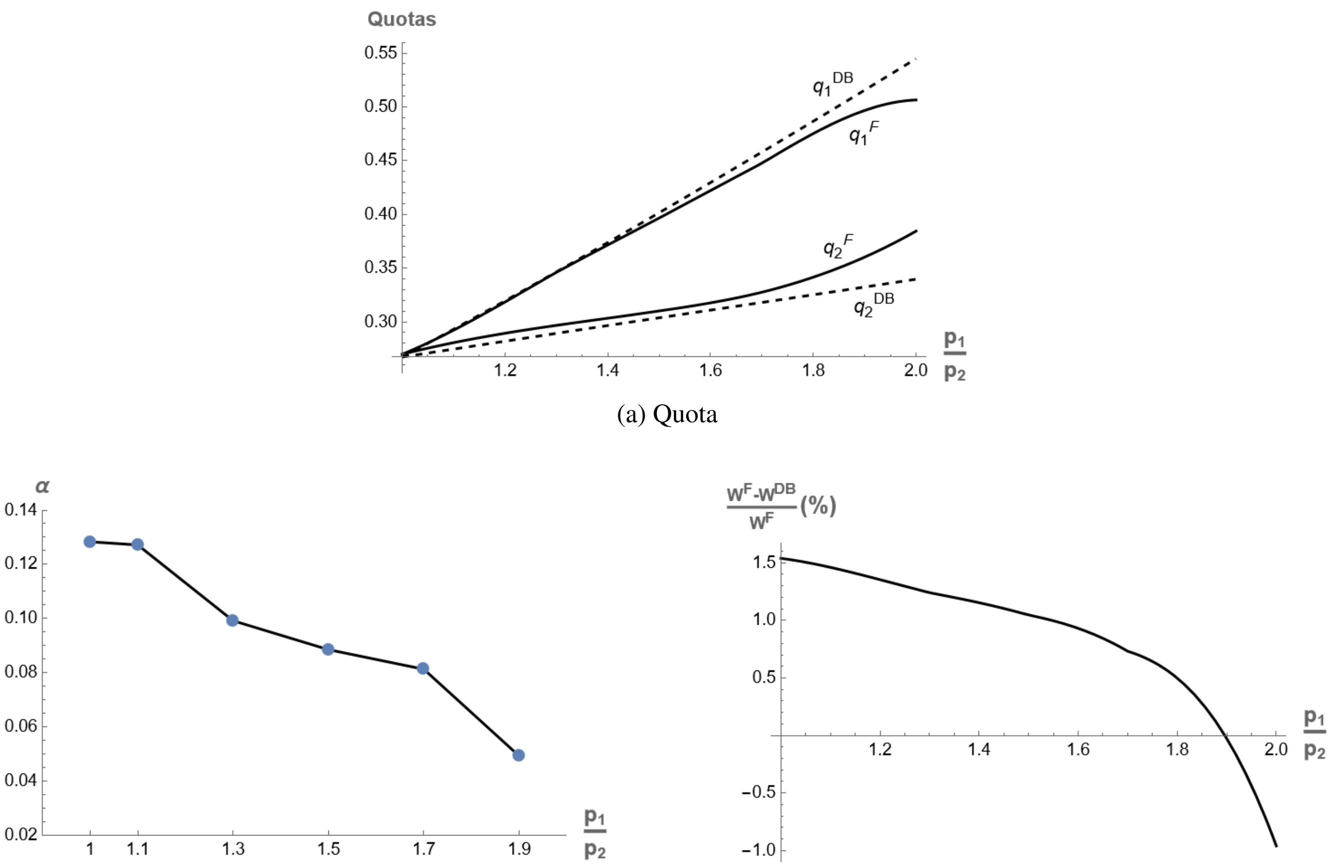
Heterogeneous prices

Figure 7 contrasts design and performance of second best regulations under varying fish prices. We hold the price of species 2 fixed at $p_2 = \$1$ and increase p_1 from \$1 to \$2 in discrete increments. For each price pair, the figure plots the second best regulations and fishery values.

Note that we have smooth interpolated results for quotas and welfare. Second best α values are reported as derived by our numerical calculations. This is because α does not vary smoothly with changes in $\frac{p_1}{p_2}$ or below with changes in $\frac{\kappa_2}{\kappa_1}$. The adjustment of α is relatively more flexible, and its slope is non-monotonic, unlike the second best quotas and fishery values.

Higher prices increase the current consumption value of the stock which prescribes increased first best extraction. Harvest of species 1 increases more than for species 2 due to the disproportionate increase in p_1. To maximize expected fishery value, both second best quota vectors q^F and q^{DB} increase to maintain *closeness* of the fisher-implemented and first best harvests.

Panel 7a reports quotas for both species as $\frac{p_1}{p_2}$ rises. Recall that the technology exhibits cost complementarities across harvested species. Thus as q_1 increases the regulator also increases q_2. Increasing q_1 as p_1 increases but holding q_2 fixed would result in quota mix that is incongruent to a subset of realized abundance mixes. Since fishers have incentives to target the higher priced species 1, a high q_1/q_2 ratio would result in too much targeting, high harvest cost and low fishery value.



(a) Quota

(b) CSF parameter

(c) Performance

Figure 7: Landings Prices and Regulatory Performance: Figure reports second best quotas, CSF flexibility parameter α, and relative fishery value under an IFQ with CSF and IFQ with discard ban regulation. Model parameters are set at $\mu = 0.5$, $\gamma = 0.7$ $c_1 = c_2 = 1$, $w = 1$, $\kappa_1 = \kappa_2 = 2.5$, $p_2 = \$1$, p_1 increases from \$1 to \$2.

Panel 7a shows that when the price of species 1 increases, it is optimal to increase the quota of species 2. Cost complementarities dictate that both quotas should rise. However, the rise of the quota for species 2 is less than for species 1, resulting in the two quotas diverging as $\frac{p_1}{p_2}$ increases. This divergence is more pronounced under a discard ban, i.e., when regulations prohibit discards and cross-species quota flexibility. Under a CSF provision, where flexibility is equally likely to be used for each species *ex ante* due to stock symmetry, a significant divergence between the two species stocks may result in discards of species 2, i.e., when species 1 abundance is particularly high. Conversely, when the stock of species 2 is high, its harvest may exceed what is justified by its resource user cost compared to its current market valuation. As a result, the quotas of the two species under a CSF provision diverge less than under a discard ban.

Figure 7b shows that the optimal α declines with $\frac{p_1}{p_2}$. Recall that α defines the length of a legal landings line segment with slope equal to -1 in $\Re^2_+$. As $\frac{p_1}{p_2}$ increases first best harvests include larger quantities of species 1 relative to species 2. Referring again to figure 6, the arc of first best harvests $h^*(x)$ shifts eastward and becomes flatter. Maintaining a close match between implemented and first best harvests requires a reduction in the value of α.

When both species have similar revenue and costs, a common flexibility parameter is most effective and aligns with optimal policies. As the price of species 1 increases, both quotas should rise due to cost complementarity across harvested species. However, there are two drawbacks to using flexibility in this scenario. First, flexibility tends to be used towards higher-priced species, which means it is no longer *ex ante* species-neutral. This is why the regulator chooses to let the quotas of both species diverge less under CSF than under a discard ban. Second, since the quotas of both species are already high with a higher price of species 1, using flexibility towards species 2 when it has a higher stock realization has a current consumption value that is lower than its resource user cost. As a result, as prices become more asymmetric, the benefit of flexibility decreases, and the regulator chooses a smaller value for α.

Figure 7c reports the percentage increase in expected value under a CSF regulation versus a DB regulation. The results show that the CSF outperforms DB when $\frac{p_1}{p_2} \in [0, 1.8]$; DB dominates for $\frac{p_1}{p_2} > 1.8$.

This relative performance result is explained by the implementability properties of the CSF and DB regulations. As $\frac{p_1}{p_2}$ becomes large any/all flexibility afforded under CSF is used by fishers toward the harvest of species 1. Flexibility no longer responds to differences in stock abundance and therefore CSF looses it advantage in implementing stock-contingent harvests. Moreover, as $\frac{p_1}{p_2}$ increases, first best harvests, $\frac{h_1^*}{h_2^*}$ also increase. At $\frac{p_1}{p_2} = 1.8$ h^* is implementable under the DB regulation only and $E_{\varphi}[W^F - W^{DB}]$ becomes negative.

In general, price differential at which relative regulatory performance switches sign is an empirical matter. The lesson in figure 7c is that performance of CSF will be good when realized stock-abundances are determinative of both the first best and the fisher-implemented harvests. If economic fundamentals are the main determinants of first-best and implemented harvests, the advantage of CSF declines.

Heterogeneous resource user costs

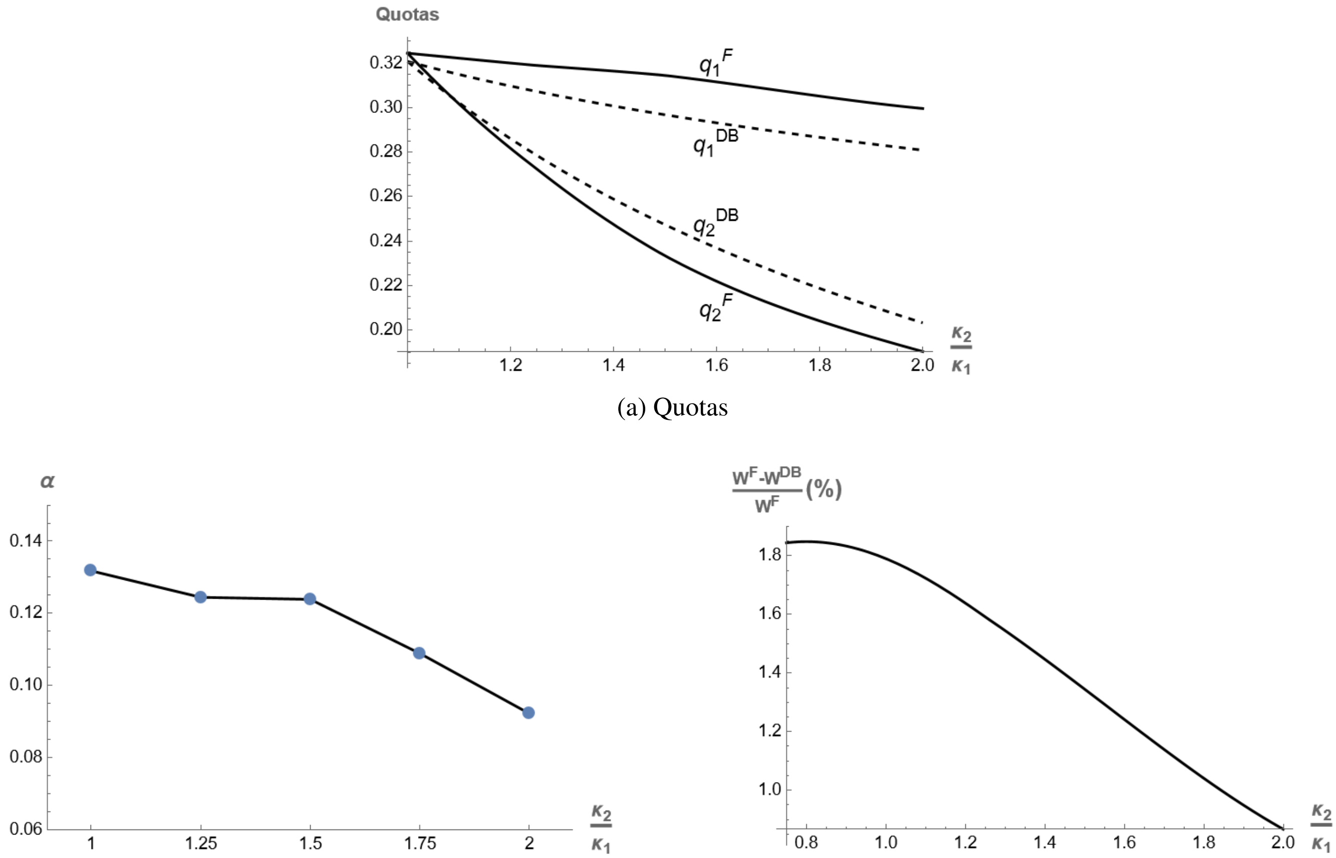
We next use our model to compare performance under heterogeneous resource user costs. Management settings arise in which a particular species stock has been overfished. Resource user costs will be high, and perhaps higher than a cohabiting species. Our second experiment keeps $\kappa_1 = 2$ constant and varies the ratio $\frac{\kappa_2}{\kappa_1}$ from 1 to 2 in increments of 0.25. Figure 8 reports the results.

The results in figure 8 align with the findings above. As $\frac{\kappa_2}{\kappa_1}$ increases, quotas for each species decrease, under both regulations. Additionally, the performance of CSF relative to a discard ban decreases.

In contrast to the asymmetric price scenario, divergence between the second best quotas is smaller under a discard ban than under CSF. In the present scenario, both species share common landings prices and stock characteristics. Differences across species is due, exclusively, to heterogenous intertemporal resource user costs. This means there is an equal chance *ex ante* that discretion under CSF will be applied to each species. As κ_2 increases, both species quotas and the CSF parameter decrease. However, when the realised stock of species 1 is higher, reducing α lowers fishery value even though prices and resource costs are unchanged. As a result, the regulator allows the quotas of the two species to diverge more under a CSF provision than under a discard ban.

5.1 CSF under asymmetric bioeconomic fundamentals

The policy experiments in this section show that the performance gains under CSF dissipate when species become particularly asymmetric. It should be emphasized that this decline in relative perfor-



(a) Quotas

(b) CSF parameter

(c) Performance

Figure 8: Resource User Costs and Regulatory Performance: Figure reports second best quotas, CSF flexibility parameter α, and relative fishery value under an IFQ with CSF and IFQ with discard ban regulation. Model parameters are set at $\mu = 0.5$, $\gamma = 0.7$ $c_1 = c_2 = 1$, $w = 1$, $p_1 = p_2 = 1$, $\kappa_1 = \$2$, κ_2 increases from \$2 to \$4.

mance conditions can be mitigated by adopting asymmetric flexibility provisions. Instead of a common α, the regulator can use α_1 when using species 1 towards species 2 and α_2 when using species 2 towards 1. This approach is simple to implement. The specifics of the design of an asymmetric CSF regulation will vary with bioeconomic fundamentals and is left for future work.

6 Conclusion

Fisheries managers set annual catch quotas under uncertainty over the size and growth characteristics of multiple cohabiting fish-species' populations. Harvesting operations are conducted by autonomous fishers with private information about stock conditions; fishers observe the productivity of their gear as harvesting is underway. We study an individual fishing quota (IFQ) regulatory design that grants fishers discretion to adjust the mix of species that are legally landed under the regulation. Discretion in the form of a cross species flexibility (CSF) provision allows fishers to respond in real time to observed productivity of gear across the different species they pursue. To the extent that gear productivity correlates with true stock abundances, CSF will reduce information asymmetry for the manager and increase fishery value.

Our results show that across a wide range of bioeconomic fundamentals, CSF obtains higher expected fishery value relative to a standard IFQ design, and relative to an IFQ regulation that bans at-sea discarding. The discard ban approach is seen by some as necessary for eliminating wasteful discards. Our results show that discards are also eliminated under a second best CSF design. Discretion under CSF can more closely match first best mortality and economic rent outcomes relative to rules-based control provided under a discard ban.

Importantly, our assessments of regulatory performance, which favor CSF, did not include the costs of administering the regulation. Counting all fish that are intercepted by gear and retrieved to the deck of a fishing vessel against available IFQ requires at-sea monitoring...of every trip taken by every vessel that operates under the IFQ regulation. The lowest cost option for monitoring commercial fishing operations at sea uses on-board cameras with subsequent viewing of video recordings (on-board observers are more expensive) Marshall (1999). Cost estimates are in the range of €7,981 per vessel per year (in \$ 2019). In 2019, 57,236 vessels participated in EU fisheries putting the total cost of enforcing the Common Fishery Policy's discard ban stipulation at roughly €456.8 million per year. An IFQ with CSF regulation requires monitoring of landings at ports, at presumably much lower cost (formal estimates are unavailable).

Our second best IFQ designs derive a rational and IFQ-market-clearing equilibrium mapping from bioeconomic fundamentals and regulations to mortality and rent outcomes. This step is information intensive and computationally demanding. Conditional on this mapping, a second step chooses parameters of the regulation to maximize expected fishery value, a derivation that is also not trivial. We contend that the two-step approach is necessary to improve quota-based management of multiple-species fisheries. Regulatory designs that do not anticipate fishers' behavioral responses to regulations and bioeconomic conditions, under market clearing and realistic technological constraints will surely disappoint (Lucas Jr, 1976).

Our second best policy designs offer blunt advice for fishery managers and stakeholders. A popular algorithm used to set quotas in multiple-species fisheries follows a "most limiting stock" principle (Batsleer et al., 2013; Briton et al., 2020; Ulrich et al., 2008).[26] Step one estimates, from past data sources and projected stock abundances, the limiting or *choke* species within a multiple-species complex. Two mortality scenarios are identified. A *min* scenario assumes fishing stops when the limiting species quota is exhausted, yielding zero discards but unutilized quota for all non-limiting species. A *max* scenario assumes fishing proceeds until all quotas bind, with positive discards for all but the least-binding species. Managers select quotas within the min-max range under an *ad hoc* behavioral rule and/or naive prediction of future fishing patterns that are estimated from past data.

The equilibrium mapping from quotas to outcomes that we derive shows that the *most limiting stock*, is an endogenous construct determined through rational endogenous targeting behavior that depend on economic fundamentals, output substitution under the available technology, realized stock abundances, all individual species' quotas and, if present, CSF allowed under the regulation. Our model offers a bioeconomic-founded approach to design and evaluate IFQ regulations that weigh the benefits of increased quota utilization and avoid over-quota discarding entirely.

A practical consideration in solving the second-best IFQ design problem is accurate measurement of the relevant bioeconomic fundamentals and extraction technology. Landings quantities, factor input allocations, and revenues and costs are observed directly and can be measured relatively easily. Meth-

[26]See also https://www.ices.dk/advice/Fisheries-overviews/Pages/fisheries-overviews.aspx.

ods to obtain internally consistent measurement of true stock abundances on the productivity of fishing gear is more challenging (Bunzel and Weninger, 2021). Management authorities may wish to prioritize data collection and analyses to facilitate robust measurement of the full set of fundamentals that are relevant to designing effective regulations.

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7 Appendix

This appendix provides additional rational for: (i) the characterization of stock abundance uncertainty and management objective and (ii) the specification for the multiple-species fishing technology.

7.1 Stock uncertainty and management goals

Our model assumptions mirror real world fisheries in which true individual-species' population sizes are unobservable.[27] We assume the manager only has beliefs about true abundances which we model as a random distribution.

Fishers on the other hand are assumed to make decisions based on direct observation of the productivity of the gear that they allocate to the water.

The management objective in equation (1) can be seen as an approximation to the objective that appears in the canonical bioeconomic fishery model (Clark, 1974). To demonstrate we abstract momentarily from stock uncertainty. Following the notation in section 2, suppose the current, pre-harvest, abundance vector is known and equal to x and that stock transitions follow, $x' = G(x - h)$, where $'$ indexes the one period ahead value and $G(\cdot)$ is the known growth of the escapement, $x - h$. The manager chooses current harvest h to maximize the present discounted value of an infinite sum of per-period fishing profits. Application of dynamic programming principles obtains the following necessary condition for an interior solution to this problem:

$$\nabla_h \Pi\left(h_1, h_2\right) = \delta \nabla_x V(x') \nabla_h G(x - h), \tag{19}$$

where ∇_k denotes partial differentiation with respect to the vector argument k, δ is the discount factor, and $V(x)$ is the optimized fishery value given x.

Optimality requires that the marginal value of current harvest be equal to its discounted marginal contribution to future value, i.e., from leaving the fish in the sea. The RHS of equation (19) is thus a *resource user cost*.

[27] Stock assessment methods combine indirect data, e.g., past mortality, samples of the age and sex distributions of the stock, indices of catch per unit of effort, with (untestable) ecological theory to formulate a *projection* of the most plausible size of a fish population. See Schnute and Richards (2001); **?**); Maunder and Piner (2015) for additional discussion of the limitations of stock assessment methods.

The necessary condition for optimality in the model of section 2 replaces the RHS of equation (19) with the term, $\kappa_1 h_1 + \kappa_2 h_2$. The approximate resource user cost is $\kappa_i h_i$ for species i. Equation (19) is simple and tractable.

Note that low values of the κ_i parameters prescribe larger current harvest and thus a larger species i quota. But the motive for increased current harvest of a higher abundance species also operates via the technology channel, i.e., higher abundance increases factor input productivity, which increases the value of current extraction.[28] Specifying κ_i's as stock-contingent parameters, in addition, will only strengthen the motive for allowing discretion to harvesters to extract more of a high-abundance stock. Nonetheless, this generalization complicates the algebraic derivations below without yielding additional insights. Therefore, unless otherwise stated, we maintain the assumption that κ_i are fixed constants.

7.2 Multiple-species fishing technologies

Models of multiple-species fishing technologies are generally of two forms. The fisheries management literature has embraced a generalization of the single-species Gordon-Schaefer harvest function (see Clark (1974)). The multiple-species version specifies a vector of individual species harvest quantities as the multiplicative product of a catchability coefficient vector, a scalar composite input bundle known as fishing *effort*, and a vector of individual species stock abundances. The model assumes that fishers do not influence the mix of species that are harvested by their gear. Rather, exogenous catchability and stock abundances fully determine the mix of harvested species. Fishing *behavior* is reduced to a simple choice of the effort quantity variable, or alternatively, the harvest scale.

The fixed output proportions assumption is restrictive and not supported empirically. Fishers choose gear types and configurations, baits, the micro-locations at which gear is set across continuous space and time in marine environments that exhibit heterogeneity in ecological suitability and correspondingly, densities of individual species stocks. Empirical observation of heterogeneous in the mix of individual species' harvests contradict the fixed output proportions assumption (Branch and Hilborn, 2008; Bunzel and Weninger, 2021; Mortensen et al., 2018).

Generalizations of the fixed output proportions assumption have appeared in the fisheries manage-

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

ment literature. Ulrich et al. (2011) assumes a fishing fleet comprised of métier's, where a single métier is defined as "a group of fishing operations targeting a similar (assemblage of) species, using similar gear, during the same period of the year and/or within the same area, and which are characterized by a similar exploitation pattern." (Ulrich et al., 2011, p. 1536). Harvests by the métier follows the multiple-species version of the Gordon-Schaefer harvest function, i.e., the fixed output proportions assumption is maintained.

The métier approach has important shortcomings. First, the number of métiers that are assumed to exist within a fleet is necessarily finite, while abundance heterogeneity across species, space and time is surely not. Fishers employing a particular métier are generally able to influence the mix of harvested species.

Second, the evaluation of regulations that are not métier-specific require the researcher specify the endogenous choice of métier's that will be utilized, and how much effort to allocate to each of the chosen métiers. Solving this problem requires use of discrete optimization methods with accompanying computational challenges (e.g., Woods et al. (2016)). Added complexities that arise under a finite set of discrete quota users, rational economic choices and equilibrium in quota trading markets is usually ignored.

A second stream of literature applies the neoclassical theory of the multi-product firm (Panzar and Willig, 1975) to multiple-species fishing technologies. This literature emphasizes endogenous factor input demands and endogenous output supply and substitution across species (Squires (1987, 1988); Kirkley and Strand (1988); see Squires and Walden (2020) for a recent review). Flexible functional forms are common.

This literature has avoided modeling complications that arise under weak output disposability and has neglected to explicitly incorporate multiple species stock abundances into harvest technologies (see Scheld and Walden (2018); Singh and Weninger (2009) for exceptions). Weak output disposability is long recognized as key to understanding the problems of bycatch (e.g., (Boyce, 1996)) and over-quota discarding in quota-regulated multiple-species fisheries Turner (1995); Singh and Weninger (2009).

In sum, a robust model of a multiple-species fishing technology must allow endogenous output substitutions (targeting), over-quota discarding under weak output disposability, and an explicit link from individual species' stock abundances to individual species harvest quantities. The technology presented in section 2 combines these elements within a tractable model.

7.3 Proof of Proposition 1

Here $\{x_1, x_2\}$ is either $\{\varphi, 1-\varphi\}$ or $\{1-\varphi, \varphi\}$ with equal probability. The example is constructed to highlight the role of flexibility when the stocks exhibit variations in relative abundance. Variations in relative abundance is best captured here by making the two stocks perfectly negatively correlated. Assuming that the two stocks have the same price $p_1 = p_2 = p$ further allows us to focus on the role of flexibility and contrast it with a discard ban in a simple tractable manner.

First best

The sole owner chooses harvests to maximize (1) subject to (3) and observed abundance $\{x_1, x_2\}$. Since $\{x_1, x_2\}$ is equally likely to be either $\{\varphi, 1-\varphi\}$ or $\{1-\varphi, \varphi\}$, the high stock species harvest as $\varphi\sqrt{z}$ and the low stock being $(1-\varphi)\sqrt{z}$ given an input choice z. As the prices are identical, the sole sole owner's problem is:

$$\max_z \left\{ p\sqrt{z} - wz - \frac{\kappa}{2}\left((1-\varphi)^2 + \varphi^2\right) z \right\}, \tag{20}$$

as stated in the main text. Then, the optimal input choice, irrespective of stock realizations is given by

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

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

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

where use of index j hereafter implies $j \neq i$. The value of the fishery is

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

IFQ without CSF

Since the two species are symmetric, quotas for both species will be equal. Let $q_1 = q_2 = q$ denote the quota choice. The optimal regulation is solved recursively. First, we derive the profit maximizing outcomes for a given q. We will assume that κ is sufficiently large (the condition is derived below), such that both species' landing constraints bind, i.e., $l_i = q$, in other words, the resource user cost κ_i is sufficiently large that limits on current extraction is warranted.

For $x_i = \varphi$ and $x_{j \neq i} = 1 - \varphi$, we have

$$h_i = \varphi z^{0.5} = \frac{\varphi}{1-\varphi} q > l_i = q \tag{21a}$$

$$h_j = (1-\varphi) z^{0.5} = l_j = q \tag{21b}$$

with discards of species i:

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

Conditional on fishermen's choices (21a) and (21b), the regulator sets quotas $\{q, q\}$ to maximize the expected fishery value. The optimal quota is

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

Which gives

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

Using the optimal quota, we obtain

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

Then, following (21a), the input allocation is

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

Recall that $\varphi > 0.5$ which implies the term $\left(2\left(1-\varphi\right)\right)^2$ on the right-hand of above expression is less than unity, and therefore $z^S < z^*$. It follows that for the species i with $x_i = \varphi$,

$$h_i^S = \varphi \frac{p\left(1-\varphi\right)}{w + \frac{\kappa}{2}\left(\left(1-\varphi\right)^2 + \varphi^2\right)}, \quad h_{j\neq i}^S = \left(1-\varphi\right) \frac{p\left(1-\varphi\right)}{w + \frac{\kappa}{2}\left(\left(1-\varphi\right)^2 + \varphi^2\right)}.$$

A comparison with the sole owner's landings and harvests finds,

$$\frac{l_i^S}{l_i^*} \leq \frac{h_i^S}{h_i^*} = 2\left(1-\varphi\right) < 1, \text{ for } i = 1, 2.$$

Summing up, we see that, under the second best regulation with no CSF, stock contingent harvests are below their first best counterpart by a factor $2(1-\varphi) < 1$, and positive discards of the high-abundant species occur, as was suggested in the example of figure 1.

A necessary condition on $\frac{\kappa}{w}$ for quotas to bind The above analysis assumes that landing constraints for both species bind, i.e., marginal fishing profits are positive providing incentive to increase harvest absent quota constraints. 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 is

$$z^* = \frac{1}{2w}\left(p - r_j\right) h_j^*, \tag{22}$$

where species $j \neq i$ has $x_j = 1 - \varphi$. Since $h_j^* = q^S$, its equilibrium quota price is

$$\begin{aligned} r_j =& p - \frac{2wq^S}{(1-\varphi)^2}, \\ =& p\left(1 - \frac{2w}{w + \frac{\kappa}{2}\left(\varphi^2 + (1-\varphi)^2\right)}\right), \end{aligned} \tag{23}$$

where the last expression follows from the above expression for the optimal quota. If the perceived resource user cost is larger relative to the input cost, i.e., $\frac{\kappa}{2}\left(\varphi^2 + (1-\varphi)^2\right) > w$, both species' quotas bind in equilibrium.[29]

IFQ with discard ban

Suppose a discard ban is imposed under the IFQ regulation. If discarding is prohibited, fishing must stop as soon as one of the species' quotas bind. As a result, the species with shock φ is fully utilized with its harvest at q while the harvest of the other species equals $q\frac{1-\varphi}{\varphi}$. Thus the combined quota utilization is $q + q\frac{1-\varphi}{\varphi} = \frac{q}{\varphi}$ and the input use is $z = \left(\frac{q}{\varphi}\right)^2$. Inserting these expressions into the regulators quota choice problem obtains,

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

which obtains,

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

and the fishery value is evaluated to,

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

A discard ban thus gets the first best.

Notice that the discard ban policy essentially sets both quotas to the higher species harvest under the first best. In the market equilibrium, fishermen employ the same amount of input as under the first

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

best.

$$q^{DB} = \frac{\varphi}{2\left(1-\varphi\right)^2} q^S.$$

Its derivative

$$\begin{aligned} \frac{dq^{DB}}{d\varphi} &= w + \frac{\kappa}{2} - \kappa\varphi^2 \\ &\gtreqless 0 \Leftrightarrow \varphi \lesseqgtr \sqrt{\frac{w}{\kappa} + \frac{1}{2}} \end{aligned}$$

However, for $\varphi = 1$:

$$q^{DB} = \frac{p}{2w + \kappa}$$

IFQ with CSF

Consider the case where the IFQ regulation permits $\alpha\%$ of the quota of any species to be used to land the other. The landing constraint for either of the species becomes:

$$l_i \leq (1+\alpha)\, q \text{ subject to } l_i + l_j \leq 2q,$$

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

$$\left.\begin{array}{c} l_i = (1+\alpha)\, q \leq h_i = \frac{\varphi}{1-\varphi}(1-\alpha)\, q \\ l_j = (1-\alpha)\, q = h_j \end{array}\right\} \text{ if } \frac{1+\alpha}{1-\alpha} \leq \frac{\varphi}{1-\varphi} \tag{24}$$

or

$$\left.\begin{array}{c} l_i = 2\varphi q = h_i \\ l_j = 2\left(1-\varphi\right) q = h_j \end{array}\right\} \text{ if } \frac{1+\alpha}{1-\alpha} \geq \frac{\varphi}{1-\varphi} \tag{25}$$

Using CSF to replicate the first best

The latter condition (25) holds when $\alpha \geq 2\varphi - 1$. In this case, neither species is discarded and the total quota is utilized, i.e., $h_1 + h_2 = 2q$. Using (25) in (1), the regulator chooses

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

Which gets

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

With $\alpha \geq 2\varphi - 1$, a market equilibrium ensures that the harvest of the two species is identical to the first best outcome. 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 $2\varphi q^F$. The other species' harvest makes up the rest, $2\,(1-\varphi)\,q^F$. 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. Finally, note that $q^F = \frac{q^{DB}}{2\varphi} < q^{DB}$. The wider the disparity in relative stock abundance, the wider is the gap in the quotas set under the two regulations.

7.4 Proof of Proposition 2

In this section we assume that φ is drawn from a continuous uniform distribution, $\varphi \sim U[\frac{1}{2}, \overline{\varphi}]$, where $\bar{\varphi}\left[\frac{1}{2}, 1\right]$. Trivially, $\bar{\varphi} = \frac{1}{2}$ represents the certainty benchmark with identical stock abundance for both species.

First best

The sole owner chooses harvests after observing the stock conditions. His input choice is the same as under a degenerate distribution of φ :

$$z^* = \left(\frac{1}{2}\frac{p}{w + \frac{\kappa}{2}\left((1-\varphi)^2 + \varphi^2\right)}\right)^2. \tag{26}$$

with

$$h_i^* = \varphi\left(z^*\right)^{\frac{1}{2}};\ h_j^* = \left(1-\varphi\right)\left(z^*\right)^{\frac{1}{2}};$$

as the harvest of the two species. Harvests and the payoffs now vary along with $\varphi \in \left[\frac{1}{2}, \bar{\varphi}\right]$].

IFQ with discard ban

Now the regulator's problem can be described as

$$q^{DB} \equiv \arg\max_q E_\varphi \left\{ p\frac{q}{\varphi} - w\left(\frac{q}{\varphi}\right)^2 - \frac{\kappa}{2}q^2\left(1+\left(\frac{1-\varphi}{\varphi}\right)^2\right)\right\}.$$

The solution is obtained by taking the first order condition and then evaluating the expectations with $\varphi \sim U[\frac{1}{2}, \overline{\varphi}]$:

$$\begin{aligned} q^{DB} &= \frac{E\left[\frac{1}{\varphi}\right]}{2wE\left[\frac{1}{\varphi^2}\right] + \kappa E\left[1+\left(\frac{1-\varphi}{\varphi}\right)^2\right]} \\ &= p\frac{\bar{\varphi}\frac{\ln 2\bar{\varphi}}{\bar{\varphi}-\frac{1}{2}}}{w+\frac{\kappa}{2}\left[\bar{\varphi}+1-\bar{\varphi}\left(\frac{\ln 2\bar{\varphi}}{\bar{\varphi}-\frac{1}{2}}\right)\right]} \end{aligned}$$

which is decreasing in input costs w and prospective costs parameter κ. Its dependence on φ, as under Binomial uncertainty, is non-monotonic. It is increasing in $\bar{\varphi}$ for all $\bar{\varphi} \in (\frac{1}{2}, \hat{\varphi}\left(\frac{w}{k}\right)]$, and then decreases. Note that $q^{DB} = \frac{p}{4w+\kappa}$ for $\bar{\varphi} = \frac{1}{2}$ and for $\bar{\varphi} = 1$, it stays at a higher level of $\frac{\frac{2\ln 2}{[1-\ln 2]}}{\frac{w}{[1-\ln 2]}+\kappa} > \frac{p}{4w+\kappa}$.

Substituting the value of q^{DB} in the regulator's benefit function evaluates to:

$$\begin{aligned} W^{DB} &= p\frac{\ln\bar{\varphi}+\ln 2}{\bar{\varphi}-\frac{1}{2}}q^{DB} \\ &= \frac{p^2}{8}\frac{\bar{\varphi}\left(\frac{\ln 2\bar{\varphi}}{\bar{\varphi}-\frac{1}{2}}\right)^2}{w+\frac{\kappa}{2}\left[\bar{\varphi}+1-\bar{\varphi}\left(\frac{\ln 2\bar{\varphi}}{\bar{\varphi}-\frac{1}{2}}\right)\right]} \end{aligned}$$

which is decreasing in $\bar{\varphi}$.

IFQ with CSF

Once again the regulator sets quotas q^F for each species with maximum landing of any species allowed to be $(1+\alpha)\,q^F$. Assuming that in a market equilibrium both species quotas bind, if the φ realization is sufficiently high such that $\varphi\left(2q^F\right) > (1+\alpha)\,q^F$, the high shock species will be discarded and the input as well as the harvest choice will be governed by the full utilization of low shock species. Specifically, the input choice will be

$$(1-\varphi)\sqrt{z} = (1-\alpha)\,q^F \Rightarrow z = \left(\frac{1-\alpha}{1-\varphi}\right)^2 \left(q^F\right)^2$$

On the other hand, for the low realizations of φ, cross-species flexibility will allow full utilization of quotas as long as $\alpha \geq 2\varphi - 1$. This logic motivates a conjecture that there exists a $\tilde{\varphi} = \frac{1+\alpha}{2} \leq \bar{\varphi}$ that demarcates the discard set such that discards occur if and only if $\varphi > \tilde{\varphi}$.

The regulator's objective in this scenario is to choose $\left\{q^F, \alpha\right\}$ to maximize its expected benefit as expressed below:

$$\begin{aligned} W^F \quad \equiv \quad & 2pq^F - w\left(\frac{1}{\bar{\varphi}-\frac{1}{2}}\right)\left(q^F\right)^2 \left(\begin{array}{c} \int_{\frac{1}{2}}^{\tilde{\varphi}} 4d\varphi \\ +\int_{\tilde{\varphi}}^{\bar{\varphi}} \left(\frac{1-\alpha}{1-\varphi}\right)^2 d\varphi \end{array}\right) \\ & -\frac{\kappa}{2}\left(\frac{1}{\bar{\varphi}-\frac{1}{2}}\right)\left(q^F\right)^2 \left(\begin{array}{c} \int_{\frac{1}{2}}^{\tilde{\varphi}} \left[(2\varphi)^2 + (2\,(1-\varphi))^2\right] d\varphi \\ (1-\alpha)^2 \int_{\tilde{\varphi}}^{\bar{\varphi}} \left[1+\left(\frac{\varphi}{1-\varphi}\right)^2\right] d\varphi \end{array}\right) \end{aligned}$$

An interior solution would require the first order condition to hold. Since the integration limits include $\tilde{\varphi} = \frac{1+\alpha}{2}$, taking derivative requires an application of Leibniz principle. The condition for an interior solution is given by

$$\begin{aligned} & -2w\int_{\tilde{\varphi}}^{\bar{\varphi}} \left(-\frac{1-\alpha}{(1-\varphi)^2}\right) d\varphi \\ & -\kappa\,(1-\alpha)\int_{\tilde{\varphi}}^{\bar{\varphi}} \left[1+\left(\frac{\varphi}{1-\varphi}\right)^2\right] d\varphi \\ = \quad & 0 \end{aligned}$$

which holds only if $\alpha = 1$. But $\alpha = 1$ contradicts the assumption of an interior solution. Essentially, *it is never optimal for the regulator to let harvests fall in the discard set*. This can only be ensured by sufficient flexibility such that discards are ruled out for the highest realization of $\varphi = \bar{\varphi}$. Thus, the only optimal choice for the regulator is to set $\alpha = 2\bar{\varphi} - 1$, and then focus its attention on the choice of q to maximize the benefit function W^F, which is now expressed as

$$\begin{aligned} W^F \quad &\equiv \quad 2pq^F - w\left(2q^F\right)^2 \\ &\quad -\frac{\kappa}{2}\left(\frac{1}{\bar{\varphi}-\frac{1}{2}}\right)\left(q^F\right)^2\left(\int_{\frac{1}{2}}^{\bar{\varphi}}\left[(2\varphi)^2+(2(1-\varphi))^2\right]d\varphi\right). \end{aligned}$$

The optimal quota choice is now given by

$$q^F = \frac{p\left(\bar{\varphi}-\frac{1}{2}\right)}{4w\left(\bar{\varphi}-\frac{1}{2}\right)+\frac{\kappa}{2}\frac{4}{3}\left(\bar{\varphi}^3-(1-\bar{\varphi})^3\right)}$$

With its given quadratic functional form, the expected benefit under flexibility

$$W^F = pq^F.$$

Proof for a necessary and sufficient condition on $\frac{\kappa}{w}$ for $W^{DB} \gtrless W^F$

Whether $W^{DB} \gtrless W^F$ requires checking

$$\frac{1}{w+\frac{\kappa}{6}\left(\frac{\bar{\varphi}^3-(1-\bar{\varphi})^3}{\bar{\varphi}-\frac{1}{2}}\right)} \gtrless \frac{\frac{1}{8}\bar{\varphi}\left(\frac{\ln 2\bar{\varphi}}{\bar{\varphi}-\frac{1}{2}}\right)^2}{w+\frac{\kappa}{2}\left[\bar{\varphi}+1-\bar{\varphi}\left(\frac{\ln 2\bar{\varphi}}{\bar{\varphi}-\frac{1}{2}}\right)\right]}$$

A manipulation restates the above as

$$\frac{\kappa}{w}\left[\bar{\varphi}+1-\bar{\varphi}\left(\frac{\ln 2\bar{\varphi}}{\bar{\varphi}-\frac{1}{2}}\right)-\frac{1}{6}\bar{\varphi}\left(\frac{\ln 2\bar{\varphi}}{\bar{\varphi}-\frac{1}{2}}\right)^2\left(\frac{\bar{\varphi}^3-(1-\bar{\varphi})^3}{\bar{\varphi}-\frac{1}{2}}\right)\right] \gtrless \bar{\varphi}\left(\frac{\ln 2\bar{\varphi}}{\bar{\varphi}-\frac{1}{2}}\right)^2-2$$

The RHS is negative for all values of $\bar{\varphi}$. The LHS is positive for all values of $\bar{\varphi} \in \left(\frac{1}{2}, \hat{\varphi}\right)$ and negative for all $\bar{\varphi} \in (\hat{\varphi}, 1]$, with $\hat{\varphi} = 0.728274$. Thus, an IFQ with CSF dominates discard ban for all $\varphi < \hat{\varphi}$.

For $\bar{\varphi} > \hat{\varphi}$, the condition becomes

$$\frac{\kappa}{w} \lesseqgtr \frac{\bar{\varphi}\left(\frac{\ln 2\bar{\varphi}}{\bar{\varphi}-\frac{1}{2}}\right)^2 - 2}{\frac{1}{6}\bar{\varphi}\left(\frac{\ln 2\bar{\varphi}}{\bar{\varphi}-\frac{1}{2}}\right)^2\left(\frac{\bar{\varphi}^3-(1-\bar{\varphi})^3}{\bar{\varphi}-\frac{1}{2}}\right) + \bar{\varphi}\left(\frac{\ln 2\bar{\varphi}}{\bar{\varphi}-\frac{1}{2}}\right) - (\bar{\varphi}+1)} \equiv \varkappa(\bar{\varphi})$$

The RHS is declining in $\bar{\varphi}$, from ∞ at $\hat{\varphi}$ to approximately 0.7267 for $\bar{\varphi} = 1$. We have assumed $\kappa > w$ to ensure that quotas bind in a decentralized equilibrium. Thus with sufficiently high $\bar{\varphi}$ $\frac{\kappa}{w} > \varkappa(\bar{\varphi})$ and a discard ban policy works better.

Proof for a necessary and sufficient condition on $\frac{\kappa}{w}$ for $W^{DB} \gtrless W^F$

Whether $W^{DB} \gtrless W^F$ requires checking

$$\frac{1}{w + \frac{\kappa}{6}\left(\frac{\bar{\varphi}^3-(1-\bar{\varphi})^3}{\bar{\varphi}-\frac{1}{2}}\right)} \gtrless \frac{\frac{1}{8}\bar{\varphi}\left(\frac{\ln 2\bar{\varphi}}{\bar{\varphi}-\frac{1}{2}}\right)^2}{w + \frac{\kappa}{2}\left[\bar{\varphi}+1-\bar{\varphi}\left(\frac{\ln 2\bar{\varphi}}{\bar{\varphi}-\frac{1}{2}}\right)\right]}$$

A manipulation restates the above as

$$\frac{\kappa}{w}\left[\bar{\varphi}+1-\bar{\varphi}\left(\frac{\ln 2\bar{\varphi}}{\bar{\varphi}-\frac{1}{2}}\right) - \frac{1}{6}\bar{\varphi}\left(\frac{\ln 2\bar{\varphi}}{\bar{\varphi}-\frac{1}{2}}\right)^2\left(\frac{\bar{\varphi}^3-(1-\bar{\varphi})^3}{\bar{\varphi}-\frac{1}{2}}\right)\right] \gtrless \bar{\varphi}\left(\frac{\ln 2\bar{\varphi}}{\bar{\varphi}-\frac{1}{2}}\right)^2 - 2$$

The RHS is negative for all values of $\bar{\varphi}$. The LHS is positive for all values of $\bar{\varphi} \in \left(\frac{1}{2}, \hat{\varphi}\right)$ and negative for all $\bar{\varphi} \in (\hat{\varphi}, 1]$, with $\hat{\varphi} = 0.728274$. Thus, an IFQ with CSF dominates discard ban for all $\varphi < \hat{\varphi}$.

For $\bar{\varphi} > \hat{\varphi}$, the condition becomes

$$\frac{\kappa}{w} \lesseqgtr \frac{\bar{\varphi}\left(\frac{\ln 2\bar{\varphi}}{\bar{\varphi}-\frac{1}{2}}\right)^2 - 2}{\frac{1}{6}\bar{\varphi}\left(\frac{\ln 2\bar{\varphi}}{\bar{\varphi}-\frac{1}{2}}\right)^2\left(\frac{\bar{\varphi}^3-(1-\bar{\varphi})^3}{\bar{\varphi}-\frac{1}{2}}\right) + \bar{\varphi}\left(\frac{\ln 2\bar{\varphi}}{\bar{\varphi}-\frac{1}{2}}\right) - (\bar{\varphi}+1)} \equiv \varkappa(\bar{\varphi})$$

The RHS is declining in $\bar{\varphi}$, from ∞ at $\hat{\varphi}$ to approximately 0.7267 for $\bar{\varphi} = 1$. We have assumed $\kappa > w$ to ensure that quotas bind in a decentralized equilibrium. Thus with sufficiently high $\bar{\varphi}$ $\frac{\kappa}{w} > \varkappa(\bar{\varphi})$ and a discard ban policy works better.

Derivation of optimal targeting

This appendix summarizes profit maximization conditions within each regions on figure 4.

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

From (13b), 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 (14) and (15). Also $d_i = 0$ for both i. Then, $l_i = h_i < (1 - \alpha) q_i$. For $q \in$ region I, profit maximizing harvest occurs at 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 (14) and (15). 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 harvesting additional species 2 fish is zero, all else equal. If the price of species 2 fish were higher, segment AB in figure 4 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, $\upsilon_1 = 0$, $a^* = 0$, $l_1 = q_1 + \alpha q_2 < \underline{h}_1 (z^*)$, where z^* solves

$$wz^* = \gamma p_2 \overline{h}_2 (z^*) .$$

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

In region III the species 2 quota is slack while the species 1 quota binds, tightly such that profit maximization involves positive discards of species 1 fish. For all $q \in$ III, harvest occurs at point A in figure 4. 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 $l_2 = h_2 = q_2 + \alpha q_1$ along with equations (14) and (15). 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 species 1 harvest is zero, all else equal. If the price of species 1 fish were higher, segment CB in figure 4 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, $\upsilon_2 = 0$, $a^* = 1$, $l_2 = q_2 + \alpha q_1 < \underline{h}_2 (z^*)$, where z^* solves

$$wz^* = \gamma p_1 \overline{h}_1 (z^*) ;$$

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

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

We now consider regions for which $\lambda > 0$. From the necessary condition (13b) we have $l_1 + l_2 = q_1 + q_2$. Here quotas are *tight* and the marginal profit from harvesting additional units of fish remains positive. The question 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 with $\upsilon_1 = 0$ and $a^* = 0$, z^* is determined by,[30]

$$\overline{h}_2 (z^*) = (1 - \alpha) q_2;$$

$l_2 = (1 - \alpha) q_2$ and $h_1 = \underline{h}_1 (z^*) > l_1 = q_1 + \alpha q_2$.

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[31]

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

$l_1 = (1 - \alpha) q_1$ and $h_2 = \underline{h}_2 (z^*) > l_2 = q_2 + \alpha q_1$.

[30] ω_1 is in turn obtained from $wz^* = \gamma (p_2 - p_1 + \omega_1) \overline{h}_2 (z^*) ;$

[31] ω_1 is in turn obtained from $wz^* = \gamma (p_1 - p_2 + \omega_2) \overline{h}_1 (z^*) ;$

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, is equal to the 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 (14) and (15) 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, which is positive in region IX, is equal to the 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 (14) and (15) determine $\{a, z, \upsilon_1, \upsilon_2, \omega_2\}$.

Region X: Species 1 constraint binds; positive species 2 discards.

Up until now there is a symmetry across partitions. This symmetry will indeed be the case if $p_1 = p_2$. However, if $p_1 > p_2$, and the aggregate constraint binds, $\lambda \geq p_2$ is required for conditions (13a-13d) 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[32]

$$\overline{h}_1 (z^*) = q_1 + \alpha q_2;$$

$l_1 = q_1 + \alpha q_2$ and $h_2 = \underline{h}_2 (z^*) > l_2 = (1 - \alpha) q_2$.

It is worth reiterating that region X exists only if prices are unequal as is assumed. To understand region X, it is instructive to contrast outcomes in regions VII and X. Recall that profit maximization requires that quota flexibility be exploited toward landing the highest marginal profit species allowed by the regulation. Quota q_2 tightly binds in regions VII and X; for h in these regions, inputs must

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

be spent to maintain low quantities of h_2. Because $\upsilon_2 = 0$ in regions VII and X, the marginal profit from allocating flexible quota to species 2 harvest is p_2, i.e., the marginal cost of harvesting h_2 is zero along ray $0C$ and thus marginal profit is equal to the marginal revenue. However, if $p_1 > p_2$, as we have assumed, and at particularly at low levels of h_1, that marginal (cost) profit from species 1 harvest will also be large (small) and can exceed p_2. Moving left to right, from region X to VII, in the figure decreases (increases) species 1 marginal profit (cost). When species 1 harvests increase, the optimal quota allocation will eventually tip from species 1 to species 2. This tipping point delineates the boundary between regions X and VII.

It is easily seen how the regions are modified when the relative prices are reversed, i.e., $p_2 > p_1$.