Uncertainty and the choice of quota program in a multi-product fishery

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Abstract

This paper considers the design of individual quota programs for fisheries where more than one market class of fish is harvested and where a manager is uncertain about the fishing technology, prices, stock levels, and compliance. In particular, the paper considers three problems that follow from a manager's uncertainty and the multi-product nature of the fishery; discarding, ex ante uncertainty, and data fouling. Since multi-product fisheries and uncertainty are the norm, the issues addressed here are fundamental to fisheries regulation. J.E.L. Classification: Q22, L51.

1 Introduction

This paper considers the design of individual quota programs for fisheries where more than one market class of fish is harvested and where a manager is uncertain about the fishing technology, prices, stock levels, and compliance.[1] Since multi-product fisheries and uncertainty are the norm, the issues addressed here are fundamental to fisheries regulation.

The literature treats many problems relevant to the design of individual quota programs.[2] This paper, however, is concerned with three problems that follow from a manager's uncertainty and from the multi-product nature of a fishery; discarding, ex ante uncertainty, and data fouling. A description of these problems follows.

Discarding: Managers typically observe quantities of fish landed and brought to market, but not actual harvests brought up on deck. Such imperfect observation makes non-compliance with a quota possible. In particular, considerable evidence shows that individual quota programs can cause fishermen to illegally discard at sea fish that they would bring to market otherwise (e.g., [3], [4]). Since mortality is high among discarded fish, discarding wastes a valuable fish stock.

Ex Ante Uncertainty: A manager facing uncertainty about technology, prices, stock levels, and compliance is uncertain about the magnitude and composition of the harvest associated with a given quota program. This uncertainty is costly if harvests close to an "optimal" harvest are desired.

Data Fouling: Harvests are the sum of observed landings and unobserved discarding. If a manager observes only landings, then uncertainty about discarding may not be resolved at the end of the season. Such corruption of a manager's information about harvests is known as "data fouling". Data fouling may induce errors in stock estimates, and hence cause errors in a manager's future behavior.

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[2] For example, optimal (subsidies) penalties for over-quota (under-quota) landings are treated in [5], optimal enforcement effort is characterized in [7], the impact of different distribution schemes is treated in [1].

There are two common types of quota in multi-product fisheries, *aggregated quota*, which regulates the total weight of all species or size classes, and *disaggregated quota*, which regulates the weight of each species or size class separately. Disaggregated quota is by far the most common choice in multi-species fisheries, although aggregated quota are also used. Single species fisheries, however, are almost always regulated by a single aggregated quota, even when the stock consists of several market (size) classes of fish. In rare cases, fishery managers use *value-based quota*, which regulates the aggregate value of landed fish (for examples and exceptions see [3]).

The choice of quota program involves both a choice of quota type and a choice of enforcement regime. The analysis considers two common enforcement regimes, simple enforcement and confiscation. (1) Under *simple enforcement* a manager observes, confiscates, and penalizes over-quota landings, but does not observe harvests. (2) Under *confiscation,* a manager observes and allows over-quota landings, provided such landings are turned over to the manager. As under simple enforcement, a manager does not observe harvests.

The paper considers the choice of quota type and enforcement regime. It first describes a simple fishery where a manager is uncertain about technology, prices, stock abundance, and compliance. It next examines a fisher's response to each type of regulation. Finally, the paper compares the maximal expected welfare attainable with each different quota program.

2 Model

Discarding, ex ante uncertainty, and data fouling are important factors in a manager's choice of quota and enforcement. This section develops a model with which to analyze these problems. The model considers a short period of time during which regulation is "fixed", say a fishing season, and each variable defined below is an aggregate value for this short time period. For example, harvests are the total harvests over the whole period, and a quota regulates the total landings from all trips taken during the time period.

The analysis begins after a manager has allocated quotas, whether this allocation takes place by fiat, lottery, or quota market. Hence, without loss of generality, the model considers the behavior of a single representative fisher.

Fishing technology: The stock consists of two types of fish. A harvest is a pair $\mathbf{h} = (h_1, h_2) \geq 0$, where h_i is the harvested weight of Type i. To concentrate on harvest choice, make the simplifying assumption that "effort" is the only input into the production technology. Denote effort by x, and suppose that it is procured at constant marginal cost c. Given the short time horizon under consideration, stock levels are assumed fixed and omitted from the model.

Considerable evidence shows that fishers control the proportions of different types of fish in their harvests, although the extent of this control is often limited.[3] The following specification of the fishing technology is among the simplest that allows imperfect control of harvest composition and decreasing returns to effort.[4]

Let $\theta_1 \in [0,1]$ be the proportion of Type 1 fish in a harvest, and $\theta_2 = 1 - \theta_1$ the proportion of Type 2. θ denotes a pair $[\theta_1, \theta_2]$. Allow a fisher to choose θ_1 from an interval whose upper and lower limits depend on ε, the relative abundance or catchability of the two types, and on δ, a fisher's ability to selectively harvest one type or the other. Let $\delta \in [0,1]$ and $\varepsilon \in [\underline{\varepsilon}, \overline{\varepsilon}] \subseteq [-\delta, 1+\delta]$. Fishers choose θ_1 from $[\underline{\theta}, \overline{\theta}] = [\varepsilon - \delta, \varepsilon + \delta] \cap [0,1]$. If $\delta = 0$ a fisher has no control over harvest composition. As δ increases so does a fisher's ability to control harvest composition. An increase in ε indicates an increase in the relative abundance or catchability of Type 1.

Let the total weight of the harvest, $F(x, \mathbf{A})$, be quadratic in effort, so that $F(x, \mathbf{A}) = A_0 x + \frac{A_1}{2} x^2$, where $\mathbf{A} = (A_0, A_1)$ reflects the influence of factors like overall species abundance and weather on the productivity of effort. All together, harvests are given by $\begin{bmatrix} h_1 \\ h_2 \end{bmatrix} = \begin{bmatrix} \theta_1 \left(A_0 x + \frac{A_1}{2} x^2\right) \\ \theta_2 \left(A_0 x + \frac{A_1}{2} x^2\right) \end{bmatrix}$, or in vector notation, $\mathbf{h} = \theta F(x, \mathbf{A}$. Since the model considers a period of time which is longer than a single trip, hold constraints and shipboard processing costs are implicit in the production function.

Fishers may discard fish at sea. Denote discards by $\mathbf{d} = (d_1, d_2) \geq 0$. Landings $\mathbf{y} = (y_1, y_2)$ are harvests net of discards: $\mathbf{y} = \mathbf{h} - \mathbf{d} \geq 0$. Demand for landings is exogenous and perfectly elastic, with $\mathbf{p} = (p_1, p_2) > 0$. If there is no discarding $\mathbf{y} = \mathbf{h}$, and $\mathbf{y}$ may refer to harvests. Note that some discarding may occur for technological reasons, e.g., ex-vessel price does not cover handling costs or the hold is full. To abstract from problems of technologically-induced discarding both shipboard processing and discarding are assumed costless, and we regard $\mathbf{h}$ as the harvest net of technologically-induced discarding.

Quotas and enforcement: Q denotes the set of legal landings associated with a given individual quota. The analysis considers three classes of quota:

[3] [2] p16, [3], [4], [6], [11].

[4] Standard multi-product technologies and their associated dual representations assume complete control over harvest composition, while Leontief, or fixed-proportions technologies, assume no control. Hence the need for a non-standard specification of the harvest technology.

1. *Aggregated quota* allows a fisher to land up to W pounds of fish regardless of type. The associated quota set is $Q = \{\mathbf{y} \geq 0 | y_1 + y_2 \leq W\}$.

2. *Disaggregated quota* allows a fisher to land q_1 units of Type 1 and q_2 units of Type 2. The quota set for disaggregated quota is $Q = \{\mathbf{y} \geq 0 | \mathbf{y} \leq \mathbf{q}\}$, where $\mathbf{q} = (q_1, q_2) > 0$ are the maximum legal landing weights for each type.

3. *Value-based quota* allows a fisher to land fish whose value is less than or equal to the value of a pair (q_1, q_2). The corresponding quota set is $Q = \{\mathbf{y} \geq 0 | \mathbf{py} \leq \mathbf{pq}\}$.[5]

These quota sets are stylized descriptions of observed regulation. Generalizing to allow for more complicated quota sets, e.g., quota sets that require a minimum proportion of one type, is a subject for further research.

A manager must also choose an enforcement regime. Such a regime involves a penalty for over-quota landings and possibly a bonus or penalty for failure to fill a quota. This analysis considers two common enforcement regimes, simple enforcement and confiscation.[6]

1. *Simple enforcement* subjects all over-quota landings to a certain penalty which is strictly larger than the value of the over-quota fish, but there is no benefit or penalty for landings below a quota. This is a stylization of cases where a manager observes, confiscates, and penalizes over-quota landings, but does not observe harvests.

2. *Confiscation* subjects all over-quota landings to a certain penalty which is exactly equal to the value of the over-quota fish, but there is no benefit or penalty for landings below a quota. This is a stylization of cases where a manager observes and confiscates over-quota landings, but does not observe harvests.

To avoid a discussion of optimal enforcement effort assume that a manager perfectly observes landings.

The enforcement regimes above are selected because they are commonly observed. The nature of an optimal enforcement regime is treated in [5]and [12]. Characterizing

[5] A simpler way to administer value-based quota is to specify the total dollar value of landings. The present specification is superior in that it is invariant to changes in the price level.

[6] A third enforcement regime, where a manager employs shipboard observers to monitor and assess a penalty for over-quota *harvests* is also common. Since observer programs require an observer on board each boat, they affect the marginal cost of fishing effort. This makes an analysis of observer programs more complicated than an analysis of simple enforcement or confiscation.

such optimal enforcement regimes for a multi-product fishery remains a topic for future research.

3 Fisher's Problem

A fisher takes prices as given and maximizes short run profit by choice of effort, discarding, and proportion. Under simple enforcement a fisher chooses effort, discarding and proportion of Type 1 to solve:

$$\max_{x,\mathbf{d},\theta} \quad \Pi = \mathbf{p}\left(\theta F(x,\mathbf{A}) - \mathbf{d}\right) - cx \tag{1}$$

$$\text{s.t. } \theta F(x,\mathbf{A}) - \mathbf{d} \in Q, \tag{2}$$

$$\theta_1 \in \left[\underline{\theta}, \overline{\theta}\right] \tag{3}$$

$$\theta_1 + \theta_2 = 1 \tag{4}$$

$$x, \mathbf{d} \geq 0. \tag{5}$$

Let $x(\varepsilon,\mathbf{A},\mathbf{p},Q)$, $\mathbf{d}(\varepsilon,\mathbf{A},\mathbf{p},Q)$, and $\theta_1(\varepsilon,\mathbf{A},\mathbf{p},Q)$ denote profit maximizing choices of effort, discarding, and proportion of Type 1, for given relative catchability, technology, prices, and regulation.

Since the response functions, $x(\varepsilon,\mathbf{A},\mathbf{p},Q)$, $\mathbf{d}(\varepsilon,\mathbf{A},\mathbf{p},Q)$, and $\theta_1(\varepsilon,\mathbf{A},\mathbf{p},Q)$, describe season aggregates they must be interpreted carefully. On any trip, save the last of the season, a fisher chooses effort, composition and discarding on the basis of expectations about whether a quota will bind. Hence, discarding and other responses to a quota are imagined to occur continuously throughout a season, not all in a lump at the end.

The statement of a fisher's problem, 1-5, supposes that a manager relies on simple enforcement. If a manager instead confiscates over-quota landings, a fisher's problem is still given by 1-5. However, a fisher's decision about whether to discard or land and forfeit over-quota harvests depends on relative costs of shipboard processing and discarding. It follows that a switch to confiscation cannot increase discarding, though it need not decrease it. In this model, where shipboard processing is not described, a fisher is indifferent between discarding over-quota fish and delivering it to a manager, so the fraction of over-quota fish discarded is determined exogenously. If we reinterpret $\mathbf{d}$ as the sum of discarding and confiscated landings of over-quota fish, then no other changes in the statement of a fisher's problem are needed to accommodate the switch from simple enforcement to confiscation.

3.1 Solving the fisher's problem

This section describes a fisher's response to different regulatory programs. In particular, the section examines the propensity of different quota programs to cause discarding and ex ante uncertainty. Data fouling will be discussed later.

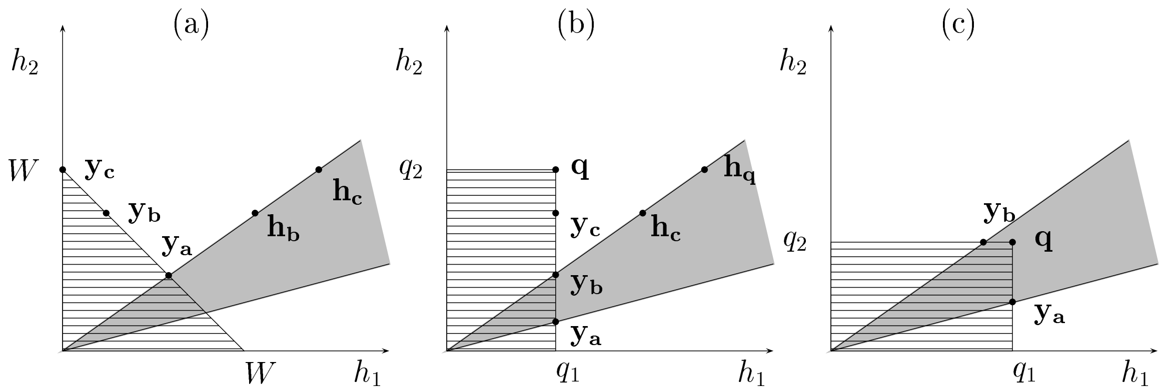

Figure 1: A fisher's problem under three different quotas. In each panel the shaded cone is the technologically feasible set and the hatched area is the quota set. Figure 1a illustrates an aggregated quota. Figures 1b and 1c illustrate disaggregated quota.

Value-based quota: With value-based quota a manager chooses quantities $(q_1, q_2) = \mathbf{q}$ of Types one and two, and allows a fisher to land any bundle of equal or lesser value. A fisher's problem is given by 1-5, with $Q = \{\mathbf{y} \geq 0 | \mathbf{py} \leq \mathbf{pq}\}$ in 2. Solving this problem with conventional techniques establishes the following qualitative features of a fisher's behavior.

If prices are low relative to costs the quota is non-binding and effort and landings are increasing in prices. A fisher chooses the maximum or minimum value of θ_1 according to whether p_2 is greater or less than p_1.

As prices rise the quota eventually binds. When this happens, further harvesting requires that a fisher discard one dollar of fish for every additional dollar landed. Therefore after a value-based quota binds the supply of effort ceases to respond to changes in prices and no fish are discarded. As is the case when a quota does not bind, a fisher chooses the maximum or minimum value of θ_1 according to whether p_2 is greater or less than p_1.

Discarding is not a problem with value-based quota, however ex ante uncertainty is a problem. With value-based quota the harvest of each type depends on uncertain prices and technology, along with the choice of (q_1, q_2). Therefore, while a manager using value-based quota exerts some control over harvests, this control is imperfect. In particular, a fisher's choice of composition, θ_1, depends on prices and on the limits of his control over composition, $\underline{\theta}$ and $\overline{\theta}$, but does not depend on (q_1, q_2). Hence a manager using value-based quota cannot influence harvest composition.

Since a fisher never harvests over-quota fish, changing between simple enforcement and confiscation enforcement regime does not affect a fisher's behavior: Such a change affects only the fate of over-quota fish.

Aggregated quota: With aggregated quota and simple enforcement, a manager chooses a weight W and allows a fisher to land any bundle of equal or lesser weight. A fisher's problem is given by 1-5, with $Q = \{\mathbf{y} \geq 0 | y_1 + y_2 \leq W\}$ in 2. This profit maximization problem may be solved with conventional techniques.

Figure 1a illustrates a fisher's problem with aggregated quota. Axes indicate quantities of Types 1 and 2. The boundary of the quota set is a line of slope -1 intersecting each axis at W. Technologically feasible harvests are indicated by the shaded region that is bounded above by a ray from the origin with slope $(1 - \underline{\theta}_1) / \underline{\theta}_1$, and bounded below by a ray from the origin with slope $\left(1 - \overline{\theta}_1\right) / \overline{\theta}_1$. The discussion below supposes $p_2 > p_1$ and simple enforcement unless noted otherwise.

If prices are low relative to costs then a quota is not binding and effort and landings are increasing in prices. Given $p_2 > p_1$ a fisher chooses the minimum value of θ_1 and concentrates on Type 2.

As prices rise a quota eventually binds. With $p_2 > p_1$ this occurs at landings $\mathbf{y}_a$ in figure 1a. After the quota binds, the marginal return to effort drops discretely from $(p_2\theta_2 + p_1\theta_1) F_x$ to $(p_2 - p_1) \theta_2 F_x$. That is, after a quota binds, further harvesting requires the discarding of a unit of Type 1 for each additional unit of Type 2 harvested. Until the price of Type 2 rises sufficiently to make such discarding profitable, there is no discarding and effort does not respond to marginal changes in price.

After the price of Type 2 rises enough to make discarding profitable, the net revenue from an additional pound of Type 2 harvested is $p_2 - p_1$ and the marginal product of effort is $\theta_2 (p_2 - p_1) F_x$. In this case effort and discarding are increasing in p_2 and decreasing in p_1. In figure 1a this occurs, for example, when a fisher harvests $\mathbf{h}_b$ and lands $\mathbf{y}_b$.

If p_2 rises high enough a fisher discards Type 1 until his landings are solely Type 2. In figure 1a, this means that a fisher's profit maximizing harvest and landings are $\mathbf{h}_c$ and $\mathbf{y}_c$. When this happens effort and discarding no longer respond to marginal changes in price.

We can now describe the incidence of discarding and ex ante uncertainty under aggregated quota. Conditional on a quota that binds at $\mathbf{p}$ with $p_i > p_j$, discarding occurs if $(p_i - p_j)\,\theta_i F_x > c$. Since discarding only occurs after the quota binds, the magnitude of discarding depends on a manager's choice of W. However the choice of species to discard depends only on relative prices, so a manager is unable to influence the choice of type to discard.

With aggregated quota ex ante uncertainty may also occur. The magnitude of harvest depends upon uncertain prices, relative abundance, and technology, along with the choice of quota. Thus a manager has only imperfect control over harvests. In particular, the choice of composition depends only on prices and the values of $\underline{\theta}$ and $\overline{\theta}$, so a manager cannot affect harvest composition.

Switching between confiscation and simple enforcement regimes affects only the disposition of over-quota harvests. Under simple enforcement all over-quota harvests are discarded. Under confiscation over-quota fish are discarded or landed and turned over to a manager.

Disaggregated quota: With disaggregated quota a manager chooses weights of each type and allows a fisher to land any smaller bundle. A fisher's problem is given by 1-5, with $Q = \{\mathbf{y} \geq 0 | \mathbf{y} \leq \mathbf{q}\}$ in 2. This profit maximization problem can be solved with conventional techniques.

Figures 1b and 1c illustrate a fisher's problem with disaggregated quota. These figures are the same as figure 1a, except that the quota set is now a rectangle with its "northeast" corner at coordinate $\mathbf{q}$. In figure 1c, $\mathbf{q}$ is in the technically feasible set of harvests. In figure 1b it is not. Unless otherwise noted the discussion below supposes $p_2 > p_1$and simple enforcement.

Consider figure 1b. If prices are low relative to costs the quota is not binding and effort and landings are increasing in prices. As prices rise, q_1 eventually binds. When $p_1 > p_2$, the quota on Type 1 binds at $\mathbf{y}_a$. As the price of Type 2 rises further, profit maximizing landings shift along the boundary of the quota set until a fisher can no longer adjust composition to increase his harvest of Type 2. This occurs at landings $\mathbf{y}_b$ in the figure. When $p_2 > p_1$, the quota on Type 1 first binds at $\mathbf{y}_b$. Regardless of relative prices, if profit maximizing landings are $\mathbf{y}_b$, further landings of Type 2 are only possible if Type 1 is discarded.

As prices rise further some discarding occurs (e.g., when landings and harvests are $\mathbf{y}_c$ and $\mathbf{h}_c$ in figure 1b). In this case, profit maximizing effort is increasing in the price of Type 2 but invariant to small changes in the price of Type 1: Marginal harvests of Type 1 have zero value to a fisher because they must be discarded. When prices rise high enough, profit maximization occurs at landings $\mathbf{q}$ and harvest $\mathbf{h}_q$. In this case both quotas are binding and effort does not respond to changes in price.

In figure 1b discarding of Type 1 may or may not occur. If $\mathbf{q}$ lies between the horizontal axis and the technologically feasible set, rather than vice-verse (as in figure 1b), then the roles of Type 1 and Type 2 are reversed. If, as shown in figure 1c, the northeast corner of the quota set is technologically feasible profit maximizing behavior is as described below.

If prices are low relative to costs then the quota is not binding and effort and landings are increasing in prices. When $p_i > p_j$ the fisher chooses the minimum value of θ_j and concentrates on Type i.

As prices rise, then q_i binds when $p_i > p_j$. This occurs at landings $\mathbf{y}_a$ or $\mathbf{y}_b$ in figure 1c. As prices rise further the profit maximizing harvest moves along the boundary of the quota set towards landings $\mathbf{q}$. In this region effort is also increasing in prices. As prices rise still further, both quotas eventually bind and effort no longer responds to changes in price.

We can now describe the incidence of discarding and ex ante uncertainty under disaggregated quota and simple enforcement. Since harvests depend on uncertain prices, relative abundance, and technology, as well as the quota, a manager using disaggregated quota faces ex ante uncertainty about the harvest. However a manager using disaggregated quota is able to affect harvest composition. In particular, a profit maximizing fisher may have an incentive to choose θ_1 as close to the ratio $\frac{q_2}{q_1+q_2}$ as is feasible.

Sufficient conditions for discarding to occur under disaggregated quota are, (1) the quota is binding for only Type j at $\mathbf{p}$, (2) the northeast corner of the quota set is not technologically feasible, and (3) $p_i\theta_i F_x > c$. An intuitive necessary condition for discarding of Type i is that the price of Type i be large enough that harvesting is profitable when only Type i is retained in the harvest. Since discarding only occurs after the quota binds, the magnitude of discarding depends on a manager's choice of (q_1, q_2). Since the choice of species to discard depends on whether (q_1, q_2) lies between the h_1 axis and the technologically feasible or *vice verse*, the choice of disaggregated quota affects the choice of type of fish to discard.

As with aggregated quota, if a manager instead uses a confiscation enforcement regime, there is no change in the statement or analysis of a fisher's problem, though we must interpret $\mathbf{d}$ as the sum of discarded and confiscated fish.

Discussion: With each type of quota, harvest depends upon uncertain prices, relative abundance, and technology, as well as the quota. Thus a manager using any of the three quota types faces ex ante uncertainty about the harvest.

Under simple enforcement, discarding is more likely under disaggregated than aggregated quota, and does not occur with value-based quota. At the boundary of a disaggregated quota set it is profitable to discard only if it is profitable to fish while retaining just the type with a non-binding quota, i.e., $p_i \theta_i F_x > c$. At the boundary of an aggregated quota set it is profitable to continue fishing only if it is profitable to fish only for the more valuable type while discarding the less valuable type, i.e., $(p_i - p_j)\,\theta_i F_x > c$ where $p_i > p_j$. Given quota of each type that binds at prices $\mathbf{p}$ but not at any smaller price, let P_d denote the set of prices larger than $\mathbf{p}$ such that discarding occurs under disaggregated quota.[7] Let P_a denote the set of prices larger than $\mathbf{p}$ such that discarding occurs under aggregated quota. Finally, $P_v = \phi$ is the set of prices larger than $\mathbf{p}$ such that discarding occurs with value-based quota. Inspection of the above conditions for discarding under disaggregated and aggregated quota establishes that $P_d \supset P_a \supset P_v$. Thus, if prices are a random variable whose support contains P_d, discarding is more likely under disaggregated than aggregated quota, and more likely under aggregated than value-based quota.

Since unobserved discarding can occur under simple enforcement with aggregated and disaggregated quota, data-fouling may be a problem with these two types of quota. Since discarding cannot occur with value-based quota, data-fouling cannot occur. Switching to confiscation may reduce the incidence of discarding and data-fouling under aggregated and disaggregated quota.

Value-based and aggregated quota do not allow a manager to affect harvest composition or the choice of species to discard. This decision depends entirely on relative prices. Disaggregated quota is the only regulation allowing a manager to exercise control over harvest composition or the choice of species to discard.

4 Manager's problem

The following chronology corresponds closely to the observed chronology of regulation and fishing. (1) A manager chooses a regulatory program at the beginning of a season on the basis of imperfect knowledge of the fishing technology, relative catchability, stock abundance, and market conditions. (2) After this choice is made, a fisher observes market conditions, relative catchability, how well his boat is working, and makes his choices about effort, discarding, and composition. (3) After a fisher makes these decisions a manager observes landings and market prices.

[7] We also require that $\mathbf{q}$ not be in the technologically feasible set, and that one quota not bind at $\mathbf{p}$.

This chronology can also be described more formally. The final outcome of a fishing season depends on; (1) market and stock conditions as summarized by ε, $\mathbf{A}$, $\mathbf{p}$, (2), a manager's choice of Q and enforcement, and (3), a fisher's choices of $x, \mathbf{d}$, and θ_1. At Time 1 a manager does not know $\varepsilon, \mathbf{A}$,and $\mathbf{p}$, but does know a density $g(\varepsilon, \mathbf{A}, \mathbf{p})$ from which they are drawn. On the basis of this imperfect information a manager chooses Q. At Time 2, $\varepsilon, \mathbf{A}, \mathbf{p}$ are revealed to a fisher, who chooses effort, discarding and composition to maximize profits. At Time 3 a manager observes landings and prices.

Assume a manager cares about fishery profits but places a higher value on harvested fish than the fisher. To represent this as simply as possible, let $V(\mathbf{h})$ denote the social cost of harvest $\mathbf{h}$, where marginal social cost is non-negative and non-decreasing in harvest levels, i.e., $DV \geq 0$ and $D^2V \geq 0$.[8] A manager's problem is to choose a quota set Q to maximize expected value of fishery profits net of the social cost of harvest, taking as given a fisher's response to regulation. More formally, a manager using simple enforcement chooses Q to solve,

$$\text{(6)} \qquad \max_Q \int_{\mathbf{p},\mathbf{A},\varepsilon} \left[\mathbf{p}\left(\theta F(x,\mathbf{A}) - \mathbf{d}\right) - cx - V(\theta F(x,\mathbf{A}))\right] g(\varepsilon,\mathbf{A},\mathbf{p}) d\varepsilon\, d\mathbf{A}\, d\mathbf{p}$$

$$\text{s.t. } x = x(\varepsilon, \mathbf{A}, \mathbf{p}, Q)$$

$$\mathbf{d} = \mathbf{d}(\varepsilon, \mathbf{A}, \mathbf{p}, Q)$$

$$\theta_1 = \theta(\varepsilon, \mathbf{A}, \mathbf{p}, Q)$$

An aversion to ex ante uncertainty, like risk aversion, arises from concavity of a manager's objective. Such concavity can have two sources. First, given decreasing marginal returns to effort, $\theta F(x, \mathbf{A})$ is concave along any ray passing through a feasible harvest and the origin. Second, V may be convex. For example, a preference for harvests close to a target set by a management committee will be reflected by convexity of V in a neighborhood of a target. Increasing convexity of V causes a manager to be increasingly averse to risk of deviations from the target. To sum up, no modification of 6 is required to reflect a manager's aversion to ex ante uncertainty.

Equation 6 does not reflect a manager's aversion to data fouling. Equation 6 varies only with the quality of a manager's information about current conditions, i.e., $g(\varepsilon, \mathbf{A}, \mathbf{p})$, it does not vary as a manager's information about future conditions varies, so that a manager's preference for good ex post estimates of harvests is not reflected in 6.

[8] One might also allow V to covary with the uncertain variables. For example, the marginal social value of Type 1 might depend on the realized relative catchability of Type 1 (ε).

A simple way to accommodate aversion to data fouling is to define $\beta(Q)$ denote a vector of parameters describing the error distribution of a manager's ex post estimate of harvests as a function of the quota and $I(\beta(Q))$ to be the value that a manager places on ex post information about harvests. We can then add $I(\beta(Q))$ to a manager's objective in 6A more elegant way to assess the value of information is to solve an explicitly dynamic version of a manager's problem in which stock size and a manager's information β are state variables.

The manager's problem above is based upon the simple enforcement regime in which no illegal landings occur. If a manager uses the confiscation regime, we suppose a fisher lands proportion α of all over-quota fish. In this case we adjust a manager's objective by allowing a manager to keep the revenue generated by the confiscated fish. That is, we add $\alpha\mathbf{pd}$ to the objective in 6.

A manager's welfare maximization problem is difficult to solve analytically in interesting generality. The analysis proceeds by considering two simple examples and a numerical solution to a particular problem.

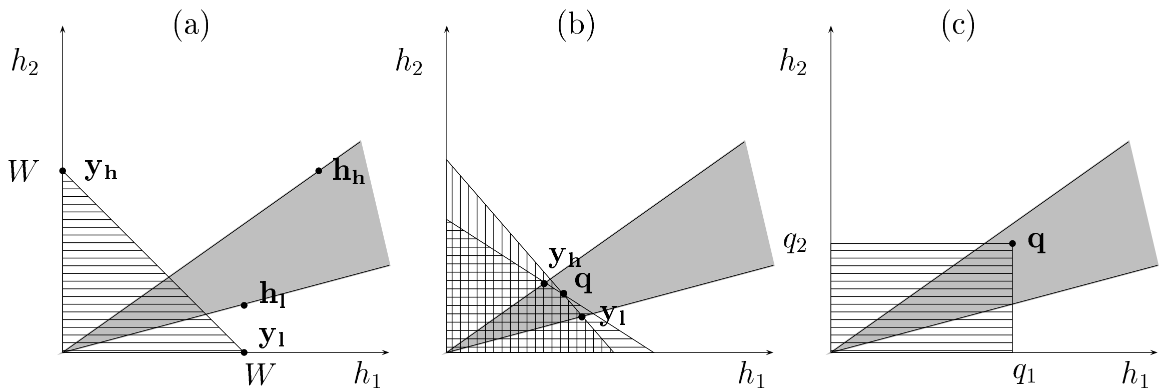

Figure 2: A fisher's response to aggregated quota (a), value-based quota (b), and disaggregated quota (c), when p_2 takes the values $p_{2l} < p_1$ and $p_{2h} > p_1$ at random. In each panel the shaded cone is the technologically feasible set. In figures 1a and 1c and the hatched area is the quota set. In figure 1b the quota set for p_{2l} (p_{2h}) is shaded with vertical (horizontal) lines. In figures 1a and 1b, $\mathbf{y_l}$ ($\mathbf{y_h}$) and $\mathbf{h_l}$ ($\mathbf{h_h}$) indicate landings and harvests when p_{2l} (p_{2h}) obtains. In figure 1c harvest $\mathbf{q}$ occurs for both realizations of p_2.

Manager's problem with only price uncertainty: Consider a special case of a manager's problem where the cost of effort is negligibly small ($c \approx 0$)[9]. There are three reasons for this assumption. (1) It is analytically convenient. (2) It is a stylization of fisheries where quotas are small relative harvesting capacity. (3) It allows the analysis to concentrate on states of the world where a quota is binding while ignoring uninteresting states where quotas do not bind.

Further suppose that a manager's only uncertainty is over prices: p_1 is certain, but p_2 takes a high or a low value at random, where $p_{2h} > p_1 > p_{2l}$. Figure 2 illustrates a fisher's response to aggregated, disaggregated, and value-based individual quota under these conditions. The discussion below assumes simple enforcement unless otherwise noted.

Since the cost of effort is negligible, a profit-maximizing fisher chooses to produce the revenue maximizing legal landings. Figure 2a illustrates a fisher's behavior under an aggregated quota allowing W pounds of landings. If the realized p_2 is high, then revenue maximizing landings are $\mathbf{y}_h$, the associated harvest $\mathbf{h}_h$, and discarding is h_{1h}. If p_2 is low, profit maximizing landings are $\mathbf{y}_l$, the associated harvest is $\mathbf{h}_l$ and discarding is h_{2l}.

In this example a manager has ex ante uncertainty about harvest magnitude and composition.[10] When he chooses W a manager does not know whether a fisher will choose harvest $\mathbf{h}_h$ or $\mathbf{h}_l$. Discarding occurs for certain in this example, although the amount of discarding is uncertain ex ante. Depending on prices, a fisher discards h_{2h} of Type 2 or h_{1h} of Type 1. Data fouling is not a problem despite the fact that unobserved discarding occurs. When a manager observes landings $\mathbf{y}_h$ he infers that harvests $\mathbf{h}_h$ certainly occurred. Similarly, when a manager observes landings $\mathbf{y}_l$ he infers that harvests $\mathbf{h}_l$ certainly occurred.

Figure 2b illustrates a fisher's behavior when a manager chooses value-based quota allowing $p_1q_1 + p_2q_2$ dollars of landings. Since revenue is constant along the boundary of a quota set a fisher's objective is to get to this boundary using as little effort as possible. For a high realization of p_2 this is accomplished at landings $\mathbf{y}_h$, on the boundary of the quota set associated with p_{2h}. For a low realization of p_2 this is accomplished at landings $\mathbf{y}_l$, on the boundary of the quota set associated with p_{2h}.

With value-based quotas and only price uncertainty a manager generally has ex ante uncertainty. At the time he chooses $\mathbf{q}$ he does not know whether harvest $\mathbf{y}_l$ or $\mathbf{y}_h$ will occur. From figure 2b it is clear that the degree of ex ante uncertainty increases

[9]If $c = 0$ then the fisher's behavior is indeterminate.

[10]Except when a fisher has no control over proportions and $\theta_1 = \frac{1}{2}$. In this case $\mathbf{h}_l = \mathbf{h}_h$ and a manager has no ex ante uncertainty about harvests or discards.

with the amount of control a fisher exercises over proportions. In the special case when a fisher has no control over proportions, a manager can eliminate ex ante uncertainty if he chooses $\mathbf{q}$ to lie on the feasible ray of harvests. With value-based quota no discarding occurs.

Figure 2c illustrates a fisher's behavior for each realization of prices when a manager chooses disaggregated quota allowing (q_1, q_2) of each type. If there is no uncertainty about the technology, a manager chooses (q_1, q_2) in the technologically feasible set. A profit maximizing fisher then chooses harvests and landings $\mathbf{q}$ for both realizations of p_2. It follows that ex ante uncertainty, discarding and data-fouling do not occur when a manager uses disaggregated quota.

From this example we learn that if there is only price uncertainty, disaggregated quota allows a manager to select any technologically feasible harvest with no ex ante uncertainty, no discarding and no data fouling. In the special case where a fisher has no control over harvest composition, value-based quota performs equally well. However, as a fisher's control over composition increases, so does a manager's ex ante uncertainty, although discarding and data fouling never occur. Finally, aggregated quota always causes ex ante uncertainty and discarding, though with only price uncertainty it does not cause data fouling. In all, this suggests that disaggregated quota has a comparative advantage in environments where there is only price uncertainty.

In this example, disaggregated and value-based quota do not induce discarding. Therefore switching to a confiscation enforcement regime does not affect behavior under these two types of quota. Since discarding does occur with aggregated quota, to the extent that a switch to confiscation reduces discarding, it improves the performance of this type of quota.

Manager's problem with only technological uncertainty: Consider a second special case of a manager's problem 6 where the cost of effort is negligibly small ($c \approx 0$), prices are certain, and technology is uncertain. In particular suppose that $p_1 > p_2$ and that θ_1 takes the value θ_{1h} or θ_{1l} at random, where $\theta_{1h} > \theta_{1l}$. The discussion below assumes simple enforcement unless noted otherwise.

Figure 3a illustrates a fisher's profit maximizing behavior for each realization of technology, conditional on a manager's choice of W pounds of aggregated quota. When $p_1 > p_2$ revenue is always maximized by landings $\mathbf{y}$, so a fisher chooses these landings regardless of the technology. If θ_{1l} occurs then a fisher chooses $\mathbf{h}_l$ and discards h_{2l} units of Type 2. If θ_{1h} occurs then a fisher chooses $\mathbf{h}_h$ and discards h_{2h} units of Type 2. Given technological uncertainty and aggregated quotas, a manager

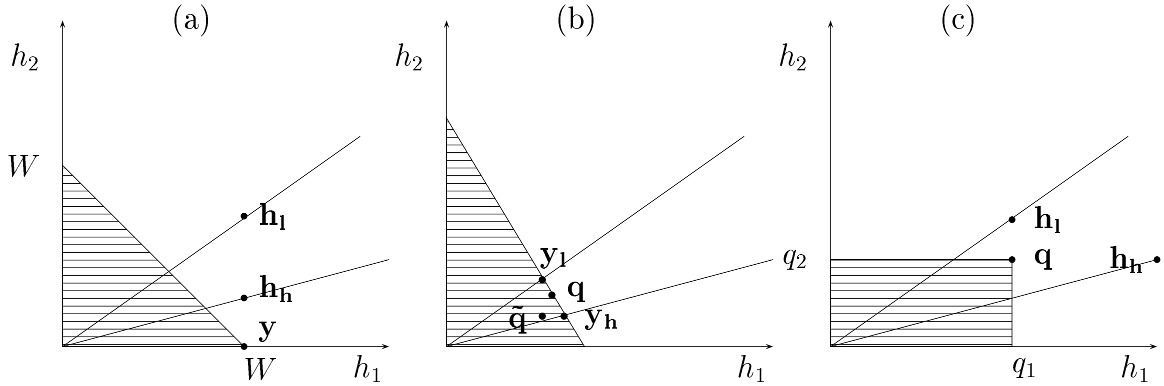

Figure 3: A fisher's response to aggregated quota (a), value-based quota (b), and disaggregated quota (c), when the technology is fixed proportions and θ_1 takes a high value θ_{1h} or a low value θ_{1l} at random. In each panel the hatched area is the quota set. The steeper (flatter) ray from the origin indicates the technologically feasible set when $\theta_1 = \theta_{1l}$ ($\theta_1 = \theta_{1h}$). In each figure, $\mathbf{y_l}$ ($\mathbf{y_h}$) and $\mathbf{h_l}$ ($\mathbf{h_h}$) indicate landings and harvests when θ_{1l} (θ_{1h}) obtains.

is uncertain about whether harvests $\mathbf{h}_l$ or $\mathbf{h}_h$ occur at the time he chooses W. Hence ex ante uncertainty is a problem. A manager knows with certainty that some discarding will occur. However, landings $\mathbf{y}$ are associated with both possible harvests, so a manager remains unable to determine whether harvest $\mathbf{h}_l$ or $\mathbf{h}_h$ occurs after he observes landings. Therefore discarding and data fouling are problems under aggregated quotas with only technological uncertainty.

Figure 3b illustrates a fisher's profit-maximizing behavior given technological uncertainty and value-based regulation. Since revenue is maximized at any point on the boundary of the quota set, profit maximization requires that a fisher get to this boundary using as little effort as possible. This occurs at harvests $\mathbf{y}_l$ or $\mathbf{y}_h$ depending on whether θ_{1h} or θ_{1l} occurs. Since harvests vary with the technology, a manager faces ex ante uncertainty about harvest size and composition. Discarding is not a problem. Data-fouling does not occur.

Figure 3c illustrates a fisher's profit-maximizing behavior given technological uncertainty and disaggregated quota. Regardless of technology, revenues are maximized by landings $\mathbf{q}$. These revenues are achieved by harvesting $\mathbf{h}_l$ or $\mathbf{h}_h$ as θ_1 takes its low or high value. Depending on the realization of θ_1 a fisher discards $h_{2l} - q_2$ of Type 2 or $h_{1h} - q_1$ of Type 1. Given technological uncertainty and disaggregated quotas, a manager is uncertain about whether harvests $\mathbf{h}_l$ or $\mathbf{h}_h$ will occur when he chooses (q_1, q_2). Hence ex ante uncertainty is a problem. A manager knows with certainty that some discarding will occur, though the amount is uncertain even after he observes landings.

Therefore discarding and data fouling are problems under disaggregated quotas with only technological uncertainty.

For this example, we can make two general statements about the welfare that can be attained with different types of quota. First, disaggregated quota can result in higher expected welfare than any arbitrary aggregated quota. To see this, consider an arbitrary aggregated quota. As in figure 2a, such a quota results in two possible harvests. Choose a disaggregated quota set with its northeast corner at the smaller of the two harvests. In figure 2a this means choosing a disaggregated quota with its northeast corner at $\mathbf{h}_h$. Such a disaggregated quota results in the same pattern of harvests as the illustrated aggregated quota, but strictly more landings. Hence, as long as the price of fish is positive, disaggregated quota dominates aggregated quota.

Second, value-based quota generates an equal value of landings from strictly less harvest than disaggregated quota. To see this, consider a disaggregated quota allowing landings $\mathbf{q}$, as in figure 1c. Now consider the value-based quota that allows harvests with value equal to the same $\mathbf{q}$. Under the value-based quota the two possible harvests lie on a price line passing through $\mathbf{q}$, while under disaggregated quota harvests lie strictly "north" or strictly "east" of $\mathbf{q}$. This means that, for the same value of landings, harvests under disaggregated quota are strictly larger than those under value-based quota.

Switching to a confiscation enforcement regime reduces the proportion of over-quota fish that discarded. Since discarding does not occur with value-based quota, and does occur with the other types, the switch in enforcement regime decreases the comparative advantage of value-based quota when there is only price uncertainty. In fact, if the switch to confiscation enforcement causes all over-quota fish to be landed instead of discarded, then we can show that disaggregated quota dominates value-based quota, reversing the result of the last paragraph.

Let $\mathbf{q}$ be the value-based quota that solves the manager's problem. As in figure 3b, this quota results in harvests $\mathbf{y}_l$ and $\mathbf{y}_h$. Now consider the disaggregated quota with $\tilde{\mathbf{q}} = (y_{1l}, y_{2h})$. Under this quota, with confiscation enforcement, a fisher chooses landings $\mathbf{y}_l$ or $\mathbf{y}_h$ depending on the realization of θ_1(this is illustrated in figure 3b). From these landings, he always sells $\mathbf{q}$ and forfeits the residual. Therefore a manager is able to induce exactly the same pattern of harvests and landings with a disaggregated quota and confiscation, as is achieved by the optimal value-based quota. It follows that an optimal disaggregated quota can be no worse than an optimal value-based quota.

Results from the Scotia-Fundy Cod-Haddock-Pollock fishery: Given simple enforcement the examples suggest that disaggregated quota has an advantage in environments where there is a lot of price uncertainty and not much technological uncertainty, while value-based quota perform relatively better in environments where there is a lot of technological uncertainty and not much price uncertainty. Given confiscation enforcement, the advantage of value-based quota under technological uncertainty is attenuated. In the extreme case where all over-quota fish are landed, disaggregated quota performs better than value-based quota in both examples.

To get some sense for the type of quota that is likely to be preferred more complex real fisheries, I solve a manager's problem numerically using data from the Scotia-Fundy Cod-Haddock-Pollock fishery in Atlantic Canada. This fishery is conducted by small bottom trawling vessels that concentrate on Cod, Haddock, and Pollock.

The solution method is as follows: (1) Generalize the model above from two to three species. (2) Estimate the density $g(\varepsilon, \mathbf{A}, \mathbf{p})$ using price and landings data. (3) Estimate the marginal cost of effort c from cost data for the fishery. (4) Estimate the limits of control over composition δ from price and landings data. (5) Solve 6 for each type of quota and enforcement numerically using estimated values for c, δ and $g(\varepsilon, \mathbf{A}, \mathbf{p})$ and a variety of specifications of the social value of harvest $V(\mathbf{h})$. (6) Compare the maximum expected welfare of different quota programs. (7) Check the sensitivity of the numerical solution to changes in estimated values of c, δ and $g(\varepsilon, \mathbf{A}, \mathbf{p})$.

The numerical results indicate that disaggregated quota generates higher expected welfare than value-based or aggregated quota. This ranking is surprisingly robust. In particular, this ranking of quotas is almost always invariant to the specification of the social value of harvest $V(\mathbf{h})$, and to sensitivity tests on estimated parameters and densities.

The results also indicate that data fouling is not a problem under any regulation. Even under simple enforcement, ex post estimates of harvest variance were always less than one percent of actual harvest weight for all quota programs. This suggests that the dominance of disaggregated quota is robust to plausible differences in the value of ex post information about the harvest. Details about the data, estimation procedures, and numerical solution method are available in [10].

The data underlying the numerical results is as good as is available without primary data collection efforts. It is, nevertheless, subject to two important problems. First, the data records only landings in a fishery that is subject to regulation by a disaggregated quota. Thus the distribution of the relative catchability ε and the limits of composition control δ are estimated from landings data and not harvest data in a fishery where discarding may occur. Second, the cost data is very poor so that the estimate of the marginal cost of effort c is suspect. While the data underlying the numerical exercise is poor, it is the best available. Fisheries managers rarely track cost data. Actual harvest data, as opposed to landings data, is available only for observer fisheries, which are typically conducted by large highly regulated vessels with extremely complex fishing behavior.

5 Conclusion

This paper considers the design of individual quota programs for fisheries where (1), more than one species or more than one size class of a single species is harvested, and (2), a manager is uncertain about the fishing technology, prices, stock levels, and compliance.

The analysis establishes several results about the comparative advantages of different quota programs. In particular, it indicates that with simple enforcement, disaggregated quota programs perform better in environments where there is a lot of price uncertainty and not much technological uncertainty. Value-based quota perform relatively better in environments where there is a lot of technological uncertainty and not much price uncertainty. Switching to confiscation attenuates the advantage of value-based quota in environments with only technological uncertainty.

The analysis also suggests that the optimal choice of quota program depends on particular characteristics of the fishery in question. For a numerical example based on a trawl fishery, the paper finds that disaggregated quota dominates the other two types, regardless of enforcement regime. The numerical results, however, should be regarded with some suspicion because of data problems. With this said, pending better data, the numerical results indicate that disaggregated quota is the appropriate choice for multi-species trawl fisheries.

A more conclusive numerical result can only be obtained with better data about control of proportions. This data is not available. While such data can in principle be gathered by shipboard observers, such programs are expensive and rely on the observer to discriminate between efficient technologically-induced discarding and wasteful quota-induced discarding. The analysis conducted here suggests proportions data could also be gathered by a test fishery regulated by value-based quota. Since value-based quota does not cause discarding, landings would accurately reflect harvests net of technologically-induced discarding. By artificially manipulating prices a manager could then determine the limits of a fisher's control over harvest composition in a straight forward way.

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