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Working Paper No. 12015
August 2012

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Revised: August 24, 2012

Preliminary and incomplete

Abstract

We develop a model of a multiple-species, stochastic harvesting technology. We examine harvesting behavior, at-sea discards and economic performance under various quota balancing mechanisms – provisions intended to help fishermen match random catches with quota holdings – in a multiple species fishery. We show that regulations that allow frictionless quota trading reduce at at-sea discards and increase economic performance. Regulations that offer fishermen flexibility to choose the mix of species landed do not eliminate discards, and can create unintended management problems. Our results provide new insights for improving the design quota-managed fisheries.

JEL Classification: Q2
Keywords: multiple species fishery, harvest uncertainty, quota trading, flexibility

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1 Introduction

An often cited concern with individual transferable quota management programs is that randomness in the harvesting process causes mismatch between a fisherman's catch and quota holdings (Copes, 1986). When this occurs, fishermen may be forced to discard overages, i.e., harvests in excess of quota holdings, at sea to avoid regulatory penalty. Discarding problems could be magnified if fishermen must balance catches and quotas across multiple species (Squires et al., 1998). In response to the problem, multiple species quota management programs often include provisions that allow or encourage fishermen to land overages instead of discarding them. Following recent literature we will referred to these provisions as quota-balancing mechanisms, or QBMs.

The intent of QBMs is to reduce discards that result from random catch-quota imbalance.[1] One important consideration is that fishermen have opportunity to influence the mix of species intercepted by their fishing gear. The choice of fishing location, date, and depth, gear type, baits, etc. allow fishermen to target species they wish to land, and avoid others. Uncertainty in the harvesting process can remain. However, when fishermen can control, at least in part, the mix of species harvested, quota flexibility permits behavioral responses that are important in harvest and discard outcomes. Since counter-factual observation is not possible, i.e., we do not observe fishing behavior with and without QBMs in place, it is difficult to know if QBMs help meet their intended management goal.

We introduce a model of a stochastic, multiple-species harvest technology to study discard incentives under various QBMs currently in use in quota-managed fisheries. Our analysis will focus on quota flexibility and real time quota trading.[2] Quota flexibility involves a provision whereby a fisherman is permitted to land any species within a specified group of species under a common quota. The motive is to help fishermen match random catches and quotas within the group of species. Real time quota trades are a form of QBM which combat random catch-quota imbalance by spreading uncertainty across a larger number of fishermen. Trading effectively eliminates idiosyncratic uncertainty facing individual fishermen. Singh and Weninger (2012) show that frictionless quota trading leads to catch/quota balance at the industry level, and minimum harvest costs for the fleet.

Our results show that flexibility provisions in a multiple species setting do no eliminate discards of catch overages and can create unintended problems for fishery managers. Flexibility invites fishermen to target species that pay higher prices at the dock, or that more abundant and/or less costly to harvest. We show that discards can remain under quota flexibility and may even increase relative to the no-flexibility case under some prices and cost structures. Moreover, because harvests depend on prices and the targeting cost structure under flexibility provisions, elements difficult to observe or predict, managers loose control of the aggregate harvest levels in the fishery. These problems do not arise under a standard, non-flexible, quota design. We also show that discarding is absent under a standard quota design when fishermen can freely trade quota. Because frictionless quota trading eliminates discards, fishermen meet aggregate harvest targets at minimum cost. The

[1] Sanchirico et al. 2006 discuss quota-balancing mechanisms currently used in rights-based fisheries throughout the world. Amendment 29 to the Reef Fish Fishery Management Plan (Gulf of Mexico Fisheries Management Council, and NOAA 2008), recently adopted a quota program for red and gag grouper which allows flexibility in the mix of species that can be landed. This regulation is intended to reduce discards due to unanticipated catch-quota imbalance.

[2] Regulations governing quota transferability are required in U.S. fisheries under the Magnuson-Stevens Act Reauthorization of 2006. Some quota managment programs impose strict limits on quota transferability. These restrictions address concerns of concentration in quota markets, unwanted changes in the spatial distribution of harvests, unwanted changes in the composition of the fishing fleet, quota ownership by individuals or agencies who do not participate directly in the fishery, or to aid with monitoring (Anderson and Holliday, 2007). See Singh and Weninger 2012 for a complete analysis of trading frictions in quota-managed fisheries.

results provide important insights for improving the design of rights-based management programs in multiple-species fisheries.

The next section introduces the model and regulations and derives optimal fishing outcomes, i.e., harvests, discards, quota prices and input allocations. Four QBMs provisions are examined. Section 3 present numerical results. Conclusions and extensions are discussed in section 4.

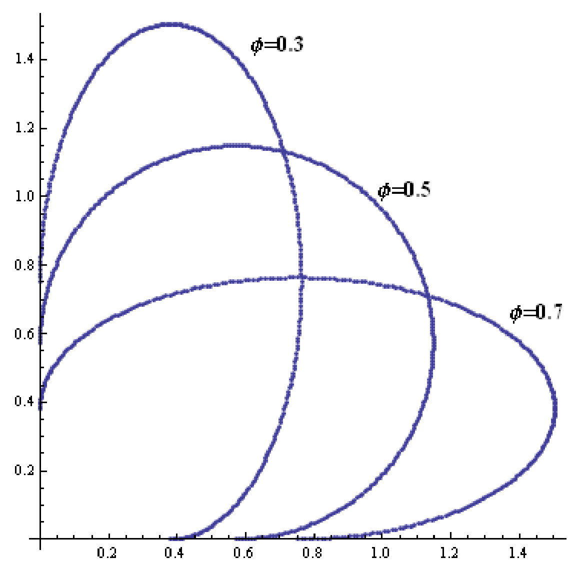
2 The model

A continuum of fishermen conduct harvesting operations during a single period. The composition of the fish stock is given; it does not change through natural forces or through the effects of fishing. There are two separate stocks. A stock may represent a distinct fish species or a size, sex or age class. Hereafter, we use the term stock rather than species to express this added generality.

The harvest of the two stocks is given by:

$$(h_1, h_2) = [A_1 \left\{1 + sin(a\frac{\pi}{2})\right\} \phi^{\gamma}, A_2 \left(1 + cos(a\frac{\pi}{2})\right) (1-\phi)^{\gamma}] \cdot z^{\beta}, \tag{1}$$

where z is a public input which we take to be a scalar for notational convenience. The input determines the scale of the total harvest. The parameter a determines the mix harvested stocks. Following Singh and Weninger (2009) we let $\phi \equiv \frac{x_1}{x_1+x_2}$ denote the share of first stock in the sea; $A_1 > 0, A_2 > 0$, and $\gamma \in (0,1)$ are parameters.[3] It is easily seen that for $\phi > 0$, $a = -1$ $\Rightarrow \{h_1, h_2\} = \{0, A_2 (1-\phi)^{\alpha}\} z^{\beta}$ and $a = 2 \Rightarrow \{h_1, h_2\} = \{A_1 \phi^{\alpha}, 0\} z^{\beta}$. The harvest technology exhibits the property of weak output disposability. Figure 1 below depicts the technology for $A_1 = A_2 = 1$, $\gamma = 0.8$, a fixed z, and $a \in [-1, 2]$.



Harvesting uncertainty is introduced as follows. We assume that at the time z is selected, the fisherman knows only the distribution of the stock abundance as reflected by the parameter ϕ.

[3] As γ gets smaller the output sets for various values of ϕ are closer to each other. As γ gets large, they expand apart. Note that $\gamma = 0.8$ turns out to be the parameter value that, for a wide range of $\phi = 0.2 - 0.8$, induces the fishermen to choose targeting mix a as close to ϕ as possible (for identical producitivties A_1 and A_2 and prices of the two stocks).

Once at sea, an actual realization of ϕ occurs. Fishermen then choose the target parameter a, e.g., adjust fishing depths, trawling speed, fine–scale fishing locations, to intercept a preferred mix of each stock. The idea is that when z is chosen, for example, when a fishing trip is planned, true stock conditions are unknown. When fishing begins the mix of stocks *under the boat* is revealed. At this point the fisherman can undertake additional steps to influence the mix of stocks intercepted and harvested by the gear.

The assumptions for uncertainty result in a choice problem that is solved in two stages. In the first stage, z is chosen based on the known distribution of ϕ. In the second stage ϕ is realized yielding a set of harvest possibilities defined by the technology in (1). Hereafter we use $H(z, \phi) = (h_1, h_2)$ to denote the stage II feasible harvest set. Given (z, ϕ), a is optimally chosen to maximize revenues given (exogenous) market prices and regulations governing landings.

2.1 Regulations

The fishery is managed with a property rights-based approach. The manager issues a fixed number of harvest permits for each stock or group of stocks. Fishermen can legally land a quantity of fish that corresponds to his permit holdings. We assume the regulator has identified aggregate harvest quantities for each stock which meet management objectives. The aggregate quota levels are fixed hereafter. Our focus is harvesting, discard, and economic rent outcomes under a fixed total quota, and varying operating rules which dictate the nature of quota trading and the quota flexibility. We first define the concept of quota flexibility. We then introduce post harvest quota trading.

Let q_i denote the quota for stock i. Landings, denoted l_i cannot exceed harvests, $l_i \leq h_i$. There is no cheating in our model and therefore landings of a single fisherman cannot exceed the quota they possess. Following Singh and Weninger (2009) we assume there is no regulatory penalty for discarding. Fishermen can costlessly discard catch overages, $h_i > l_i$, at sea.

Hereafter quota flexibility will refer to a stipulation in the regulation that allows a portion of the stock i quota to be used to land stock j fish. The regulation takes a simple form. We use $\alpha \in [0, 1]$ to denote the proportion of stock i quota that can be used to legally land stock j fish. If a fisherman holds a pair of quotas (q_1, q_2), the effective landings constraint under quota flexibility becomes

$$\begin{aligned} l_i &\leq q_i + \alpha q_j, \\ l_1 + l_2 &\leq q_1 + q_2, \end{aligned}$$

for $i = 1, 2$, and $i \neq j$. Below we focus attention on the case of no flexibility $\alpha = 0$ and limited flexibility, $0 < \alpha < 1$.[4]

All cases examined below will assume the existence of a pre-harvest, hereafter a primary, quota trading market. Primary quota trades occur simultaneously with input choices, that is, before the fishermen go to sea, and before the uncertainty over the stock composition is resolved. The second quota balancing provision allows for additional post harvest quota trades. Some early quota programs required all quota trades be registered and approved by the regulating body. Time lags were required for trades to be approved, which introduced frictions in quota markets. An alternative regulatory environment places no restrictions on quota exchanges among fishermen. To capture

[4] Limited flexibility is currently used in the Gulf of Mexico grouper and tilefish individual quota program. The regulation allows fishermen to use a portion of red grouper quota to land gag groupers, and vice versa. Similar provisions are included for other shallow and deep water groupers and other reef fish species.

the no-trade-restrictions environment we will study a second class of regulations for which a post harvest, or secondary quota trading market exists.

As is standard in the fisheries economics literature we will begin by defining a first best outcome which could be achieved under centralized control of fishing activities, i.e. the sole owner outcome. We then compare outcomes under the regulatory instruments introduced above, with and without flexibility, and with and without a secondary quota trading market to the sole owner optimum .

2.2 Sole owner problem

The sole owner takes the fish and input prices as given and chooses harvest inputs. At this point ϕ is uncertain, but the sole owner can visualize his choice of a and actual harvests for all possible realizations of ϕ. The problem is solved backwards.

2.2.1 Stage II

In the second stage, given z, the individual fisherman's problem is:

$$\Pi = \left[(p_1 - \widetilde{r}_1)A_1\left(1+\sin(\frac{a\pi}{2})\right)\phi^{\gamma} + (p_2-\widetilde{r}_2)A_2\left(1+\cos(\frac{a\pi}{2})\right)(1-\phi)^{\gamma})\right]\cdot z^{\beta} - w\ z,$$

where p_1 and p_2 are fish stock prices, w is the input price, and $\widetilde{r}_1$ and $\widetilde{r}_2$ are the shadow prices of the *in situ* fish stock.[5]

The necessary condition for an optimal a is given by:

$$\tilde{a} = \frac{2}{\pi}\tan^{-1}\left[\frac{A_1}{A_2}\frac{p_1-\widetilde{r}_1}{p_2-\widetilde{r}_2}\left(\frac{\phi}{1-\phi}\right)^{\gamma}\right] \tag{2}$$

Notice that when $\phi = \frac{1}{2}, A_1 = A_2$, and $p_1 = p_2$, for any value of γ, $a = \phi$.[6] When $\phi = 0$, $a = 0$, $\{u_1, u_2\} = \{0, 2A_2\}\, z^{\beta}$ when $\phi = 1$, then $a = 1$ and $\{u_1, u_2\} = \{2A_1, 0\}\, z^{\beta}$. Thus, while the feasible choice set of a is $[-1, 2]$, its optimal values are confined in the subset $[0, 1]$; essentially, $[-1, 0]$ and $[1, 2]$ are strictly dominated areas (see also Singh and Weninger, 2009). The harvest of both stocks is higher for $a \in [0, 1]$.

2.2.2 Stage I

In stage I z is chosen to maximizing *ex-ante* profits:

$$\Pi = E_{\phi}\left[(p_1 - \widetilde{r}_1)A_1\left(1+\sin(\frac{\tilde{a}\,(\phi)\,\pi}{2})\right)\phi^{\gamma} + (p_2-\widetilde{r}_2)A_2\left(1+\cos(\frac{\tilde{a}\,(\phi)\,\pi}{2})\right)(1-\phi)^{\gamma})\right]\cdot z^{\beta} - w\ z$$

where $\tilde{a}\,(\phi, p)$ solves the second stage choice of a as given by (2). The necessary condition for optimal z is:

$$\tilde{z} = \left[\beta\frac{E_{\phi}\left[(p_1 - \widetilde{r}_1)A_1\left(1+\sin(\frac{\tilde{a}(\phi)\pi}{2})\right)\phi^{\gamma} + (p_1-\widetilde{r}_1)A_2\left(1+\cos(\frac{\tilde{a}(\phi)\pi}{2})\right)(1-\phi)^{\gamma})\right]}{w}\right]^{\frac{1}{1-\beta}}, \tag{3}$$

which we see is a function of prices, technology parameters and stock conditions as reflected in the distribution of ϕ. If fishermen are identical, as we assume, the ex ante input choice is identical.

[5] To simplify the presentation we have assumed the sole owner has derived the solution to the infinite horizon planning problem under given bioeconomic conditions and thus knows the shadow prices of the individual stocks.

[6] In general, with $\alpha = 0.8$,over a large range of $\phi \in [0.2, 0.8]$, $\alpha \simeq \phi$, when $p_1 = p_2$.

2.2.3 Stage II harvests

The harvests of a fisherman realizing a stock mix ϕ are:

$$\begin{aligned} h_1(\phi) &= A_1\left(1+\sin\left(\frac{\tilde{a}(\phi)\pi}{2}\right)\right)\phi^{\gamma}\tilde{z}^{\beta}; \\ h_2(\phi) &= A_2\left(1+\cos\left(\frac{\tilde{a}(\phi)\pi}{2}\right)\right)(1-\phi)^{\gamma}\tilde{z}^{\beta}. \end{aligned}$$

The uncertainty captures that some fisherman will end up harvesting more of stock 1 and less of stock 2, while for others the reverse will be true. Notice that uncertainty over ϕ translates into uncertainty of harvests in two dimensions. Aggregate harvests are evaluated over the unit mass of fishermen:

$$\begin{aligned} h_1^* &= A_1 z^{*\beta} E_{\phi}\left\{\left(1+\sin\left(\frac{a^*(\phi)\pi}{2}\right)\right)\phi^{\gamma}\right\}; \\ h_2^* &= A_1 z^{*\beta} E_{\phi}\left\{\left(1+\sin\left(\frac{a^*(\phi)\pi}{2}\right)\right)\phi^{\gamma}\right\} \end{aligned}$$

It is easy to see that with no uncertainty, all fishermen obtain an identical realization of ϕ. Then $h_i = h_i^*$.

A few additional features of the sole owner solution are worth noting. First, if $p_i > 0$ and discarded fish do not survive, all harvested fish will be landed at port. If discarded fish die they yield no reproductive value whereas landing the fish yields the unit price p_i.

The next sections consider outcomes under decentralized management. We begin with a regulation that does not offer fishermen flexibility, $\alpha = 0$, and contrast outcomes, harvests, inputs and rents with and without a secondary quota market.

2.3 No flexibility, with post-harvest quota trades

Under this regulation, individual fisherman choose $\{q_1, q_2\}$ and z in stage I with the goal of maximizing private expected profits. The per unit price of quotas will be $\{r_1, r_2\}$. The optimization problem is solved recursively.

2.3.1 Stage II

The fishermen here enter with already purchased quotas $\{q_1, q_2\}$ and input choice of z. If they want to harvest and land more or less than their existing quota, they can enter the secondary market. It bears emphasis that without any *aggregate* uncertainty and without any transactions costs, quota prices in the secondary market will be identical to prices in the primary market (no arbitrage profits will exist in equilibrium).[7]

Now, the *ex-post* profit maximization problem is

$$\begin{aligned} \Pi(\phi) &= p_1 l_1 + r_1(q_1 - l_1) + p_2 l_2 + r_2(q_2 - l_2) \\ &= (p_1 - r_1) l_1 + (p_2 - r_2) l_2 + r_1 q_1 + r_2 q_2; \text{ s.t. } l_i \le h_i; \end{aligned}$$

[7] It can be easily shown by combining stage 1 and 2 problems.

and where h_i are given by (1). The Lagrangean for the problem is:

$$\begin{aligned}\mathcal{L} &= (p_1 - r_1)\, l_1 + (p_2 - r_2)\, l_2 \\ &\quad + \mu_1 (h_1 - l_1) + \mu_2 (h_2 - l_2) + r_1 q_1 + r_2 q_2\end{aligned}$$

The choice variables are $\{l_1, l_2\}$ and a. The necessary conditions are:

$$p_i - r_i = \mu_i;\ \mu_i \geq 0;\ \mu_i (h_i - l_i) = 0 \tag{4a}$$

$$\tilde{a} = \frac{2}{\pi} \tan^{-1}\left[\frac{\mu_1}{\mu_2}\frac{A_1}{A_2}\left(\frac{\phi}{1-\phi}\right)^{\gamma}\right] \tag{4b}$$

Thus, when stock 1 is discarded $r_1 = p_1$, and $\tilde{a} = 0$; if stock 2 is discarded $r_2 = p_2$, and $\tilde{a} = 1$. Given dockside prices $\{p_1, p_2\}$ and quota prices $\{r_1, r_2\}$ the optimal harvest responses are completely determined by their idiosyncratic realization of ϕ in the second stage.

2.3.2 Stage I

In stage I fishermen can foresee the stage II optimal response to all possible realizations of ϕ. Those responses determine their harvests, landings and revenues. In particular, given the dockside prices (exogenous) and quota prices (endogenously determined in the equilibrium but fixed at the time a is chosen), they can also see what point in the feasible set will be chosen. For example if the stock i quota price is equal to the dockside price, stock i will be discarded yielding an outcome at the *corner* of the harvest set $H(z, \phi)$. For interior cases, landings will depend on the realization of ϕ. State contingent landings revenues for all (z, ϕ) are known and the stage I problem is thus to maximize *expected* profits by choosing optimal z and $\{q_1, q_2\}$. In a quota market equilibrium, $\{q_1, q_2\}$ will be equal the quotas set by the manager and thus we solve for the equilibrium quota (rental) prices. In turn, these quota prices indicate whether stage II choices are at corners or in the interior of $H(z, \phi)$. In other words, ϕ-contingent stage II behavior must be consistent with quota prices determined in stage I as well as the priced that prevail (by arbitrage) in stage II.

We next solve for the optimal choices under all possible outcomes that can arise in stage II.

- No quotas bind, i.e. $r_i = 0$ for both i;

  This case has already been discussed in Section 2.2 above.

- Both quota bind but neither is in the discard region, i.e., $p_i > r_i > 0$ for both i

Recall that when quota of stock i binds $r_i > 0$; if it does not $r_i = 0$. First note that in a no-discard equilibrium

$$q_1 = z^{\beta} A_1 E_{\phi}\left\{\phi^{\gamma}\left[1 + \sin\left[\tan^{-1}\left[\frac{p_1 - r_1}{p_2 - r_2}\frac{A_1}{A_2}\left(\frac{\phi}{1-\phi}\right)^{\gamma}\right]\right]\right]\right\}; \tag{4ea}$$

$$q_2 = z^{\beta} A_2 E_{\phi}\left\{(1-\phi)^{\gamma}\left[1 + \cos\left[\tan^{-1}\left[\frac{p_1 - r_1}{p_2 - r_2}\frac{A_1}{A_2}\left(\frac{\phi}{1-\phi}\right)^{\gamma}\right]\right]\right]\right\}, \tag{4eb}$$

where $\tilde{a}$ has been substituted from (4a) and (4b). An optimal choice of z is obtained by maximizing:

$$\Pi = \underbrace{E_{\phi}\left[\begin{array}{c}(p_1 - r_1)\, A_1 \left(1 + \sin\left[\tan^{-1}\left[\frac{p_1 - r_1}{p_2 - r_2}\frac{A_1}{A_2}\left(\frac{\phi}{1-\phi}\right)^{\gamma}\right]\right]\right)\phi^{\gamma} \\ + (p_2 - r_2)\, A_2 \left(1 + \cos\left[\tan^{-1}\left[\frac{p_1 - r_1}{p_2 - r_2}\frac{A_1}{A_2}\left(\frac{\phi}{1-\phi}\right)^{\gamma}\right]\right]\right)(1-\phi)^{\gamma})\end{array}\right]\cdot z^{\beta}}_{E_{\phi}[(p_1 - r_1) q_1 + (p_2 - r_2) q_2]} - w\ z$$

which readily obtains:

$$wz = \beta\left(\left(p_1 - r_1\right)q_1 + \left(p_2 - r_2\right)q_2\right) \tag{4f}$$

Equation (4f) simply states that the share of revenues allocated to input cost is β as expected from the production technology. Thus (4ea) - (4f) obtain the three unknowns r_1, r_2, and z; the rest are either parameters or policy variables.

Quota i binds, no quotas in discard region, $p_i > r_i > 0$; $r_j = 0$
The equilibrium is identical as in (b) except that $r_i = 0$ for the stocks for which the quota does not bind.

Both quotas bind, one stock's quota is in discard region, e.g., $p_i > r_i > 0; r_j = p_j$
Let q_1 be in the discard region. (By symmetry, a similar equilibrium will hold if stock 2 is instead in the discard region.) Then, the set of equations that define the equilibrium z and r_2 are

$$\begin{aligned} q_2 &= z^{\beta} A_2 E_{\phi}\left\{2\left(1-\phi\right)^{\gamma}\right\}, && \text{(4ga)} \\ wz &= \beta\left(p_2 - r_2\right)q_2 && \text{(4gb)} \end{aligned}$$

An example: Let ϕ be uniform on $[\phi_{\min}, \phi_{\max}]$. Then, using (4ga), one gets

$$\begin{aligned} z &= \left[\frac{q_2\left(\alpha+1\right)}{2A_2}\frac{\phi_{\max} - \phi_{\min}}{\left(1-\phi_{\min}\right)^{\gamma+1} - \left(1-\phi_{\max}\right)^{\gamma+1}}\right]^{\frac{1}{\beta}} \\ r_2 &= p_2 - \frac{wz}{\beta q_2} \end{aligned}$$

On the other hand for the discard of stock 1 to be positive

$$\begin{aligned} d_1 &= \underbrace{z^{\beta} A_1 \int \phi^{\gamma} f\left(\phi\right) d\phi}_{h_1} - q_1 \\ &= \frac{q_2}{2}\frac{A_1}{A_2}\frac{\phi_{\max}^{\gamma+1} - \phi_{\min}^{\gamma+1}}{\left(1-\phi_{\min}\right)^{\gamma+1} - \left(1-\phi_{\max}\right)^{\gamma+1}} - q_1 > 0 \end{aligned}$$

Thus, discard of stock 1 occurs when

$$\frac{q_1}{q_2} < \frac{1}{2}\frac{A_1}{A_2}\frac{\phi_{\max}^{\gamma+1} - \phi_{\min}^{\gamma+1}}{\left(1-\phi_{\min}\right)^{\gamma+1} - \left(1-\phi_{\max}\right)^{\gamma+1}}$$

For a uniform distribution with $E\left(\phi\right) = \frac{1}{2}$ and $A_1 = A_2$; the above reduces to

$$\frac{q_1}{q_2} < \frac{1}{2}$$

One quota is slack and the other is in the discard region, for example, $r_i = 0$ and $r_j = p_j$.
Is the same as above, but with $r_2 = 0$.

2.4 No flexibility, no post-harvest trades

We next assume that fishermen head out to the sea with $\{q_1, q_2\}$ as landing constraints, and no further quota trade occurs.

2.4.1 Stage II

Now, the *ex-post* profit maximization problem is:

$$\begin{aligned}\Pi &= p_1 l_1 + p_2 l_2; \text{ s.t. } l_i \leq q_i \text{ and } l_i \leq h_i; \\ \text{if } l_i &< h_i, \text{ then } l_i = q_i; \text{ if } l_i < q_i, \text{ then } l_i = h_i\end{aligned}$$

Notice that here we allow landing to be less than the quota since a fisherman might enter with a quota that ex-post is not feasible with his realized $H(z, \phi)$; i.e., quotas exceed feasible harvests. The Lagrangean for the above problem is:

$$\begin{aligned}\mathcal{L} &= p_1 l_1 + p_2 l_2 + \lambda_1 (q_1 - l_1) + \lambda_2 (q_2 - l_2) \\ &\quad + \mu_1 (h_1 - l_1) + \mu_2 (h_2 - l_2)\end{aligned}$$

The necessary conditions for optimal l_is are:

$$\begin{aligned}p_i &= \lambda_i + \mu_i; \ \lambda_i \geq 0, \ \mu_i \geq 0, \ \mu_i (h_i - l_i) = 0; \\ \lambda_i \mu_i &= 0\end{aligned}$$

While $\lambda_i > 0$ implies that i's landing is constrained by its quota, $\mu_i > 0$ means that l_i is constrained by technology; $\mu_i = 0$ implies that stock i fish is discarded. As the fisherman can choose any point in $H(z, \phi)$, there may lie a continuum of points that allow full utilization of the available quota but yield different levels of discards. We will assume the fisherman chooses the harvest combination that minimizes fish wastage in terms of its monetary value. Since the fisherman is already utilizing his quota, this appears to be a reasonable assumption to make.

When no discard takes place, i.e., $\mu_i = p_i$ for both i, then harvests are determined by:

$$\tilde{a} = \frac{2}{\pi} \tan^{-1} \left[\frac{\mu_1}{\mu_2} \frac{A_1}{A_2} \left(\frac{\phi}{1 - \phi} \right)^{\gamma} \right]$$

If any $\mu_i = 0$, on the other hand, stock i is under a (possibly continuum of) discard options. Here, following the assumption discussed above, given $q = \{q_1, q_2\}$, z, and the realized ϕ, we choose a that governs the harvest vector such that:

$$\tilde{a} (q_1, q_2, z, \phi) = \arg\min_{a} \{p_1 (h_1 - q_1) + p_2 (h_2 - q_2) : h_i (a, z, \phi) \geq q_i, i = 1, 2\} \tag{8}$$

where $h_i (a, z, \phi) \in H(z, \phi)$. There are two main cases to consider

$\{q_1, q_2\}$ lies in the interior of $H(z, \phi)$ Clearly, there are a continuum of points where $\{h_1, h_2\} \geq \{q_1, q_2\}$. The choice here is completely governed by (8).

$\{q_1, q_2\}$ lies outside $H(z, \phi)$ There are many sub-cases to consider here. First define

$$\left\{ \begin{array}{c} \tilde{h}_{i\min} = \min\{h_i \in H(z, \phi)\} \\ \tilde{h}_{i\max} = \max\{h_i \in H(z, \phi)\} \end{array} \right\}$$

as the stock i's minimum and maximum harvests in the set $H(z, \phi)$. Then:

- $q_1 < \tilde{h}_{1\min}$, $q_2 < \tilde{h}_{2\max}$

  Here, the optimal choice of $a < 0$ is such that

$$h_2 = q_2$$

  The case $q_2 < \tilde{h}_{2\min}$, $q_1 < \tilde{h}_{1\max}$ is symmetric.

- $q_1 < \tilde{h}_{1\min}$, $q_2 > \tilde{h}_{2\max}$

$$a = 0$$

  Symmetrically, for $q_1 > \tilde{h}_{1\max}, q_2 < \tilde{h}_{2\min}$

$$a = 1$$

- $\tilde{h}_{1\max} > q_1 > \tilde{h}_{1\min}$

$$a = \arg \max_{a \in [0,\hat{a}]} \{p_1 h_1 + p_2 h_2 : h_1(\hat{a}) = q_1\}$$

Symmetrically, for $\tilde{h}_{2\max} > q_2 > \tilde{h}_{2\min}$

$$a = \arg \max_{a \in [\hat{a},1]} \{p_1 h_1 + p_2 h_2 : h_2(\hat{a}) = q_2\}$$

- $q_1 > \tilde{h}_{\max}, q_2 > \tilde{h}_{2\max}$

$$a = \frac{2}{\pi} \tan^{-1} \left[\frac{p_1}{p_2} \frac{A_1}{A_2} \left(\frac{\phi}{1-\phi} \right)^{\gamma} \right]$$

2.4.2 Stage I

The analysis above determines the optimal $\tilde{a}(q_1, q_2, z, \phi)$ for all z, $\{q_1, q_2\}$, for any realization of ϕ. Thus, the choice of z, q_1, q_2 will be determined by

$$\max_{\{z,q_1,q_2\}} \left[E_\phi \left\{ \begin{array}{c} p_1 \underbrace{\min \left\{ A_1 \left(1 + \sin \left[\tilde{a}(q_1,q_2,z,\phi) \frac{\pi}{2} \right] \right) \phi^\gamma, q_1 \right\}}_{l_1(q_1,q_2,z,\phi)} + \\ p_2 \underbrace{\min \left\{ A_2 \left(1 + \cos \left[\tilde{a}(q_1,q_2,z,\phi) \frac{\pi}{2} \right] \right) (1-\phi)^\gamma, q_2 \right\}}_{l_2(q_1,q_2,z,\phi)} \end{array} \right\} z^\beta \atop -wz - r_1 q_1 - r_2 q_2 \right]$$

Notice that stage II optimal behavior as characterized by $\tilde{a}(q_1, q_2, z, \phi)$ does not depend on quota prices since no quota trade occurs in stage II. Since $\{q_1, q_2\}$ is determined exogenously by the regulator, the above expression determines the equilibrium quota prices.

2.5 Limited flexibility

We now consider a stock-specific quota regime that allows a fraction α of stock i quota to be used to land stock j fish and vice versa. As before, we contrast outcomes with pre harvest quota trade only, and the case of secondary quota trading period in stage II. Quota flexibility further complicates the choice problem for the fisherman, as well as the equilibrium price determination in the quota market(s). To build intuition, we first consider outcomes with no uncertainty. Harvest uncertainty is reintroduced below.

2.5.1 No uncertainty

The no uncertainty case is analogous to fixing ϕ. Here, all choice variables, (z, a, q_1, q_2) plus the amount if any of the available quota i used to land stock j fish, can be made in stage I . The fisherman's profits are

$$\begin{aligned} \Pi &= p_1 l_1 + p_2 l_2 - r_1 q_1 - r_2 q_2 - wz; \text{ s.t. } l_i \leq h_i; \\ l_1 &\leq q_1 + \alpha q_2; \; l_2 \leq q_2 + \alpha q_1; \; l_1 + l_2 \leq q_1 + q_2 \end{aligned}$$

The Lagrangian for the problem is:

$$\begin{aligned} \mathcal{L} &= p_1 l_1 + p_2 l_2 - r_1 q_1 - r_2 q_2 + \lambda \left(q_1 + q_2 - l_1 - l_2\right) \\ &\quad \omega_1 \left(q_1 + \alpha q_2 - l_1\right) + \omega_2 \left(q_2 + \alpha q_1 - l_2\right) \\ &\quad + \mu_1 \left(h_1 - l_1\right) + \mu_2 \left(h_2 - l_2\right) - wz \end{aligned}$$

Necessary conditions for optimal q_i, l_i and h_i include:

$$\begin{aligned} r_1 &= \lambda + \omega_1 + \alpha \omega_2; \\ r_2 &= \lambda + \omega_2 + \alpha \omega_1; \\ r_1 - r_2 &= (1-\alpha)\left(\omega_1 - \omega_2\right) = 0 \text{ if } \alpha = 1 \\ \lambda &\geq 0; \lambda \left(q_1 + q_2 - l_1 - l_2\right) = 0 \\ p_i - \lambda - \omega_i - \mu_i &\leq 0; \; l_i(p_i - \lambda - \omega_i - \mu_i) = 0 \\ \mu_i &\geq 0; \; \mu_i \left(h_i - l_i\right) = 0; \\ \omega_1 \left(q_1 + \alpha q_2 - l_1\right) &= 0; \omega_2 \left(q_2 + \alpha q_1 - l_2\right) = 0; \omega_i \geq 0 \end{aligned}$$

Clearly, if none of the landing constraints bind (individually), i.e., $\{l_1, l_2\}$ is in the interior of the range of quotas allowed, $r_1 = r_2 = r = \lambda$. Also, either ω_1 or ω_2 is zero; i.e., one of the individual quota constraints is slack given the aggregate constraint. If constraint for stock i binds then $r_i = r_j + (1-\alpha)\, \omega_i > r_j$, for $i = 1, 2, i \neq j$. If neither individual constraint binds, and neither does the aggregate, i.e., $\lambda = 0$, then $r_1 = r_2 = 0$. If the aggregate does not bind, i.e., $l_i + l_j < q_i + q_j$, but that of stock i binds, we have $r_i = \omega_i$, and $r_j = \alpha \omega_i$.

Further implications of the necessary conditions can be summarized as follows:

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

- Neither individual constraint binds, $\omega_1 = \omega_2 = 0$, $r_1 = r_2 = r$:

$$\tilde{a}(\phi) = \begin{cases} = \frac{2}{\pi} \tan^{-1} \left[\frac{p_1 - r}{p_2 - r} \frac{A_1}{A_2} \left(\frac{\phi}{1-\phi} \right)^{\gamma} \right] \text{ if } r < p_1 \text{ and } p_2 \\ = 0, \text{ if } r \geq p_1 \text{ and } r < p_2 \\ = 1, \text{ if } r \geq p_2 \text{ and } r < p_1 \end{cases}$$

  Accordingly for the above three cases:

$$\begin{aligned} wz &= \beta \left(p_1 - r\right) h_1 + \beta \left(p_2 - r\right) h_2; h_1 + h_2 = q \equiv q_1 + q_2; \\ wz &= \beta \left(p_2 - r\right) h_2; h_2 = l_2 = \tilde{h}_{2\,\max}; h_1 = \tilde{h}_{1\,\min}; l_1 = q - \tilde{h}_{2\,\max} \\ wz &= \beta \left(p_1 - r\right) h_1; h_1 = l_1 = \tilde{h}_{1\,\max}; h_2 = \tilde{h}_{2\,\min}; l_2 = q - \tilde{h}_{1\,\max} \end{aligned}$$

- Stock 1 individual constraint binds, $\omega_1 > 0; \omega_2 = 0$, $r_1 = r_2 + (1-\alpha)\omega_1$:

$$l_1 = q_1 + \alpha q_2; l_2 = (1-\alpha) q_2$$

  Also,

$$\tilde{a}(\phi) = \begin{cases} = \frac{2}{\pi}\tan^{-1}\left[\frac{p_1 - r_1}{p_2 - r_2}\frac{A_1}{A_2}\left(\frac{\phi}{1-\phi}\right)^{\gamma}\right] \text{ if } r_1 < p_1 \text{ and } r_2 < p_2 \\ = 0, \text{ if } r_1 \geq p_1 \text{ and } r_2 < p_2 \\ = 1, \text{ if } r_2 \geq p_2 \text{ and } r_1 < p_1 \end{cases}$$

  Accordingly, for the above three cases:

$$\begin{aligned} wz &= \beta(p_1 - r_1) h_1 + \beta(p_2 - r_2) h_2;\ h_1 = l_1; h_2 = l_2; \\ wz &= \beta(p_2 - r_2)\tilde{h}_{2\max}; \tilde{h}_{2\max} = l_2;\ h_1 = \tilde{h}_{1\min}; \\ wz &= \beta(p_1 - r_1)\tilde{h}_{1\max}; \tilde{h}_{1\max} = l_1;\ h_2 = \tilde{h}_{2\min}; \end{aligned}$$

  In the first case, there are four equations in four unknowns, a, z, r_1, and r_2. In the second and third case a is either 0 or 1, z is determined from either $\tilde{h}_{2\max} = l_2$ or $\tilde{h}_{1\max} = l_1$, and r_1 or r_2 is determined from the input choice necessary condition.

- The case where the stock 2 individual constraint binds, $\omega_1 = 0; \omega_2 > 0$ is symmetric.

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

- If none of the individual constraints bind, $r_1 = r_2 = 0$, the conditions simplify as follows:

- $\omega_1 > 0$, $\omega_2 = 0$, then $r_2 = \alpha r_1$. Here, $l_1 = q_1 + \alpha q_2$

$$\tilde{a}(\phi) = \begin{cases} = \frac{2}{\pi}\tan^{-1}\left[\frac{p_1 - r_1}{p_2 - \alpha r_1}\frac{A_1}{A_2}\left(\frac{\phi}{1-\phi}\right)^{\gamma}\right] \text{ if } r_1 < p_1 \text{ and } \alpha r_1 < p_2 \\ = 0, \text{ if } r_1 \geq p_1 \text{ and } \alpha r_1 < p_2 \\ = 1, \text{ if } \alpha r_1 \geq p_2 \text{ and } r_1 < p_1 \end{cases}$$

  Accordingly, for the above three cases:

$$\begin{aligned} wz &= \beta(p_1 - r_1) h_1 + \beta(p_2 - \alpha r_1) h_2; h_1 = l_1; \\ wz &= \beta(p_2 - \alpha r_1)\tilde{h}_{2\max}; h_1 = \tilde{h}_{1\min}; \\ wz &= \beta(p_1 - r_1)\tilde{h}_{1\max}; h_2 = \tilde{h}_{2\min}; \end{aligned}$$

  In the first case there are three equations in three unknowns: z, r_1, and a. In second and third, we have two equations in two unknowns, r_1 and z.

2.6 Flexibility with post harvest quota trade

We now re-introduce uncertainty to the model. In stage II $\{q_1, q_2\}$ is fixed, however under flexibility, the *effective* quota, and thus the effective landings constraint is defined by the pair $\{\hat{q}_1, \hat{q}_2\}$. Again, we solve the decision problem beginning with stage II.

Stage II The profit maximization problem is:

$$\begin{aligned} \Pi &= p_1 l_1 + p_2 l_2 - r_1 (\hat{q}_1 - q_1) - r_2 (\hat{q}_2 - q_2) \text{; s.t. } l_i \leq h_i; \\ l_1 &\leq \hat{q}_1 + \alpha \hat{q}_2;\ l_2 \leq \hat{q}_2 + \alpha \hat{q}_1;\ l_1 + l_2 \leq \hat{q}_1 + \hat{q}_2 \end{aligned}$$

Since q_1 and q_2 are at this point are given (as are the equilibrium prices r_1 and r_2), they do not affect the choice problem:

$$\begin{aligned} \mathcal{L} &= p_1 l_1 + p_2 l_2 - r_1 \hat{q}_1 - r_2 \hat{q}_2 + \lambda (\hat{q}_1 + \hat{q}_2 - l_1 - l_2) \\ &\quad \omega_1 (\hat{q}_1 + \alpha \hat{q}_2 - l_1) + \omega_2 (\hat{q}_2 + \alpha \hat{q}_1 - l_2) \\ &\quad + \mu_1 (h_1 - l_1) + \mu_2 (h_2 - l_2) + r_1 q_1 + r_2 q_2 \end{aligned}$$

The necessary conditions for optimal choice of $\hat{q}_i$, l_i and h_i are identical to those of the certainty case and are not repeated. The only difference is that at stage II, z is given. Fishermen enter with the same z and $\{q_1, q_2\}$ and, depending on the realization of ϕ, trade quotas and choose a point in the feasible harvest set $H(z, \phi)$ to maximize landings revenue.

2.7 Flexibility, no post harvest trading

The profit maximization problem is:

$$\begin{aligned} \Pi &= p_1 l_1 + p_2 l_2 \text{; s.t. } l_i \leq h_i; \\ l_1 &\leq \hat{q}_1 + \alpha \hat{q}_2;\ l_2 \leq \hat{q}_2 + \alpha \hat{q}_1;\ l_1 + l_2 \leq \hat{q}_1 + \hat{q}_2 \end{aligned}$$

To save space the optimization analysis is not repeated (necessary conditions are available from the authors). The next section presents numerical results for the model outcomes under the various regulations.

3 Numerical Results

Symmetric prices, asymmetric quotas

The results in rows 1-3 of Table 1 report equilibrium harvests, landings, and discards as a percentage of quotas, quota prices, the factor input allocated to fishing operations, and the profit earned. The results are reported for the four regulation combinations studied above, and for three price and quota scenarios. Hereafter we abbreviate the regulations as follows: no flexibility, no post-harvest trade (NF-NT); no flexibility, with post harvest trade (NF-T); flexibility, no post-harvest trade (F-NT), and flexibility, with post harvest trade (F-T). The parameter space for our model is large and the numerical results that follow are clearly not exhaustive. The results we present are intended to be representative of conditions that may be encountered in quota-managed fisheries.

All results in Table 1 assume ϕ is uniformly distributed on the interval [0.3, 0.7] with mean value 0.5; the composition of fish stock is symmetric (see Figure 1). The technology parameters are set to $A_1 = A_2 = 1$, $\gamma = 0.8$, and $\beta = 0.7$. The input price is $w = \$1$.

In the first scenario of Table 1, prices are symmetric, $p_1 = p_2 = \$1$, but quotas are set asymmetrically with stock 1 quota relatively scarce; $q_1 = .3$, and $q_2 = .6$. Results indicate that under the NF-NT regulation (row 1), the stock 2 harvest falls slightly below its quota while at the same time stock 2 fish, as well as stock 1 fish are discarded. Discards of stock 1 are 3.3% of the stock 1 quota while discards of stock 2 fish are 2.9% of its quota. Under uncertainty, some fishermen realize stock

Symmetric prices, asymmetric quotas									
	Regulation		Harvests	Landings	Discards (% of q)	Quota prices	Input	Profit
Row	Flex.	Trade	(h_1, h_2)	(l_1, l_2)	(d_1, d_2)	(r_1, r_2)	z	Π
1.	no	no	0.31, 0.59	0.30, 0.57	3.3, 2.9	0.93, 0.58	0.34	0.53
2.	no	yes	0.30, 0.60	0.30, 0.60	0 , 0	1.00, 0.53	0.40	0.50
3.	yes	no	0.33, 0.57	0.33, 0.56	2.4, 2.3	0.87, 0.62	0.33	0.56
4.	yes	yes	0.36, 0.54	0.36, 0.54	0, 0	0.78, 0.27	0.35	0.55
Asymmetric prices and quotas								
	Regulation		Harvests	Landings	Discards	Quota prices	Input	Profit
Row	Flex.	Trade	(h_1, h_2)	(l_1, l_2)	(d_1, d_2)	(r_1, r_2)	z	Π
5.	no	no	2.73, 4.46	2.00, 4.00	36.0, 12.0	0.18, 1.07	6.53	7.47
6.	no	yes	2.00, 4.00	2.00, 4.00	0 , 0	1.00, 0.86	5.98	8.02
7.	yes	no	2.12, 4.12	1.94, 4.03	9.2, 2.16	0.84, 1.76	5.23	8.80
8.	yes	yes	2.10, 4.20	1.80, 4.20	15.0, 0.0	1.00, 0.97	6.41	7.99
Symmetric prices and quotas								
	Regulation		Harvests	Landings	Discards	Quota prices	Input	Profit
Row	Flex.	Trade	(h_1, h_2)	(l_1, l_2)	(d_1, d_2)	(r_1, r_2)	z	Π
9.	no	no	0.57, 0.57	0.57, 0.57	0,0	0.27, 0.27	0.49	0.65
10.	no	yes	0.60, 0.60	0.60, 0.60	0,0	0.41, 0.41	0.49	0.71
11.	yes	no	0.59, 0.59	0.59, 0.59	0,0	0.20, 0.20	0.49	0.68
12.	yes	yes	0.60, 0.60	0.60, 0.60	0,0	0.41, 0.41	0.49	0.71

Table 1: **Numerical results.** Rows 1-4 assume $p_1 = p_2 = 1$; $q_1 = 0.3$ and $q_2 = 0.6$; rows 5-8 assume $p_1 = 1$, $p_2 = 3$, $q_1 = 2$, and $q_2 = 4$; rows 9-12 assume $p_1 = p_2 = 1$, $q_1 = q_2 = 0.6$.

conditions that do not allow them to harvest their full quota, while others discard overages. The paradoxical result of simultaneous quota under utilization and discarding of valuable fish occurs when there is no possibility to make post harvest quota trades. Existence of a post-harvest trading market remedies this problem, as shown in row 2 results, i.e., the NF-T regulation. Notice that post harvest trading also leads to full utilization of the quotas.

Flexibility leads to interesting adjustments by fishermen. With F-NT (row 3 results), fishermen use stock 2 quota to land stock 1 fish. While prices and stock conditions are symmetric, stock 1 quota is scarce. Targeting the quota mix is costly with (on average) symmetric abundance. Fishermen take advantage of the flexibility offered in the regulation and land a mix of stocks that more closely mirrors abundance.

Quota prices reflect the scarcity of the stock 1 quota. Notice, the quota price is equal to the dockside price under the NF-T regulation in row 2. The quota and targeted harvest mix is on the boundary of the discard set and thus marginal cost of harvesting a unit of stock 1 is zero; the price fishermen will pay for this quota is just equal to the dockside price (Singh and Weninger, 2009).

A larger input allocation occurs under the NF-T regulation (row 2). This is due to the stringent targeting efforts undertaken by fishermen. The harvest ratio is $h_2/h_1 = 2$ under NF-T; it is smaller under all other regulations. Targeting a mix of stocks that differs from abundance is costly. The existence of a secondary trading market helps incentivize fishermen to under take costly targeting effort. The equilibrium quota price indicates that the quota mix $q_2/q_1 = 2$ is at a boundary $(r_1 = p_1)$ in the sense that a further reduction in q_1 (or increases in q_2) would induce discarding.

In all but the NF-T regulation (see rows 1, 3 and 4 of Table 1) harvest, and therefore stock mortality, differs from the quota set by the regulator. The difference is caused by the lack of a secondary quota market and discarding, or is the consequence of allowing flexibility. It may be possible to manipulate quotas to implement a desired mortality target. It is clear however that a first best outcome will not be achieved in the absence of post-harvest trading where discards occur, since discards must be zero under a first best outcome.

Asymmetric prices and quotas
Our second scenario assumes higher and asymmetric quota prices ($p_1 = \$1$, $p_2 = \$3$) and a larger and asymmetric quota ($q_1 = 2$, $q_2 = 4$). The results are reported in rows 5-8 of Table 1. The results follow a similar pattern as above with a few exceptions. First, we see that discard percentages have increased considerably in all but the NF-T regulation (row 6). Notice that the allocation of inputs is largest under the NF-NT regulation in row 5.[8] When dockside prices are high, the allocation of factor inputs is also high. Fishermen allocate inputs to balance the losses due to missed revenue under a catch underage, with the cost of additional inputs. Discards are high with no post-harvest trade because the opportunity cost of a catch underage is high. With post harvest quota trading fishermen can sell unused quota, eliminating the cost of an underage. The result is less inputs allocated to the fishery and no discards.

The results under the FT regulation show positive discards of stock 1 fish (15% of its quota). This result is due to the sharp price differential at the dock, combined with the flexibility offered under the regulation. Notice that the fishermen use all available flexibility to land the higher price stock, i.e., $l_2 = 4.2 = q_2 + \alpha q_1$. This leave 1.8 units of quota which is used to land stock 1 fish. Harvesting at this same stock mix is costly. Fishermen can save costs by harvesting a mix that more closely mirrors the symmetric stock abundance, and discarding overages of stock 1 fish. Lastly, as required, the equilibrium quota price is equal to the dockside price when discards are positive.

Symmetric prices and quotas
Our third scenario considers a fully symmetric fishery (prices are $p_1 = p_2 = \$1$, and quotas are set to $q_1 = q_2 = 0.6$). The results are reported in rows 9-12 of Table 1. An interesting result is the lack of discarding under all forms of regulation. With symmetry fishermen choose harvests that are interior to the discard sets under all realizations of stock uncertainty. Discard can occur in the absence of a secondary quota trading market if fishermen have overages. However, for this result to occur, fishermen must be willing to allocate factor inputs sufficiently large to generate the overage. The relative prices in our third scenario do not justify the additional allocation of inputs. Rather, the profit maximizing input allocation yield landings less than the available quota in the absence of secondary quota trading. On the contrary, post-harvest quota trading leads to full utilization of the available quota.

We now examine fishing profits under the various combinations regulation and fishery conditions. Note that profits have been calculated as the sum of dockside revenue less input costs, wz. Consider the asymmetric fishery scenarios in Table 1 (results in rows 1-8). As noted above, targeting efforts tend to be most stringent in the presence of post-harvest quota trading. These efforts close the gap between harvests and quotas, and pay an additional benefit not reflected in a static measure of fishing profits. Targeting aligns harvests with quotas, but comes at a cost in terms of additional factors of production. A fishery sole owner who wishes to implement a particular stock mortality and land whatever is harvested would incur these added targeting costs. That is, the costs required to target a first best harvest goal and land the entire harvest are by definition part of the first best management policy.

Notice that the rents obtained under flexibility with trade are lower relative to the case with no

[8] The increased variance in harvesting due to increased scale of production likely contributes to, and counfoud this result. Further analysis is needed to isolate forces that determine the magnitide of discards.

flexibility in quotas (compare line 8 with 6 in Table 1). When flexibility is allowed, given the equilibrium lease prices, it is rational for fishermen to use 10% of their stock 1 quota (the profit due to this stock is zero anyway since $r_1 = p_1$) to land stock 2 fish (and gain $(3 - 0.86) * 0.2 = 0.428$) even though this requires an increase in input costs.

4 Conclusions

We have introduced a technology that captures the realistic property whereby fishermen in a multiple-stock fishery can partially control the mix of stocks harvested by gear. We examine the problem of discards caused by a mismatch between random harvests and quota holdings. Equilibrium harvesting, landings, discards and economic performance under various quota regulations designed to reduce discards were derived.

Our results show that regulations that offer flexibility to fishermen do not eliminate discards. Flexibility may create further unintended problems causing managers to loose control over aggregate harvests in a fishery. Under flexibility, harvests and discards depend on prices, the targeting technology and the relative abundance of stocks. Since prices, technologies and stock abundance can be difficult to observe, and quota flexibility can introduce added costs for managers responsible for setting sustainable harvest policies.

We find, not surprisingly, that regulations which allow frictionless quota trading after random harvests are realized, can eliminate at at-sea discards and enhance long term economic performance in a rights-based fishery.

Our results provide important guidance for improving the design of quota management programs; the most effective quota balancing mechanism may involve a standard, no-flexibility, design with no restrictions on quota trading among fishermen.

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