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Optimal quota programs

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Abstract:

Optimal quota programs

This paper considers the choice among three different types of individual quota programs in a multi-product fishery when technology, prices, and compliance are all uncertain: (1) *Aggregated quota*, which regulates the total weight of all species; (2) *Disaggregated quota*, which regulates the weight of each species separately, and (3), *Value-based quota*, which regulates the total value of all species. The paper first considers the welfare maximization problem in the context of simple stylized models of the fishery. These examples show that different types of quota programs are preferred in different fisheries. To learn which type of quota program should be preferred in an actual fishery, the paper then solves the welfare maximization problem numerically, where uncertainty about prices and technology is described by densities estimated from data on the Scotia-Fundy Cod-Haddock-Pollock fishery. In this application, a disaggregated quota program almost always dominates the other choices, and is at worst slightly inferior to a value-based quota program. J.E.L. Classification: Q22, L51.

1 Introduction

A choice of environmental regulation is typically made under conditions of extreme uncertainty.[1] A regulator of a fishery, forest, or airshed, is uncertain about fundamental features of a regulated technology, the benefits of regulation, and the amount of non-compliance he should anticipate. This paper considers one such choice of environmental regulation: The regulation of fisheries where more than one species or more than one size class of a single species is harvested.

Specifically, given uncertainty about prices, stock abundance, technology, and compliance, this paper analyzes a choice between three types of individual quota program: (1) *Aggregated quota*, which regulates the total weight of all species or size classes, (2) *Disaggregated quota*, which regulates the weight of each species or size class separately, and (3), *Value-based quota*, which regulates the total value of all species or size classes. Of these three, disaggregated quota is by far the most common choice in multi-species fisheries, although aggregated and value-based quota are also used (Muse and Schelle 1989). 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. (for examples and exceptions see Muse and Schelle 1989). Since these three types of quota, aggregated, disaggregated, and value-based, constitute a nearly exhaustive list of the types of individual quota programs used in multi-product fisheries, and since multi-product fisheries are the norm rather than the exception, the problem of regulatory design considered here is fundamental to fisheries management. Since the problem of choosing policy instruments under uncertainty is also very common, the problem considered here is of wider interest.

A planner choosing a quota program faces a number of difficult problems. First, he must usually commit to a regulatory program at the beginning of a fishing season when prices, stock abundance and the technology are uncertain. This uncertainty causes the relationship between any particular regulatory program and the resulting harvest to be uncertain. Second, considerable evidence shows that individual quota programs can cause fishermen to discard fish at sea that they would otherwise bring to market (Muse and Schelle 1989, Muse 1991, Copes 1986). Since mortality among discarded fish is very high, discarding wastes a valuable resource. Discarding also creates information problems for the planner. Since discarding constitutes non-compliance with the quota program, it is usually both illegal and unobserved. Therefore, the

[1] I would like to thank Leo Brander and Paddy Wong of the Department of Fisheries and Oceans for their help in procurring the data and learning institutional details. I would also like to thank Angelo Melino, Mike Berkowitz, Steven Kohlhagen, Huw Lloyd-Ellis, Nancy Gallini, Ralph Winter, Jim Smith, and participants at the 1998 UBC Summer I/O conference for helpful comments. This research was supported by grants from the Connaught foundation and the Social Science and Humanities Research Council of Canada.

possibility of unobserved discarding may exacerbate a planner's uncertainty about the relationship between regulatory programs and their associated harvests. Finally, since harvests are the sum of observed landings and unobserved discarding, uncertainty about the size of this season's harvest may not be resolved at the end of the season when only landings are observed. In the jargon of fisheries management this is called "data fouling", and it may induce errors in a planner's future behavior.

Given pre-season uncertainty about prices, stock abundance, technology, and unobserved discarding, one might want to choose the quota program that maximizes expected social welfare. However, as the discussion above indicates, a planner's problem is more difficult than this. Since the size of the harvest is an important determinant of next period's policy, a planner also needs to know how many fish were harvested. Not only does a planner want to choose a policy that elicits harvests that are close in expectation to the ex post optimum, but in order to choose tomorrow's target harvest wisely, a planner may also need to choose regulation so that observed landings provide him with good ex post information about the unobserved harvest. Thus a planner would like to identify the individual quota program that maximizes expected social welfare while accounting for the expected ex post quality of information about the realized harvest.

The paper first formulates this welfare maximization problem, and then provides both a theoretical analysis and an application to a particular fishery. The theoretical analysis considers the welfare maximizing choice of quota type in the context of simple stylized models of the fishery. This demonstrates that the three types of quota program cannot be ranked unambiguously—different types of quota program are preferred in different fisheries. The application provides a numerical solution to the welfare maximization problem for the Scotia-Fundy Cod-Haddock-Pollock Fishery. In this application uncertainty about prices and technology is described by densities estimated from fishery data. To test for robustness the paper solves many different versions of the welfare maximization problem. While the analytical examples show that there is no clear ranking of different types of individual quota program, the numerical example indicates that a disaggregated quota program almost always dominates the other choices, and is at worst slightly inferior to a value-based quota program.

2 Related literature

The economic literature on quota regulation in fisheries (e.g., Anderson 1994, Arnason 1994, Turner 1996, Turner 1997, Muse and Schelle 1989) is almost exclusively positive. It describes the three types of individual quota program, aggregated, disaggregated, and value-based, and the way that fishers respond to these programs. Unlike this paper, they provide little basis for choosing between quota programs in an uncertain environment.

This paper compares the different quota programs using a measure of expected welfare. Although, the notion of comparing policy instruments on the basis of their expected welfare is not new, e.g., Weitzman (1974) and Stavins (1995), this paper's use of estimated densities to calculate expected welfare is innovative. With few exceptions, e.g., Mendelsohn (1986), applied papers compare policy instruments by estimating parameter values and conducting welfare calculations with expected parameter values.

In addition, existing theory does not consider the possibility of non-compliance. Firms are assumed to respond to regulation only by changing the quantity of goods they produce, and not by qualitatively different non-compliant behavior. This simplifying assumption must be abandoned in fishery economics. Quota programs in multi-product fisheries can result in qualitative changes in behavior—discarding—as well as changes in harvest quantity. This analysis allows a planner to anticipate non-compliance and adjust the regulatory program accordingly.

Although Malik (1990), Harford (1976), and others, consider the problem of regulation when non-compliance is possible, they do not solve for an optimal regulatory policy when the degree of non-compliance is uncertain. While non-compliance with environmental regulation has been examined, a manager's optimal response to it has not. Note that the need to consider non-compliant behavior extends beyond fisheries. Firms may cease polluting when faced with a binding pollution regulation, they may emit illegally, or substitute less regulated forms of emissions. Consumers may not simply reduce their trash output when faced with marginal cost pricing of disposal, they may dump or burn their garbage illegally.

An analysis of non-compliance also requires us to consider ex post uncertainty about the extent of non-compliant behavior. Since non-compliance can only be a problem when a planner is uncertain about its occurrence, in an environment where non-compliance occurs, a planner's information about the amount of a regulated activity may be imperfect even after the activity has occurred. In the context of a fishery with unobserved discarding, this means that, if only landings are observed, a planner may continue to be uncertain about harvests after the end of the season. If ex post information about the extent of non-compliance is valuable, we should expect a planner to choose regulatory instruments with this in mind. The impact of instrument choice on ex post information has not previously been considered.

Lastly, this paper considers regulation of a joint production industry, a multi-product fishery. The problem of regulating joint production is general, (e.g. a smokestack that emits a number of pollutants) and has received little attention.

3 Model and manager's problem

3.1 Model

The object of this section is to present a model of the fishery accurate enough to form a basis for a simulation exercise, but simple enough to provide intuition about the results of this simulation. While a fishery is understood to consist of many fishers, this analysis examines the way that a single fisher responds to an individual quota program. The analysis should be interpreted as beginning after the planner has allocated quotas, whether this allocation takes place by fiat, lottery, or through a quota market.

To begin, suppose that the stock of fish consists of three types of fish. To be consistent with the simulation exercise in Section 6, call these three types, "Cod", "Haddock" , and "Pollock", though they could also refer to different size classes of a single species. A harvest is a 3-tuple indexed by i, $\mathbf{h} = (h_c, h_h, h_p) \geq 0$, where h_i is the harvested weight of type i.[2] Assume that "effort" is the only input into the production technology. Denote effort by x, and suppose that it may be procured at a constant cost c. This simplifying assumption facilitates solving the model, and is not rejected by data from the simulated fishery (see appendix 2).

There is considerable evidence that fishers can affect the proportions of different types of fish in their harvest by choice of time place or technique, however 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 $\boldsymbol{\theta} = (\theta_c, \theta_h, \theta_p)$ be a vector describing the proportion of each type of fish in a harvest. Allow fishers to choose $\boldsymbol{\theta}$ from a subset of the positive unit simplex, $\boldsymbol{\Theta}(\boldsymbol{\theta}^0) \subset \mathcal{S}_+^m$. In particular,

$$\boldsymbol{\theta} \in \boldsymbol{\Theta}(\boldsymbol{\theta}^0) = \left(\left[\theta_c^0 - C_c, \theta_c^0 + C_c\right] \times \left[\theta_h^0 - C_h, \theta_h^0 + C_h\right] \times \left[\theta_p^0 - C_p, \theta_p^0 + C_p\right]\right) \cap \mathcal{S}_+^3,$$

where $\boldsymbol{\theta}^0$ is a (vector valued) random variable reflecting the relative abundance of the different types of fish, and the C_i are parameters reflecting the degree to which fishers are able to control harvest composition. If the C_i are all zero then the fishers have a fixed-proportions technology. If they are large enough the fishers can choose any harvest composition.

[2] Bold type denotes vectors and regular typeface denotes scalars. $\mathbf{pq}$ denotes the inner product of $\mathbf{p}$ and $\mathbf{q}$, while $\mathbf{p}q$ is a vector times a scalar.

[3] McKloskey 1990 p16, Muse and Schelle 1989, Muse 1991, Squires 1987, Warner 1983.

[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.

Let the total weight of the harvest be quadratic in effort, so that

$$F(x, \mathbf{A}) = A_0 x + \frac{A_1}{2} x^2,$$

where the parameter vector $\mathbf{A} = (A_0, A_1)$ is a random variable reflecting the influence of factors like overall species abundance and weather on the productivity of effort. All together, harvests are given by:

$$\begin{bmatrix} h_c \\ h_h \\ h_p \end{bmatrix} = \begin{bmatrix} \theta_c \left(A_0 x + \frac{A_1}{2} x^2 \right) \\ \theta_h \left(A_0 x + \frac{A_1}{2} x^2 \right) \\ \theta_p \left(A_0 x + \frac{A_1}{2} x^2 \right) \end{bmatrix},$$

or in vector notation, $\mathbf{h} = \boldsymbol{\theta} F(x, \mathbf{A})$.

Fishers may discard fish at sea and discards are denoted $\mathbf{d} = (d_c, d_h, d_p) \geq 0$. To simplify the analysis, discarding is assumed costless.[5] Landings are the net of harvests and discards, $\mathbf{y} = (y_c, y_h, y_p) = \mathbf{h} - \mathbf{d} \geq \mathbf{0}$, and sell at an exogenous market price $\mathbf{p} = (p_c, p_h, p_p) > 0$. Absent discarding $\mathbf{y} = \mathbf{h}$, and it may be convenient to refer to $\mathbf{y}$ as the harvest as well. To avoid an analysis of technologically-induced discarding, all harvested fish are marketable. Alternatively $\mathbf{h}$ may be regarded as the harvest of marketable fish after technologically-induced discarding has occurred. Fishers choose effort, discarding, and harvest composition to maximize profits.

Denote the set of legal landings associated with a given individual quota program by Q. In aggregated quota programs, a planner issues a fisher quotas that entitle him to land and bring to market up to W pounds of fish, regardless of type. The quota set associated with this sort of quota program is $Q = \{\mathbf{y} \geq \mathbf{0} | \sum y_i \leq W\}$. In a disaggregated individual quota program a planner issues a fisher quotas for each type of fish. The quota set for a disaggregated quota program is $Q = \{\mathbf{y} \geq \mathbf{0} | \mathbf{y} \leq \mathbf{q}\}$, where $\mathbf{q} = (q_c, q_h, q_p) > \mathbf{0}$ are the maximum legal landing weights for each type. Finally, in a value-based quota program, a planner issues quotas allowing a fisher to land fish whose value is less than or equal to the value of landings $\mathbf{q}$. The corresponding quota set is $Q = \{\mathbf{y} \geq \mathbf{0} | \mathbf{p}\mathbf{y} \leq \mathbf{p}\mathbf{q}\}$.[6]

3.2 Fishers's Problem

Fishers take prices and regulation as given, and maximize instantaneous profits by choice of effort, x, discarding $\mathbf{d}$, and proportions $\boldsymbol{\theta}$. Although this assumption

[5]Readers interested in an analysis of costly discarding technologies are referred to Anderson 1994, Arnason 1994, and Turner 1996.

[6]A simpler way of administering value-based quota would be to simply specify the total dollar value of landings. The more complicated specification is superior in that it is invariant to changes in the price level.

eliminates investment from the model, it results in a dramatic simplification of the problem and allows the analysis concentrate on the choice of proportions and discarding. Moreover, since the harvests in the Scotia-Fundy Cod-Haddock-Pollock fishery were fairly stable over the 3-5 year period preceding the year my data was collected, a static equilibrium is a plausible stylization.[7]

If fishers maximize profits while taking prices and regulation as given, then the fishers choose $x, \mathbf{d}$, and $\boldsymbol{\theta}$ to solve:

$$\begin{aligned} \max_{x,\mathbf{d},\boldsymbol{\theta}} \quad & \Pi = \mathbf{p}\left(\boldsymbol{\theta} F(x, \mathbf{A}) - \mathbf{d}\right) - cx \\ & \text{s.t. } \boldsymbol{\theta} F(x, \mathbf{A}) - \mathbf{d} \in Q, \\ & \boldsymbol{\theta} \in \boldsymbol{\Theta}(\boldsymbol{\theta}^0) \\ & x, \mathbf{d} \geq 0. \end{aligned}$$

Profit maximizing choices of effort, discarding and composition will be functions of all of the characteristics of the economic environment and a planner's choice of regulation,

$$\begin{aligned} x^* &= x(\mathbf{A}, \boldsymbol{\theta}^0, \mathbf{p}, Q), \\ \mathbf{d}^* &= \mathbf{d}(\mathbf{A}, \boldsymbol{\theta}^0, \mathbf{p}, Q), \\ \boldsymbol{\theta}^* &= \boldsymbol{\theta}(\mathbf{A}, \boldsymbol{\theta}^0, \mathbf{p}, Q). \end{aligned}$$

3.3 Planner's problem

A 1996 report by the managers of the Scotia-Fundy Cod-Haddock-Pollock fishery states, **"as a first principle ... fisheries management must always be guided by conservation rather than economic objectives** " (FRCC.96.R.2, p.17. Emphasis in original). More generally, target harvests are often set by biologists with relatively little input from economists. Given this, the canonical assumption of a planner who maximizes the discounted present value of fishery profits is unreasonably restrictive.

Instead, make the weaker assumptions that a planner cares about today's profits, and about the remaining stock. Formally, let $s(\mathbf{h}, p_s)$ denote the social cost of harvest $\mathbf{h}$, conditional on the value of a parameter p_s. The parameter p_s reflects a planner's uncertainty about the rate of stock growth and the discount rate. The marginal social cost of harvest is non-negative and non-decreasing in harvest levels, hence $Ds \geq 0$ and $D^2 s \geq 0$.

The following chronology corresponds closely to the observed chronology of regulation and fishing. (1) At the beginning of a season, on the basis of imperfect

[7] Normalizing 1991 harvests to 1, harvests of Cod by the mobile gear fleet in the Scotia-Fundy region from 87 to 91 were: (0:66, 0.77, 0.87, 0.74, 1.00). Similarly for Haddock: (2.44, 2.15, 1.20, 0.96, 1.00), and Pollock: (1.06, 1.14, 1.10, 0.81, 1.00). (Personal Communication, Leo Brander).

knowledge of the fishing technology, relative abundance, and market conditions, a planner chooses a regulatory program. (2) After this choice is made, a fisher observes market conditions, relative abundance, how well his boat is working, and makes his choices about effort, discarding, and types of fish to target. (3) After a fisher makes these decisions the planner observes landings and market prices.

This chronology can also be described with the more formal language developed above. The final outcome of a fishing season depends on: (1) market and stock conditions as summarized by the variables $\mathbf{A}, \boldsymbol{\theta}^0, \mathbf{p}$, and p_s, (2) the planner's choice of Q, and (3) the fisher's choices of $x, \mathbf{d}$,and $\boldsymbol{\theta}$. At time 1 the planner does not know $\mathbf{A}, \boldsymbol{\theta}^0, \mathbf{p}$, and p_s, but does know the densities from which they are drawn: $g_{A_0}(A_0)$, $g_{A_1}(A_1)$, $g_p(\mathbf{p})$, $g_\theta(\theta_c, \theta_h)$, and $g(p_s)$. On the basis of this imperfect information the planner chooses Q. At time 2, $\mathbf{A}, \boldsymbol{\theta}^0$, and $\mathbf{p}$ are revealed to the fisher, who then chooses effort, discarding and composition to maximize profits. At time 3 the planner observes landings and prices.

Since a planner places a higher value on harvested fish than fishers, unregulated fishers do not choose a planner's optimum harvest. A planner's problem is to choose a quota set Q to maximize expected welfare, taking as given fishers' responses to this regulation. More formally, this suggests that a planner choose Q to solve,

$$\max_Q E\left[\mathbf{p}(\boldsymbol{\theta}^* F(x^*, \mathbf{A}) - \mathbf{d}^*) - cx^* - s(\boldsymbol{\theta}^* F(x^*, \mathbf{A}), p_s)\right] \tag{1}$$
$$\text{s.t. } x^* = x(\mathbf{A}, \boldsymbol{\theta}^0, \mathbf{p}, Q)$$
$$\mathbf{d}^* = \mathbf{d}(\mathbf{A}, \boldsymbol{\theta}^0, \mathbf{p}, Q)$$
$$\boldsymbol{\theta}^* = \boldsymbol{\theta}(\mathbf{A}, \boldsymbol{\theta}^0, \mathbf{p}, Q).$$

To the extent that $s(\mathbf{h}, P_s)$ reflects the contribution of stocks to value of future fishery profits, this formulation resembles the canonical problem of profit maximization over an infinite horizon. On the other hand, 3.1 is also consistent with a more realistic process where targets are formulated with less regard for economic considerations.

Equation **??** reflects a planner's interest in maximizing expected market value of the harvest while conserving the stock. However, a planner may also be interested in three other objectives: (1) The accuracy with which harvests can be predicted at the time regulation is selected. (2) The accuracy with which landings can be predicted at the time regulation is selected. (3) The accuracy with which harvests can be known after landings and prices are observed.

A preference for a particular target harvest will be reflected by concavity of $s(\mathbf{h}, p_s)$ in a neighborhood of the target—concavity of s causes the manager to be averse to risk of deviations from the target harvest. Hence no modification of **??** is required to reflect a preference for policies that achieve target harvests more accurately.

If each year's landings are like the last, then a greater degree of specialization may be possible for processors and purchasers, and long term relationships may be easier to develop. To the extent that this is true, it would be reflected in **??** by concavity of the demand function. In this case equation **??** would naturally penalize regulation which resulted in highly variable landings. To simplify the analysis, demand for fish is assumed perfectly elastic.

In order to choose next year's target harvest a planner needs to know what the harvest is ex post, after he has learned landings and prices. Let $\sigma(Q)$ denote the variance of a planner's ex post estimate of harvests. Equation **??** does not vary as $\sigma(Q)$ varies, so that a planner's preference for good ex post estimates of fishing mortality is not reflected in **??**. To accommodate this, define $V(\sigma(Q))$ to be the value that a planner places on ex post information about harvests, and add this term to the planner's objective in **??**. With this done, a planner's problem is to choose Q to solve,

$$\begin{aligned}
&\max_{Q} E\left[\mathbf{p}(\boldsymbol{\theta}^* F(x^*, \mathbf{A}) - \mathbf{d}^*) - cx^* - s(\boldsymbol{\theta}^* F(x^*, \mathbf{A}), P_s) + V(\sigma(Q))\right] \qquad (2)\\
&\text{s.t. } x^* = x(\mathbf{A}, \boldsymbol{\theta}^0, \mathbf{p}, Q)\\
&\mathbf{d}^* = \mathbf{d}(\mathbf{A}, \boldsymbol{\theta}^0, \mathbf{p}, Q)\\
&\boldsymbol{\theta}^* = \boldsymbol{\theta}(\mathbf{A}, \boldsymbol{\theta}^0, \mathbf{p}, Q).
\end{aligned}$$

If we were prepared to speculate about an equation of motion for the underlying fish stocks and about a planner's time preferences, then a more elegant approach to valuing information would be available. The value of information would be a consequence of the shape of tomorrow's objective function. The current approach is that it does not rely on such speculation, but is still consistent with the fact that fishery managers do want good harvest data.

The balance of the paper is devoted to solving the planner's problem (**??** and **??**). The next section solves for a fisher's responses to the different types of regulation. Section 5 solves some simple examples of the planner's problem, and Section 6 solves the planner's problem numerically using parameter values and densities estimated for the Scotia-Fundy Cod-Haddock-Pollock fishery.

4 Solving the fisher's problem

A planner's choice of quota program is governed by fishers' responses to the program. Hence, the three parts of this section describe a fisher's response to value-based, aggregated, and disaggregated quota programs. That is, this section solves for the profit maximizing choices of effort, discarding, and proportion, as functions of technology, prices, and regulation.

4.1 Value-based quota

Under a value-based quota program, a planner chooses a vector of weights, one for Cod, Haddock, and Pollock, and then allows a fisher to land any bundle of equal or lesser value. A fisher's problem is to choose effort, composition, and discarding to solve:

$$\begin{aligned}
\max_{x,d,\boldsymbol{\theta}} \quad & \Pi = \mathbf{p}\left(\boldsymbol{\theta}(A_0 x + \frac{A_1}{2}x^2) - \mathbf{d}\right) - cx \\
& \text{s.t. } \mathbf{p}\boldsymbol{\theta}(A_0 x + A_1 x^2) - d \leq \mathbf{pq} \\
& \theta_c \in \left[\underline{\theta_c}, \overline{\theta_c}\right] \\
& \theta_h \in \left[\underline{\theta_h}, \overline{\theta_h}\right] \\
& \theta_p \in \left[\underline{\theta_p}, \overline{\theta_p}\right] \\
& \theta_c + \theta_h + \theta_p = 1 \\
& x, \mathbf{d} \geq 0.
\end{aligned}$$

This problem may be solved with standard techniques, and expressions for $x^v(\mathbf{A}, \boldsymbol{\theta}^0, \mathbf{p}, \mathbf{q})$, $\mathbf{d}^v(\mathbf{A}, \boldsymbol{\theta}^0, \mathbf{p}, \mathbf{q})$, and $\boldsymbol{\theta}^v(\mathbf{A}, \boldsymbol{\theta}^0, \mathbf{p}, \mathbf{q})$ are given in Appendix 1.

To develop some intuition about a fisher's response to value-based quota, consider a fishery where there are only two types of fish and θ_1 is selected from the interval $[\underline{\theta}, \overline{\theta}]$.

1. If prices are low relative to costs then the quota is non-binding and effort and landings are increasing in prices. A fisher chooses the maximum or minimum value of θ according to whether $\frac{p_2}{p_1}$ is greater or less than 1.

2. As prices, rise the quota eventually binds. When this happens, the marginal return to harvesting goes to zero. Further harvesting requires that a fisher discard one dollar of fish for every additional dollar landed. Thus the supply of effort is unresponsive to changes in prices and no fish are discarded. A fisher chooses the maximum or minimum value of θ according to whether $\frac{p_2}{p_1}$ is greater or less than 1.

With value-based quota, the quantity of fish harvested depends on a planner's choice of q_1 and q_2 and on prices. Discarding never occurs, and harvest composition is the same as in an unregulated fishery.

4.2 Aggregated quota

To see that an aggregated quota program may lead to discarding of fish at sea, consider a fisher who harvests big and small fish in fixed proportions, where big fish are more valuable per pound than small. Suppose a planner issues aggregated quota allowing a fisher to land a certain weight of fish regardless of type. Since a planner does not observe discarding, fish discarded at sea will not count against a fisher's quota, and a fisher may discard little fish in order conserve his quota for more valuable big fish. The analysis below formalizes this intuition, provides a more precise description of fishing behavior, and identifies conditions under which discarding occurs.

Under an aggregated quota program, a planner chooses an aggregate weight of Cod, Haddock, and Pollock, and then allows a fisher to land any bundle of equal or lesser weight. A fisher's problem is to choose effort, composition, and discarding to solve:

$$\begin{aligned}
\max_{x,\mathbf{d},\boldsymbol{\theta}} \quad & \Pi = \mathbf{p}\left(\boldsymbol{\theta}(A_0 x + \frac{A_1}{2}x^2) - \mathbf{d}\right) - cx \\
& \text{s.t. } (A_0 x + \frac{A_1}{2}x^2) - d_c - d_h - d_p \le W \\
& \theta_c \in \left[\underline{\theta_c}, \overline{\theta_c}\right] \\
& \theta_h \in \left[\underline{\theta_h}, \overline{\theta_h}\right] \\
& \theta_p \in \left[\underline{\theta_p}, \overline{\theta_p}\right] \\
& \theta_c + \theta_h + \theta_p = 1 \\
& x, \mathbf{d} \ge 0,
\end{aligned}$$

Expressions for $x^a(\mathbf{A}, \boldsymbol{\theta}^0, \mathbf{p}, \mathbf{q}), \mathbf{d}^a(\mathbf{A}, \boldsymbol{\theta}^0, \mathbf{p}, \mathbf{q})$, and $\boldsymbol{\theta}^a(\mathbf{A}, \boldsymbol{\theta}^0, \mathbf{p}, \mathbf{q})$ are given in Appendix 1.

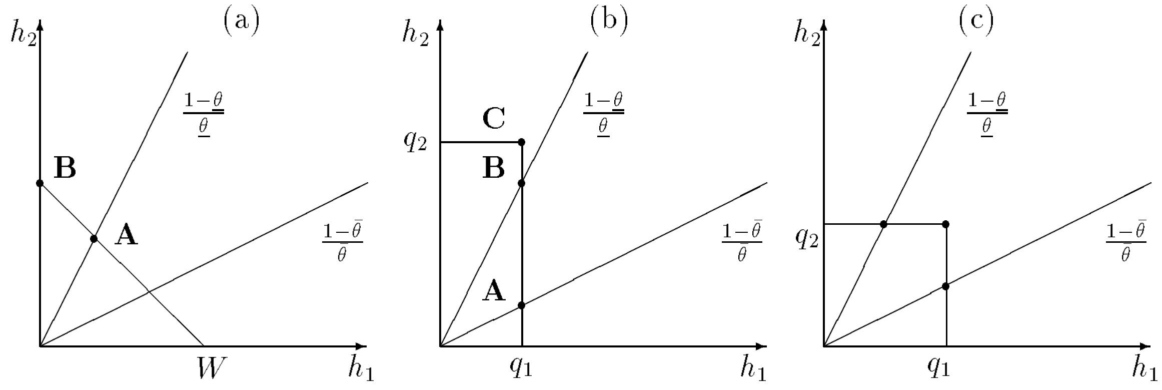
To develop some intuition about a fisher's response to aggregated quota, Figure 1a illustrates a two type fishery, where θ_1 is selected from the interval $[\underline{\theta}, \overline{\theta}]$, and a planner uses aggregated quota.

1. If prices are low relative to costs then the quota is not binding and effort and landings are increasing in prices. A fisher chooses the maximum or minimum value of θ according to whether $\frac{p_2}{p_1}$ is greater or less than 1.

2. As prices rise the quota eventually binds. When this happens, the marginal return to harvesting changes discretely because further harvesting requires a fisher to discard a unit of type 1 for each additional unit of type 2 harvested. Until the price of type 2 rises sufficiently to make this discarding profitable, effort does not respond to changes in price.

3. As prices rise further, a fisher harvests more of both types, discards type 1 in order to move along the boundary of the quota set from point A to point B. In this region effort and discarding are increasing in the price of type 2 and decreasing in the price of type 1.

Figure 1.



4. At point B, the quota binds and effort and discarding do not respond to changes in price. Additional harvests all have zero value to a fisher since they must be discarded.

In this example, the quantities of fish harvested and discarded are sensitive to a planner's choice of W. However the quota has no impact on harvest composition or a fisher's choice of which species to discard. These decisions are determined by prices and technological parameters about which a planner is uncertain. Behavior in the two-type fishery corresponds closely the three-type fishery with a small exception. In the three-type fishery the fisher discards all of the least valuable type before deciding to discard the intermediate type. Thus, return to effort undergoes discrete shifts at two points rather than just one.

4.3 Disaggregated quota

To see that a disaggregated quota program may lead to discarding of fish at sea, consider a fisher who harvests big and small fish in fixed proportions, and suppose a planner issues disaggregated quotas which specify limits for each type of fish. In this case, if a fisher fills his quota for one type of fish before he fills the other, then he may continue fishing until the second quota is filled, and discard any over-quota fish of the first type. The analysis below formalizes this intuition, provides a more precise description of fishing behavior, and identifies conditions under which discarding occurs.

Under a disaggregated quota program, a planner chooses target harvests for Cod, Haddock, and Pollock, and then allows a fisher to land any bundle that does not exceed any of the targets. A fisher's problem is to choose effort, composition, and discarding to solve:

$$
\begin{aligned}
\max_{x,d,\boldsymbol{\theta}} \quad & \Pi = \mathbf{p}\left(\boldsymbol{\theta}(A_0 x + \frac{A_1}{2}x^2) - \mathbf{d}\right) - cx \\
& \text{s.t. } \boldsymbol{\theta}(A_0 x + \frac{A_1}{2}x^2) - \mathbf{d} \leq \mathbf{q} \\
& \theta_c \in \left[\underline{\theta_c}, \overline{\theta_c}\right] \\
& \theta_h \in \left[\underline{\theta_h}, \overline{\theta_h}\right] \\
& \theta_p \in \left[\underline{\theta_p}, \overline{\theta_p}\right] \\
& \theta_c + \theta_h + \theta_p = 1 \\
& x, \mathbf{d} \geq 0.
\end{aligned}
$$

I solve this problem in two stages. A fisher chooses effort, conditional on a choice of $\boldsymbol{\theta}$, and then chooses $\boldsymbol{\theta}$. The first stage problem is,

$$
\begin{aligned}
\max_{x,\mathbf{d}} \quad & \Pi = \mathbf{p}\left(\boldsymbol{\theta}(A_0 x + \frac{A_1}{2}x^2) - \mathbf{d}\right) - cx \\
& \text{s.t. } \boldsymbol{\theta}(A_0 x + \frac{A_1}{2}x^2) - \mathbf{d} \leq \mathbf{q} \\
& x, \mathbf{d} \geq 0.
\end{aligned}
$$

This problem is solved with standard techniques, and expressions for $x^d(\mathbf{A}, \mathbf{p}, \mathbf{q}, |\boldsymbol{\theta})$ and $\mathbf{d}^d(\mathbf{A}, \mathbf{p}, \mathbf{q}, |\boldsymbol{\theta})$ are given in Appendix 1. Given these conditional effort and discarding functions, in Section 6 the profit maximizing choice of $\boldsymbol{\theta}$ is made numerically.

To get some intuition about behavior under this type of regulation, suppose there are only two types of fish and that θ_1 is selected from the interval $[\underline{\theta}, \overline{\theta}]$. A fisher's problem is illustrated in Figures 1b and c for two different quota programs. Begin with the case in Figure 1b, and suppose that $p_1 > p_2$.

1. If prices are low relative to costs, then the quota is not binding and effort and landings are increasing in prices. A fisher chooses the maximum, minimum, or any value of θ according to whether $\frac{p_2}{p_1}$ is greater, less, or equal to 1.

2. As prices rise, q_1 eventually binds.

3. As prices rise further a fisher shifts along the boundary of the quota set to point B.

4. Beyond point B, increases in effort generate only landings of type 1 (q_1 binds and type 1 must be discarded). Thus at point B effort is unresponsive to small changes in prices until the price of type 2 rises high enough that it is profitable to fish while retaining only type 1.

5. In the region between point B and C in Figure 1b, effort is increasing in the price of type 2, but invariant to changes in the price of type 1—marginal harvests of type 1 have zero value to a fisher because they must be discarded.

6. At point C in Figure 1a, both quotas are binding and effort does not respond to changes in price. Additional harvests all have zero value to a fisher since they must be discarded.

If $\frac{1-\underline{\theta}}{\underline{\theta}} > \frac{q_2}{q_1}$, instead of $\frac{1-\overline{\theta}}{\overline{\theta}} < \frac{q_2}{q_1}$, then the roles of 1 and 2 are reversed in the discussion above, though the intuition is unchanged. If $\frac{1-\overline{\theta}}{\overline{\theta}} < \frac{q_2}{q_1} < \frac{1-\underline{\theta}}{\underline{\theta}}$, as in Figure 1c, then we get somewhat different behavior.

1. If prices are low relative to costs then the quota is not binding and effort and landings are increasing in prices. A fisher chooses the maximum, minimum, or any value of θ according to whether $\frac{p_2}{p_1}$ is greater, less, or equal to 1.

2. As prices rise, then either q_1 or q_2 bind according to which type is more valuable. As prices rise further a fisher moves along the boundary of the quota set until both quotas bind. In this region effort is also increasing in prices.

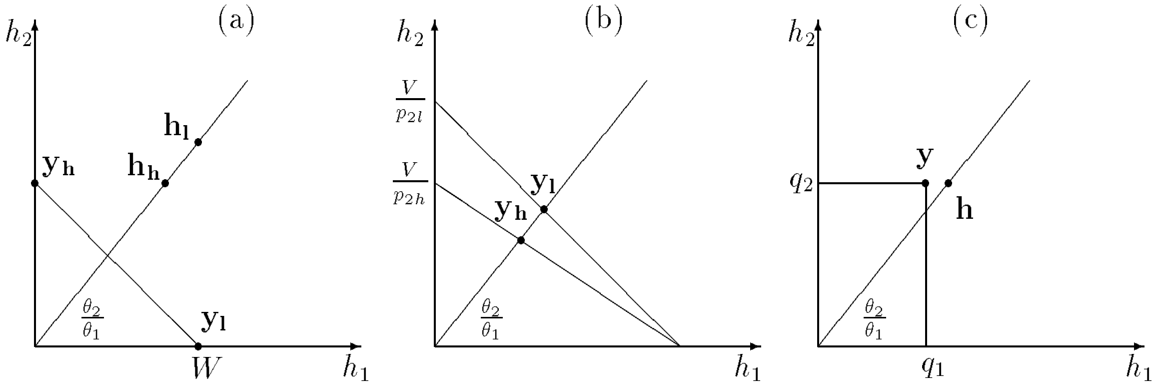
3. As prices rise still further, both quotas eventually bind and effort supply no longer responds to changes in price.

In this example, no discarding occurs, while in the example illustrated in Figure 1b, discarding of type 1 may or may not occur. From a planner's point of view these examples mean that the quantity of discarding and the choice of type to discard, as well as the composition of harvest and supply of effort, are all sensitive to the choice of q_1 and q_2 . However, the nature of this relationship depends on uncertain technological parameters, and prices.

4.4 Discussion

Fishers respond to the different types of quota in very different ways. Disaggregated quota provides the strongest incentive to discard. At the boundary of such a quota set it is profitable to discard if it is profitable to fish while retaining only one species. At the boundary of an aggregated quota set it is profitable to continue fishing only if it is profitable to fish only for one type and also discard one unit of a less valuable type for each unit of a more valuable type. Value-based quota, on the other hand, removes all incentive to discard. Disaggregated quota is the only regulation that affects the

Figure 2.



composition of harvest. Neither value-based or aggregated quota have any impact on this choice.[8]

5 Simple examples of the manager's problem

5.1 Only price uncertainty

Consider a fishery like the one presented in Sections 3 and 4, but, to simplify the problem, assume there are only two types of fish, that the cost of effort is negligibly small ($c0$), and that the fishing technology is fixed proportions (Θ is a singleton: $\theta_1 = 1 - \theta_2$). In this case, a regulated fisher's profit maximization problem is

$$\begin{aligned}
&\max_{x,d_1,d_2} \left[p_1\theta_1 + p_2(1-\theta_1)\right] F(x,\mathbf{A}) - p_1 d_1 - p_2 d_2 \\
&\text{s.t. } \left[\theta_1 F(x,\mathbf{A}) - d_1, (1-\theta_1)F(x,\mathbf{A}) - d_2\right] \in Q, \\
&d_1, d_2, x \geq 0.
\end{aligned}$$

Since effort is costless, a profit-maximizing fisher chooses harvests and discards to produce the revenue maximizing legal landings. Suppose that a planner'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 problem when he is subject to aggregated, disaggregated, and value-based individual quota. In each panel, the axes

[8]This is an artifact of the weak convexity of the technology. If the technology were strictly convex, then Value-based quota would have no effect on the choice of harvest composition, while aggregated quota could have small effects.

denote quantities of each type harvested and landed, and the locus of technologically feasible harvests is a line through the origin with slope $\frac{\theta_2}{\theta_1}$.

Figure 2a illustrates a fisher's behavior for each realization of prices when a planner chooses an aggregated quota program 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 the difference between the two. If p_2 is low, profit maximizing landings are $\mathbf{y}_l$, the associated harvest is $\mathbf{h}_l$, and discarding is the difference between the two.

With aggregated quota a planner is uncertain about the harvest, and the amount of discarding—although he can be sure that some discarding occurs. Given that technology is known for certain, after prices are revealed a planner can calculate the exact harvest, so there is no ex post uncertainty. With aggregated quotas and only price uncertainty, a planner can reasonably expect some unpredictable amount of discarding, and can know exactly what happened ex post. However, a planner cannot hit a target harvest with perfect accuracy (except where $\theta_1 = \frac{1}{2}$).

Figure 2b illustrates a fisher's behavior for each realization of prices when a planner chooses value-based quota, allowing landings of V dollars of harvest regardless of type. Since revenue is constant along the boundary of the quota set, a fisher can never gain by discarding, and a fisher's objective is to get to this boundary using as little effort as possible. For the high realization of p_2 this is accomplished by harvesting and landing $\mathbf{y}_h$. For the low realization of p_2 this is accomplished by harvesting and landing $\mathbf{y}_l$. It follows that, with value-based quotas and only price uncertainty a planner cannot be certain about the amount of fish that will be harvested until after prices are revealed. However, he can be sure that no discarding will occur and can know harvests exactly once landings are revealed.

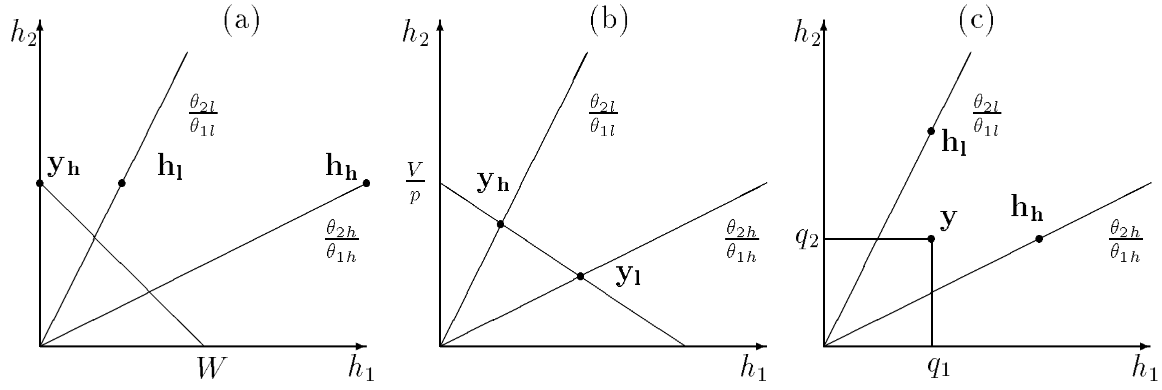
Figure 2c illustrates a fisher's behavior for each realization of prices when a planner chooses disaggregated quota allowing (q_1, q_2) of each type. For all positive prices, a fisher maximizes revenues by landing $\mathbf{y}$ and harvesting $\mathbf{h}$. Discarding is the difference between harvests and landings, and if a planner chooses $\frac{q_2}{q_1} = \frac{\theta_2}{\theta_1}$ harvests and landings coincide and discards are zero.

5.2 Only technological uncertainty

Now consider a second example, like the first except that prices are certain and technology is uncertain. In particular, suppose that $p_2 > p_1$ and that θ_1 takes the value $\theta_{1h} > \theta_{1l}$ at random.

Figure 3a illustrates a fisher's profit maximizing behavior for each realization of technology, conditional on a planner's choice of W pounds of aggregated quota. Since revenue is always maximized by landings $\mathbf{y}$, a fisher generates these landings regardless of the technology. If θ_{1l} occurs then a fisher chooses $\mathbf{h}_l$. If θ_{1h} occurs then a fisher chooses $\mathbf{h}_h$. Given technological uncertainty and aggregated quotas, a planner will

Figure 3.



know with certainty what landings will occur and that some discarding will occur with certainty. Since the same landings are observed for both realizations of θ_1, a planner will be uncertain both ex ante and ex post about the amount of fish that were harvested and the amount discarded.

Figure 3b illustrates a fisher's profit-maximizing behavior given technological uncertainty and value-based regulation. Since revenues are maximized at all points along the boundary of the quota set, profit maximization requires that a fisher get to this boundary using as little effort as possible. Since there is no incentive to discard, a planner is certain that harvests and landings coincide. Therefore, a planner is uncertain ex ante about landings and harvests, but after landings are revealed, he knows exactly what harvest occurred.

Figure 3c illustrates a fisher's behavior under disaggregated quota. Regardless of technology, revenues are maximized at $\mathbf{y}$. These revenues are achieved by harvesting $\mathbf{h}_l$ or $\mathbf{h}_h$ as θ takes its low or high value. In this case, a planner will know landings ex ante, but since the same landings are observed for both realizations of the technology, a planner is uncertain ex ante and ex post about harvests and discards.

¿From Figure 3 it is clear that value-based quota allows a planner to generate the same value of landings from strictly smaller harvests of fish. Moreover, value-based quota provides him with better ex post information about the harvest. On the other hand it is not obvious whether value-based quota allows a planner to achieve a target harvest with more or less accuracy than the other types.

5.3 Discussion

In the presence of technological or price uncertainty, the three different type of individual quota programs differ in the following four ways. (1) They allow different variances in realized landings. (2) They result in different amounts of discarding. (3) They differ in the ex ante variance of harvest. (4) Finally, they allow a planner to know harvests with different degrees of accuracy ex post, after landings and prices have been observed.

The first example demonstrates that when there is only price uncertainty, disaggregated quota is strictly better than the other types. It allows a planner to pick any technologically feasible harvest and to achieve this harvest with zero variance and zero discarding.

The second example demonstrates that when there is only technological uncertainty, value-based quota allows the same landings to be produced from strictly smaller harvests. It is unclear whether value-based quota is more or less accurate than disaggregated or aggregated quota. Altogether, these examples suggest that disaggregated quota programs will have an absolute advantage in environments where there is a lot of price uncertainty and not much technological uncertainty, and that value-based quota may perform relatively better in environments where there is a lot of technological uncertainty and not much price uncertainty.

6 Optimal quota for the The Scotia-Fundy Cod, Haddock, Pollock fishery

This section finds the optimal type of individual quota program for a particular fishery, the Scotia-Fundy Cod, Haddock, Pollock fishery in Atlantic Canada. The section is in two parts. Section 6.1 presents the estimated densities for prices and technology parameters ($g_{A_0}(A_0)$, $g_{A_1}(A_1)$, $g_p(\mathbf{p})$, and, $g_\theta(\theta_c, \theta_h)$), and describes a strategy for dealing with uncertainty about the social cost of harvests, $s(\mathbf{h}, p_s)$. Section 6.1 also develops estimates for the cost per unit effort parameter c, and the control of composition parameters (C_c, C_h, C_p). The details of these estimations are described in Appendix 2. Finally, section 6.1 also proposes tests to see how sensitive a planner's optimum is to errors in the specification of the model. Section 6.2 states the planner's problem and describes the numerical methods and results.

6.1 Estimated densities

The Scotia-Fundy Cod-Haddock-Pollock fishery is conducted in Atlantic Canada by mobile and fixed gear vessels. The mobile gear fishery consists of 324 vessels and accounts for 35% of the Cod, Haddock, and Pollock harvest from the region in 1991. We consider only vessels in this fleet that use mobile nets and specialize in Cod, Haddock and Pollock. Attention is restricted to this subset because, (1) the mobile and fixed gear vessels behave differently and are regulated separately, and (2), within the set of mobile gear vessels there are vessels that specialize in Cod, Haddock and Pollock. This specialization is reported by Department of Fisheries and Oceans (DFO) officials and is borne out in the data.[9] The available data consists of; daily price and landings data by species and vessel for all mobile gear vessels, daily aggregate landings of Cod, Haddock, and Pollock for mobile and fixed gear vessels, and highly aggregated cost information for mobile gear vessels.

I analyze this fishery for the following reasons. (1) The harvest is predominately only three species—among multi-species fisheries this is relatively simple. I could not find a multi-species fishery which harvested only two types, while fisheries harvesting tens of types are common. This makes analysis of this fishery relatively tractable. (2) Since the specialist vessels are only a fraction of the mobile fleet, which in turn accounts for only 35% of the landings from this fishery, which is in turn one of many regional fisheries, I can reasonably treat prices as exogenous. (3) The fishery is conducted with a very common gear type, trawling gear, for species which are widely subject to commercial exploitation. As such, results from this fishery are probably relevant to many other fisheries. (4) Finally, rudimentary cost data is available, for most fisheries cost data is not available at all.

With this said, there is an important problem with the data. The Scotia-Fundy fishery is regulated by a disaggregated tradable quota program during 1991 and the data records landings and not harvests.[10] At first glance, the analysis of Section 4 suggests the possibility of making inferences about the harvesting technology, given enough data about landings, prices, and regulations. In fact the harvesting technology is only identifiable through assumptions about functional form. Landings data cannot distinguish a harvest technology allowing any harvest less than x for one unit of effort, from a harvest technology allowing only x to be harvested for a unit of effort, and any amount of fish to be costlessly discarding. This intuition appears to be quite general and in particular is robust to costly discarding.

I solve this problem with the simplest possible identifying assumption; that harvests and landings perfectly coincide. This assumption is consistent with the fact that fishery managers are not aware of quota induced discarding (managers sometimes are aware of such problems, see Muse 1991). It is also consistent with the high variability in the proportions of each type in the harvest. (see Table 6.1 and

[9]There are 162 mobile vessels for which Cod, Haddock, and Pollock comprised more than 70% of their annual harvest. For these vessels Cod, Haddock, and Pollock comprised 84% of their annual harvest, versus 50% for non-specialist. Specialists vessels are responsible for about 80% of the mobile fleet's harvest.

[10]Data sets which reflect harvests reather than landings are available only for fisheries in which harvests are recorded by shipboard observers. Such observed fisheries are conducted by larger boats which typically harvest large numbers of species from several off shore fishing grounds. All of the observed fisheries I found were too complex for the purposes of this paper.

Appendix 2). We would expect low variability in proportions if disaggregated quotas were always binding.

Densities of $\mathbf{A}, \mathbf{p}$, and $\boldsymbol{\theta}^0$ Table ?? gives estimated densities for $\mathbf{p}, \mathbf{A}$, and $\boldsymbol{\theta}^0$. A realization of g_p is a price per kilogram of each type of fish (in 1991 Canadian dollars). I use trips per month as a measure of variable effort, x. Hence, a realization of g_{A_0} or g_{A_1} is a parameter which relates trips per month to kilograms (of all types) per month. A realization of g_θ is the proportion of Cod and Haddock in the harvest for a particular month. The residual fraction is Pollock.

Control of proportions Results in the appendix indicate that, while proportions are sensitive to changes in prices, they are not very sensitive. If we regress θ_c, θ_h and, θ_p on prices and vessel characteristics, and then allow prices to vary within one standard deviation of their respective means, proportions stay in the following intervals: Proportion Cod$\in [0.49, 0.58]$, Proportion Haddock$\in [0.17, 0.26]$, Proportion Pollock$\in [0.25, 0.25]$. These price driven changes in proportions provide an ad hoc measure of the degree to which fishers control the composition of their harvest. In particular, choose C_i to be half the amount of variance induced in harvest proportions by a one standard deviation in prices. Thus $(C_c, C_h, C_p) = (0.045, 0.045, 0.00)$. Since this is an ad hoc measure of control, I check whether the planner's optimum is sensitive to this assumption by also considering the case when fishers have no control and $(C_c, C_h, C_p) = (0.0, 0.0, 0.0)$.

Fishing costs Data on fishing costs come from 1991 interviews by DFO personnel with vessel captains. Interviewers spoke to skippers or owners of 31 mobile net vessels in the 35-45 foot range, and to 26 mobile net vessels in the 45-65 foot range. The interviewers collected information on a variety of variable, fixed, and labor costs. The resulting cost data overlap imperfectly with landings data: not all of the surveyed vessels were Cod, Haddock, Pollock specialists, and not all specialist vessels reported.

Evaluating the planner's problem requires an estimate of per trip variable costs. To construct this estimate, sum the annual variable and labor costs[11] for the surveyed boats, and divide by the average number of trips taken by a mobile vessel in 1991. There were 84 vessels less than 45' with annual variable costs of \$115,922, and 76 vessels longer than 45' with annual variable costs of \$228,884. Together these 160[12]

[11] Variable costs included in the survey are: fuel, bait, ice, salt, provisions, workmens compensation, non-fish labour, facilities operating, other operating, repair and maintenance, gear expense. Labor costs include the crewshare, and the skipper's share. In the event that the skipper is the owner, the skipper's share is not available so this will understates labor costs.

[12] Length was not reported for two of the 162 specialist vessels and these vessels are ommtted from cost calculations.

Price Density

$$g_p(p) = \begin{cases} 0.833 & \text{if} \quad p = (1.22, 1.67, 0.67) \\ 0.833 & \text{if} \quad p = (1.27, 1.73, 0.76) \\ 0.833 & \text{if} \quad p = (1.28, 1.74, 0.78) \\ 0.833 & \text{if} \quad p = (1.21, 1.86, 0.75) \\ 0.833 & \text{if} \quad p = (1.20, 1.89, 0.74) \\ 0.833 & \text{if} \quad p = (1.19, 1.59, 0.77) \\ 0.833 & \text{if} \quad p = (1.22, 1.56, 0.77) \\ 0.833 & \text{if} \quad p = (1.24, 1.54, 0.74) \\ 0.833 & \text{if} \quad p = (1.24, 1.54, 0.78) \\ 0.833 & \text{if} \quad p = (1.27, 1.60, 0.84) \\ 0.833 & \text{if} \quad p = (1.28, , 1.55, 0.81) \\ 0.833 & \text{if} \quad p = (1.28, 1.65, 0.78) \end{cases}$$

Production parameter densities

$$g_{A_0}(A_0) = \begin{cases} \frac{1}{128} & \text{if} \quad A_0 = 196 \\ \frac{7}{128} & \text{if} \quad A_0 = 485 \\ \frac{21}{128} & \text{if} \quad A_0 = 774 \\ \frac{35}{128} & \text{if} \quad A_0 = 1063 \\ \frac{35}{128} & \text{if} \quad A_0 = 1353 \\ \frac{21}{128} & \text{if} \quad A_0 = 1642 \\ \frac{7}{128} & \text{if} \quad A_0 = 1931 \\ \frac{1}{128} & \text{if} \quad A_0 = 2220 \end{cases} \qquad g_{A_1}(\tfrac{A_1}{2}) = \begin{cases} \frac{35}{99} & \text{if} \quad -12.5 \\ \frac{35}{99} & \text{if} \quad -27.5 \\ \frac{21}{99} & \text{if} \quad -42.6 \\ \frac{7}{99} & \text{if} \quad -57.7 \\ \frac{1}{99} & \text{if} \quad -72.8 \end{cases}$$

Proportions Density

$g_{\boldsymbol{\theta}^0}(\theta_c^0, \theta_h^0) =$

θ_c^0 \ θ_h^0	$.0\overline{3}$	$.1\overline{3}$	$.2\overline{3}$	$.3\overline{3}$	$.4\overline{3}$	$.5\overline{3}$	$.6\overline{3}$	$.7\overline{3}$	$.8\overline{3}$	$.9\overline{3}$
$.0\overline{3}$	.037	.006	.005	.001	.002	.000	.000	.002	.001	.013
$.1\overline{3}$	.040	.014	.006	.005	.003	.006	.002	.005	.012	
$.2\overline{3}$	.032	.022	.005	.006	.006	.007	.014	.016		
$.3\overline{3}$	.047	.015	.012	.011	.013	.022	.013			
$.4\overline{3}$	.041	.006	.011	.011	.021	.015				
$.5\overline{3}$	.035	.021	.022	.021	.013					
$.6\overline{3}$	.039	.021	.021	.015						
$.7\overline{3}$	.046	.021	.014							
$.8\overline{3}$	.049	.027								
$.9\overline{3}$	.132									

Table 1: Parameter densities

vessels made 13,355 trips in 1991. This results in an average cost per trip of \$2,032. The survey does not provide information on the variance of these estimates.[13]

At this cost per trip, given technology parameters, an average fisher chooses zero trips per month for most possible draws of prices, technology, and $\boldsymbol{\theta}^0$. This probably reflects an increasing, rather than constant marginal cost of trips. However, the data provides no basis for estimating a second order cost term. Instead I use the cost parameter to calibrate the model. If we choose c so that at sample average values for p, and θ, an unregulated fisher chooses the sample average number of trips (11.69/month for the specialist fleet), then $c = \$1045$/trip. This is within a factor of two of DFO's estimate.

The discussion above suggests that the actual profit function may be more concave than the one that I have specified and estimated. To check the implications of a more concave profit function, make the current profit function more concave by doubling the mean of A_1 to -55.2, while holding its variance constant, and adjusting c to \$664/trip. These changes increase the concavity of the profit function while keeping average trips per month constant for average values of $\mathbf{p}$, $\boldsymbol{\theta}$ and A_1.

Social cost of harvests Uncertainty over the social cost of harvests is so great that it cannot reasonably be reduced to parametric uncertainty without using an intractably large number of parameters. Instead consider two families of social cost function, one for which different types are perfect complements and one for which they are perfect substitutes, and then allow the slope and intercepts of these two functions to vary.

The logic for considering these two "pure" cases follows. Since only disaggregated quota allows a planner to exercise any control over harvest proportions and since Leontief social cost function gives a planner a strong preference over harvest proportions, if we find that value-based or aggregated quota is preferred under the Leontief function, we can reasonably expect aggregated quota to be preferred for most types of cost functions. Conversely, since the perfect substitutes social cost function does not prefer any particular composition, if disaggregated quota is preferred under this type of social cost function, then it is probably preferred under all types.

More specifically, consider the following families of social cost functions, where p_s and $\overline{\mathbf{h}}$ vary:

$$\begin{aligned} s(h_{\text{cod}}, h_{\text{had}}, h_{\text{pok}}, p_s) &= \\ & p_s \max\left(\max\left[0, h_{\text{cod}} - \overline{h_{\text{cod}}}\right], \max\left[0, h_{\text{had}} - \overline{h_{\text{had}}}\right], \max[0, h_{\text{pok}} - \overline{h}_{\text{pok}}]\right) \end{aligned} \tag{3}$$

[13]Although disaggregated cost data exists, confidentiality requirements prohibit its release except in aggregated form.

$$s(h_{\text{cod}}, h_{\text{had}}, h_{\text{pok}}, p_s) = \quad (4)$$
$$p_s \left(\max\left[0, h_{\text{cod}} - \overline{h_{\text{cod}}}\right] + \max\left[0, h_{\text{had}} - \overline{h_{\text{had}}}\right] + \max[0, h_{\text{pok}} - \overline{h}_{\text{pok}}]\right)$$

These two functions are respectively, Leontief and perfect substitutes. The $\overline{h}$'s allow the social cost of harvests to be zero in a neighborhood of the origin. This is important for two reasons. (1) If the social value of the stock is positive near the origin then simulations indicate that the optimal policy is to drive harvest nearly to zero for all but very small values of p_s. (2) Allowing positive values of $\overline{h}$ converts these functions into piecewise linear approximations of convex functions. By allowing the value of p_s to vary, I allow the marginal social cost of harvests to vary.

There is a second justification for using the Leontief preferences of **??**. Harvests are often determined by political or biological considerations, and then given to a fishery manager to implement. In this case a manager has little discretion in choice of harvests and is likely to put a high value on achieving a harvest that does not exceed the target. In 1991, these targets were $\overline{\mathbf{h}} = (5697, 1443, 5125)$, per specialist vessel, per month, for Cod, Haddock, and Pollock respectively.[14] If we use these values in **??** and interpret p_s as a planner's aversion to exceeding his target, then these preferences reflect the political and administrative process actually in place, and can be justified by revealed preference arguments.

6.2 Solving the manager's problem

For each type of quota program, a planner would like to solve for the amount of quota that maximizes social welfare as given by **??**. Given the densities listed in the last section, this problem becomes:

$$\max_{Q} \sum_{\mathbf{A},\boldsymbol{\theta}^0,\mathbf{p}} \left[\mathbf{p}(\boldsymbol{\theta}^* \left(A_0 x + \frac{A_1}{2}x^2\right) - \mathbf{d}^*) - cx^* - s(\mathbf{h}, p_s)\right] g_{A_0}(A_0) g_{A_1}(A_1) g_p(\mathbf{p}) g_\theta(\theta_c, \theta_h)$$
$$\text{s.t. } x^* = x(\mathbf{A}, \boldsymbol{\theta}^0, \mathbf{p}, Q) \quad (5)$$
$$\mathbf{d}^* = \mathbf{d}(\mathbf{A}, \boldsymbol{\theta}^0, \mathbf{p}, Q)$$
$$\boldsymbol{\theta}^* = \boldsymbol{\theta}(\mathbf{A}, \boldsymbol{\theta}^0, \mathbf{p}, Q).$$

To solve this problem we first sum over the pdf's of $\mathbf{p}, (\theta_c, \theta_h)$, A_0, and A_1, and then optimize with respect to Q. The problem is complicated by the non-differentiability

[14] I calculated these targets by dividing the target harvest for the Cod-Haddock-Pollock specialist fleet for 1991 by 12 and by the number of vessels. This gives the monthly target harvest for an average vessel.

of the constraint functions, $x^*(\mathbf{A}, \boldsymbol{\theta}^0\mathbf{p}, Q)$ and $\mathbf{d}^*(\mathbf{A}, \boldsymbol{\theta}^0\mathbf{p}, Q)$, and the discontinuity of $\boldsymbol{\theta}^* = \boldsymbol{\theta}(\mathbf{A}, \boldsymbol{\theta}^0\mathbf{p}, Q)$.

This section presents numerical solutions to this problem under a variety of different assumptions (described below). Solutions are calculated by the GQOPT software package. Initial runs of the optimization procedure applied the Davidson-Fletcher-Powell algorithm and the Gradient method iteratively until the two solution methods agreed on a solution. This process was too slow so subsequent optimization is conducted with the DFP algorithm alone.[15] The two solution methods almost always agreed to 3 or 4 significant figures. As a further check on the solutions, for a few cases I evaluated the objective functions at a large number of grid points in order to confirm that the procedure arrived at a global rather than a local maximum. The only cases when the algorithm failed to converge were for large starting values of quota. This is unsurprising since the objective is flat in this region—the quota is non-binding. In addition to individually testing the different parts of the algorithm, I also used the program to evaluate problems based on the two examples of Section 5. The solutions it produced were correct.

Best guess cases: First consider the solution to **??** when all densities and parameters take their estimated values, and a planner places a zero social value on small harvests. Figures 4a and b present the maximum welfare that can be achieved with each quota type, for the two different social value functions, as p_s ranges between 0 and 10, when $\overline{\mathbf{h}} = (5697, 1443, 5125)$. At about .7\$/kilogram a planner loses interest in conservation and becomes indifferent between regulatory instruments. When the fish stock is more valuable, disaggregated quota programs can generate significantly higher welfare than value-based quota, which in turn generate higher welfare than aggregated quota programs.

Figures 4c and d are identical to 4a and 4b, except that $\overline{\mathbf{h}} = (100.0, 100.0, 100.0)$. As in 4a and 4b, there is little basis for preferring one type to another when the marginal value of the stock is low. Unlike the 4a and 4b, there is also little basis for preferring one type to another when the marginal value of the stock is high. With these welfare functions, if a planner cares at all about conserving fish, then he cares enough that he wants to shut down the fishery, and each quota type does this equally well. Although the difference between types is too small to be visible in the figures, disaggregated quota is still preferred to value-based quota which is preferred to aggregated quota.[16]

[15] Even with this simplification, it typically took 18 hours of processing time (on computer with a Pentium microprocessor with a 100mhz clock-speed) to generate each of the figures presented below.

[16] While the figures only allow p_s to range over 0 to 10, for figures 4a-d, I also evaluated the problem as p_s ranged from 10 to 20. The rankings were unchanged in this region.

In general, the behavior illustrated in Figure 4a-d conforms to our intuition. (1) Welfare increases as the marginal social cost of harvests declines and welfare is higher as $\overline{\mathbf{h}}$ as is larger. (2) Welfare is the same under all quota types when $p_s = 0$. In this case the manager's problem and the fisher's problem coincide, and the planner optimally chooses regulation that is never binding. (3) Although it is barely visible in the figures, welfare is higher under perfect substitutes than Leontief since the region where marginal social value is zero is larger.

Sensitivity check—change in control of harvest composition: Figures 4a-d suggest that disaggregated quota programs cannot be worse than the alternatives, and may be considerably better. To check the robustness of this result to changes in a fisher's degree of control over harvest composition, I set the fisher's control over composition to zero (i.e. $(C_c, C_h, C_p) = (0.0, 0.0, 0.0)$ instead of $(C_c, C_h, C_p) = (0.045, 0.045, 0.00.)$ and duplicate the "best guess" analysis of Figures 4a and 4b. These results are presented in Figures 5a and 5b.

These figures show that welfare decreases when fishers have less control over harvest composition. They also confirm the dominance of disaggregated quota. Although the first result was expected, the second was surprising. Since disaggregated quota is the only type that allows a planner to manipulate the composition of harvest, my expectation was that as control over harvest composition became less important, disaggregated quota would cease to dominate. While the comparative advantage of disaggregated quota is smaller when fishers do not control harvest composition, disaggregated quota continues to win out.

Sensitivity check—more concave profit function: The calibration of the cost per trip parameter suggested that costs per trip may be increasing rather than constant. If so, a fisher's profit function would be more concave. Figures 6a and 6b duplicate the analysis of Figures 4a and 4b when (1) the mean of A_1 is doubled to -55.2, variance constant, and (2) c is decreased to \$642/trip. These changes cause the profit function to become more convex and keep the number of trips constant at average parameter values. While disaggregated quota is dominant over most of the range of p_s, unlike the other examples, for large values of p_s value-based quota is slightly superior to disaggregated quota.

By increasing the concavity of a fisher's profit function I reduce the sensitivity of his behavior to changes in prices. This effectively reduces the importance of price uncertainty relative to technological uncertainty. Thus the results of this test are consistent with the intuition suggested by the examples of Section 5—value-based quota performs relatively better as price uncertainty is less important. It is worth noting that the only other way that I could invert the rankings of value and disaggregated quota was to follow the second example of Section 5.2 and eliminate price uncertainty while leaving technological parameters uncertain. This resulted in slightly higher welfare for value-based quota than for disaggregated quota. This result is also consistent with the intuition suggested by the examples of Section 5.

Expected value and standard deviation of harvests and discards: A planner is interested in the mean and standard deviation of harvests and discarding. Figures 7a-d present these quantities for the different quota types, for the example illustrated in Figure 4b. In Figures 7a and b we see that harvest standard deviation is about equal to the harvest mean for all three types of quota, even though the quota is selected in a way that reflects a planner's aversion to harvest variance. Note that this figure shows (1) that discarding is zero when p_s is zero and regulation is non-binding, (2) that discarding rises for low values of p_s when a planner is more concerned about fishing inputs than the stock, and (3) falls as the stock becomes more valuable. These figures, as well as 7c and d are similar to those (not presented) that correspond to Figures 4acd, 5ab, 6ab.

Figure 7c shows that on average very little of the harvest is discarded and confirms that discarding is more prevalent under disaggregated quota than under aggregated quota. Figure 7d shows that the standard deviation of discarding is large, it accounts for about one tenth of the harvest variance, and is about ten times as large as the mean amount of discarding. This reflects the fact that discarding is costly for fishers and occurs only in high productivity states, which occur with low probability.

Ex post standard deviation of discarding: The version of the planner's problem described by **??** does not reflect a planner's desire to have good ex post estimates of harvest.

Since a planner observes both landings and prices ex post, if prices and landings provide information about the level of discarding, his ex post estimate will be more accurate. Given the low standard deviation of discarding reported in Figures 7d, this suggests that a planner's ex post estimate of harvests should be very accurate.

To calculate the expected value of the ex post standard deviation of a planner's estimate of harvest, I employ the following procedure. For given parameter values, find the largest possible landings. Given this number, divide the set of possible observed landings into 100 equal "bins". Now assign every realization of prices and landings to one of the 1200 resulting price/landings bins. Calculate the probability of observing a price/landings realization in each bin. Conditional on observing a price/landings realization in a particular bin, calculate the standard deviation of discarding for states in the bin. Together these two calculations describe a random variable whose realizations are the standard deviation of a planner's ex post estimate of discarding. Taking the expectation of this variable gives a planner's expected ex post standard deviation in estimating the harvest.

I calculated this expected ex post standard deviation for every quota program analyzed in Figures 4-6. In no case was it even as large as 10 kilograms. This result appears to be driven by the fact that the probability of discarding is quite low, so that for most states of the world a planner can be certain that no discarding is occurring. As expected this standard deviation changes inversely with the number of bins, though these changes are not dramatic. Changing the number of bins from 12 to 12000 typically decreases the expected ex post standard deviation by a little more than one order of magnitude. Figure 8 graphs the ex post standard deviation of harvest for the example of Figure 4b.

Since value-based quota always allows a planner to estimate discarding with perfect accuracy, value-based quota provides strictly better estimates of the harvest ex post. Given that the ex post uncertainty over the magnitude of discarding is so small, this advantage could not plausibly reverse the ranking of regulatory instruments. I conclude from this that the solutions to **??** and **??** coincide.

6.3 Conclusion

This paper considers the regulation of a multi-product fishery when technology, prices, and stock abundance are uncertain, and discarding is unobserved. More specifically, it identifies the type of individual quota program, disaggregated, value-based, or aggregated, that maximizes welfare.

Four aspects of the analysis are novel. First, it chooses an instrument on the basis of an expected welfare calculation, where this calculation is based on estimated densities. This is at variance with most applied work, which makes welfare calculations on the basis of estimated parameter means. Second, the paper allows the optimal regulatory program to adjust in response to the possibility of non-compliance. Previous analyses of non-compliance have been largely positive. Third, this paper considers the possibility that the planner will adjust the regulatory program in order to generate better ex post information about the level of non-compliant behavior. This is also novel. Finally, the paper considers the regulation of a joint production industry. This is a topic that has received relatively little attention in the environmental economics literature.

The analysis conducted here also gives insight into how the different regulatory instruments behave. It finds that (1) none of the regulatory instruments allow a planner to hit a target harvest very accurately, (2) discarding is a relatively small problem, (3) ex post estimates of harvests based on observed landings and prices are very accurate.

The following extensions are also of interest and are the subject of future research.

First, restricting a planner to choose value-based, aggregated, or disaggregated quota involves restricting the slope and shape of the boundary of the quota set. What is the shape of the optimal quota set if we allow the manager more latitude in the choice of this shape? Second, failure to meet the quota implicitly involves no benefit, while exceeding it involves an infinite penalty for the fisher. One might also want to consider the repurchase of unused quota at the end of the season and the sale of additional quota during the season, i.e., the sorts of subsidies and pressure valves described by Roberts and Spence (1976).

Finally, while this paper has concerned itself primarily with regulations for a particular fishery, this fishery is characterized by joint production, along with uncertainty over technology, prices and compliance. These characteristics are also common to a number of other regulated industries, e.g., regulated smokestacks which emit a combination of compounds, trade quotas on certain agricultural products, and the management of forests which contain many types of trees. Thus, much of the intuition and methodology developed here extends to this broader class of problems.

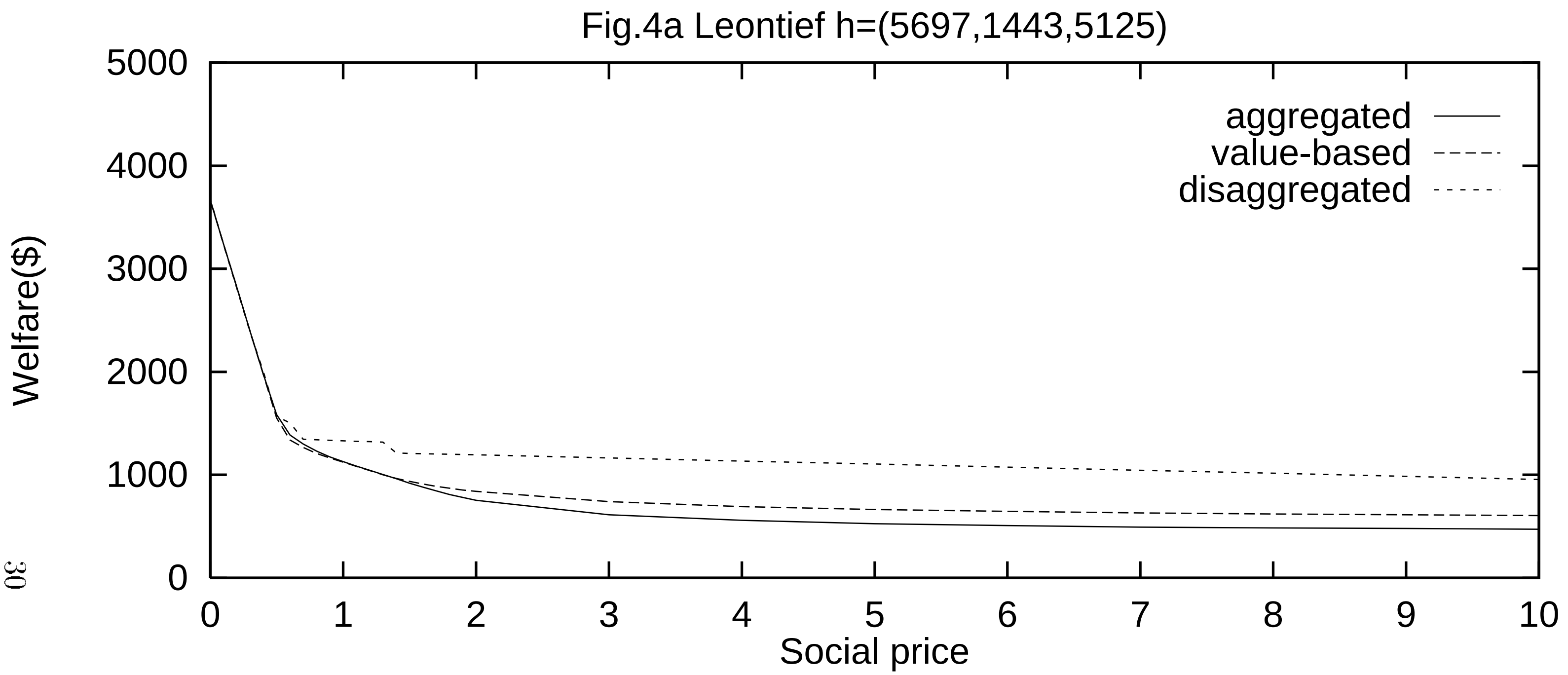
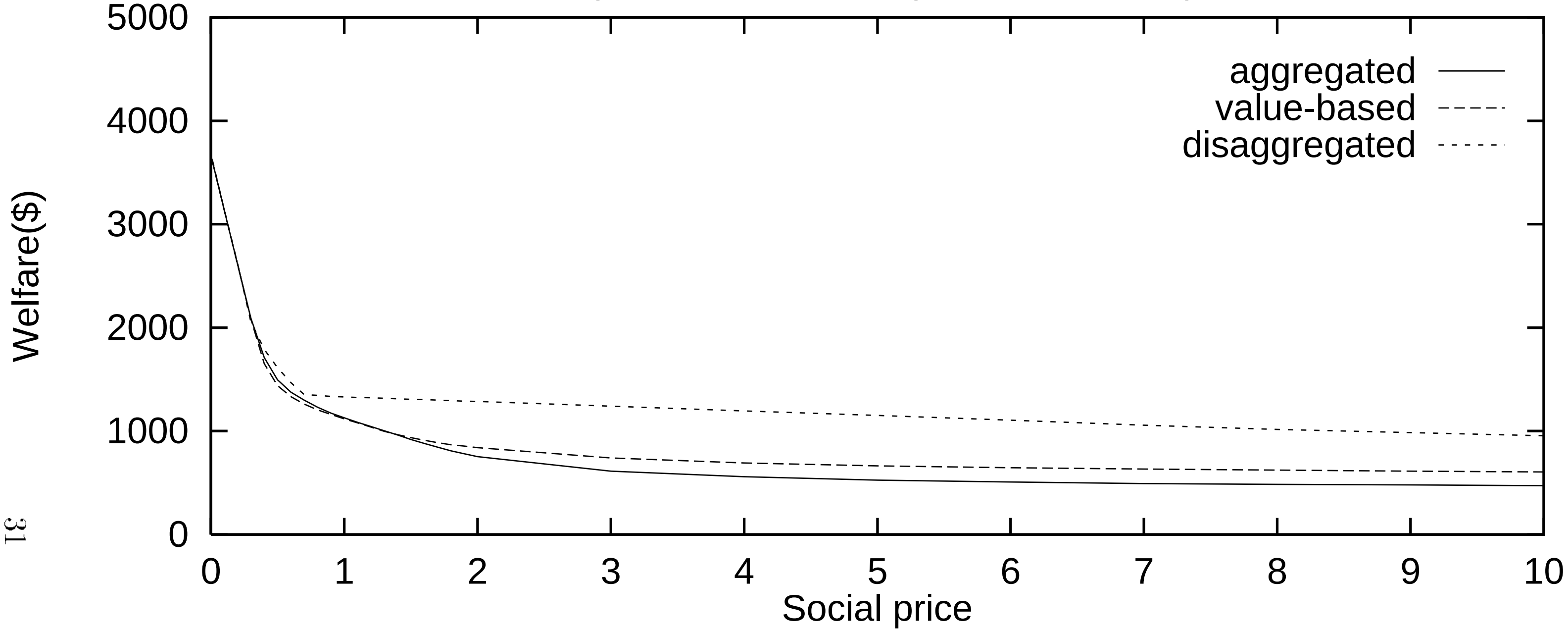


Fig.4a Leontief h=(5697,1443,5125)
Welfare($)
5000
4000
3000
2000
1000
0
0
1
2
3
4
5
6
7
8
9
10
Social price
aggregated
value-based
disaggregated

Fig.4b Substitutes h=(5697,1443,5125)



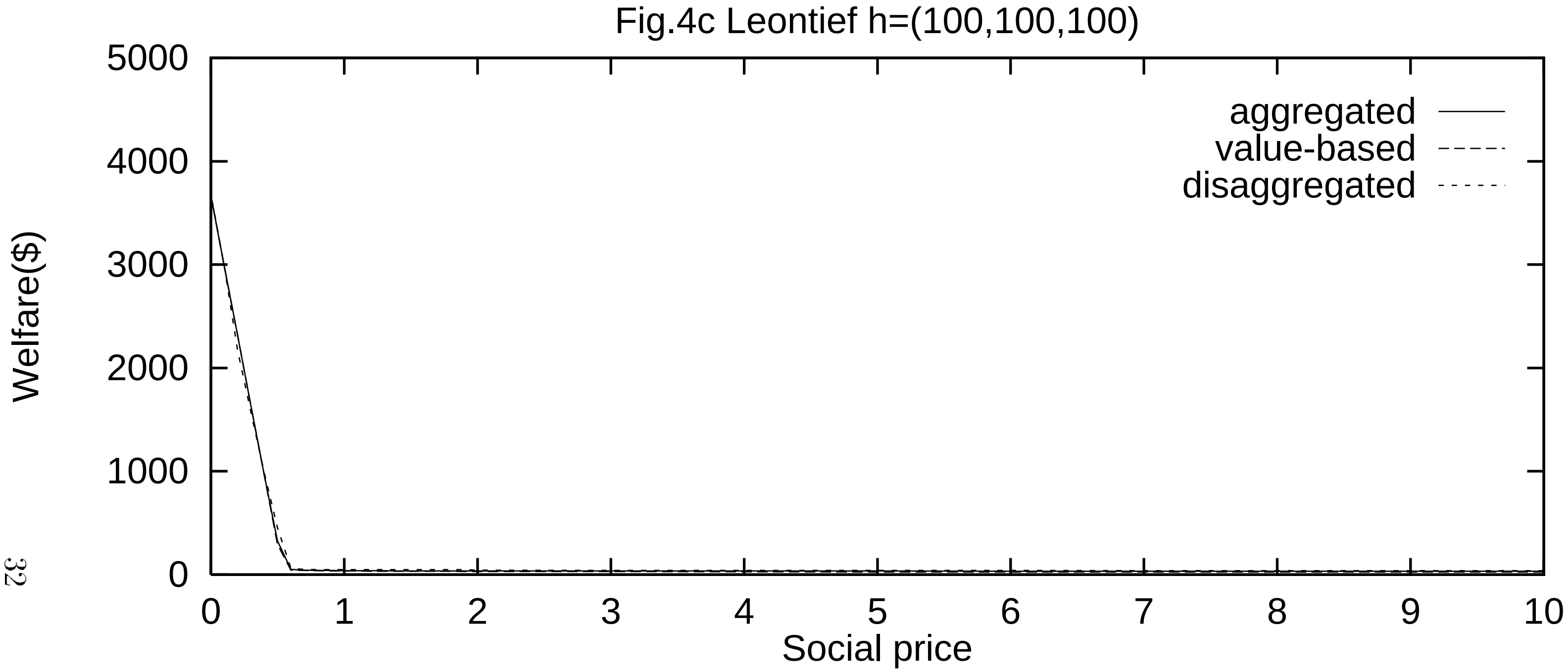


Fig.4c Leontief h=(100,100,100)
Welfare($)
5000
4000
3000
2000
1000
0
0
1
2
3
4
5
6
7
8
9
10
Social price
aggregated
value-based
disaggregated

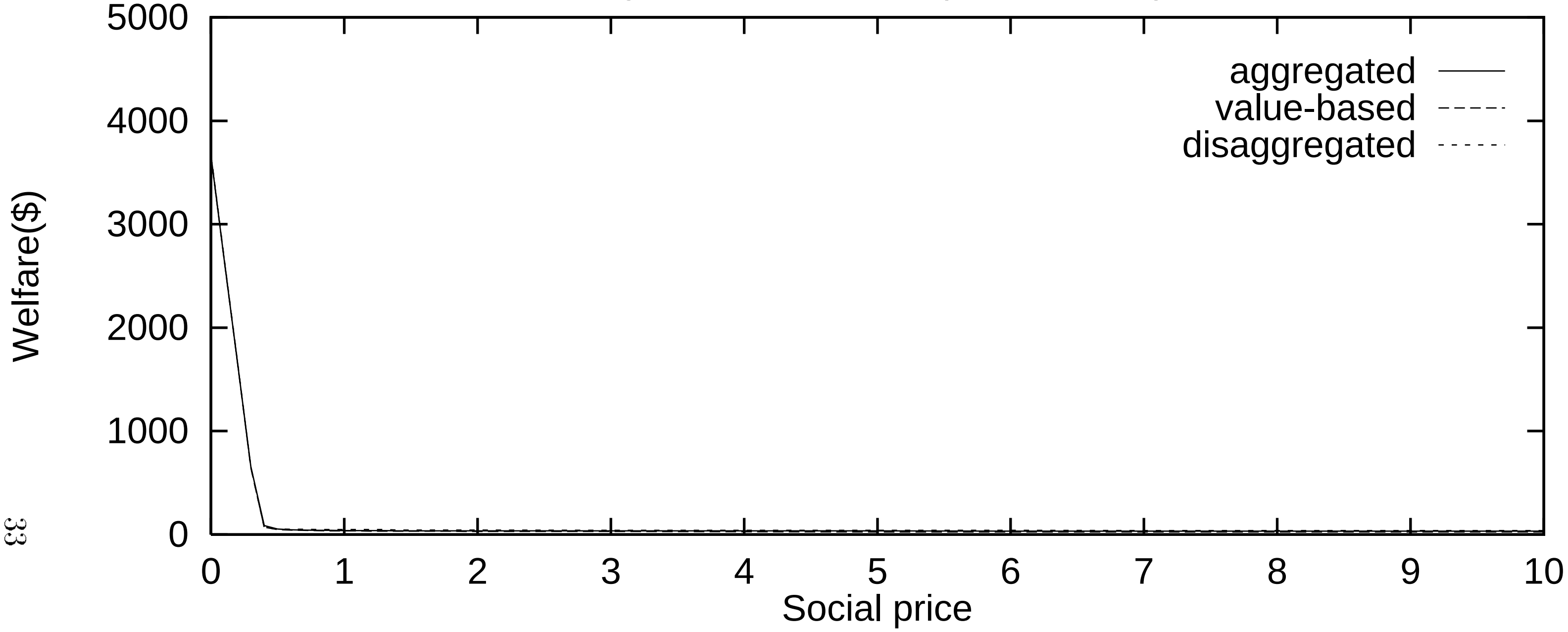


Fig.4d Substitutes h=(100,100,100)

Fig.5a Leontief h=(5697,1443,5125) no control

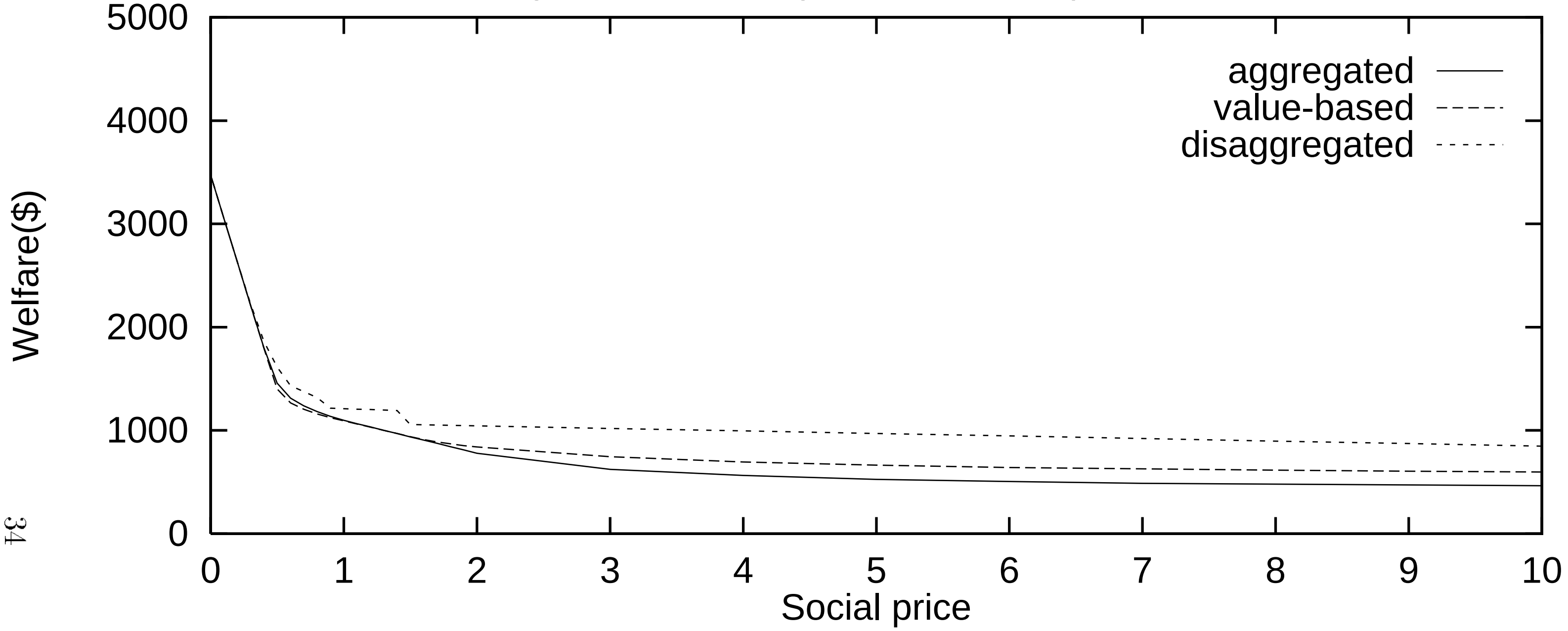


Fig.5b Substitutes h=(5697,1443,5125) no control

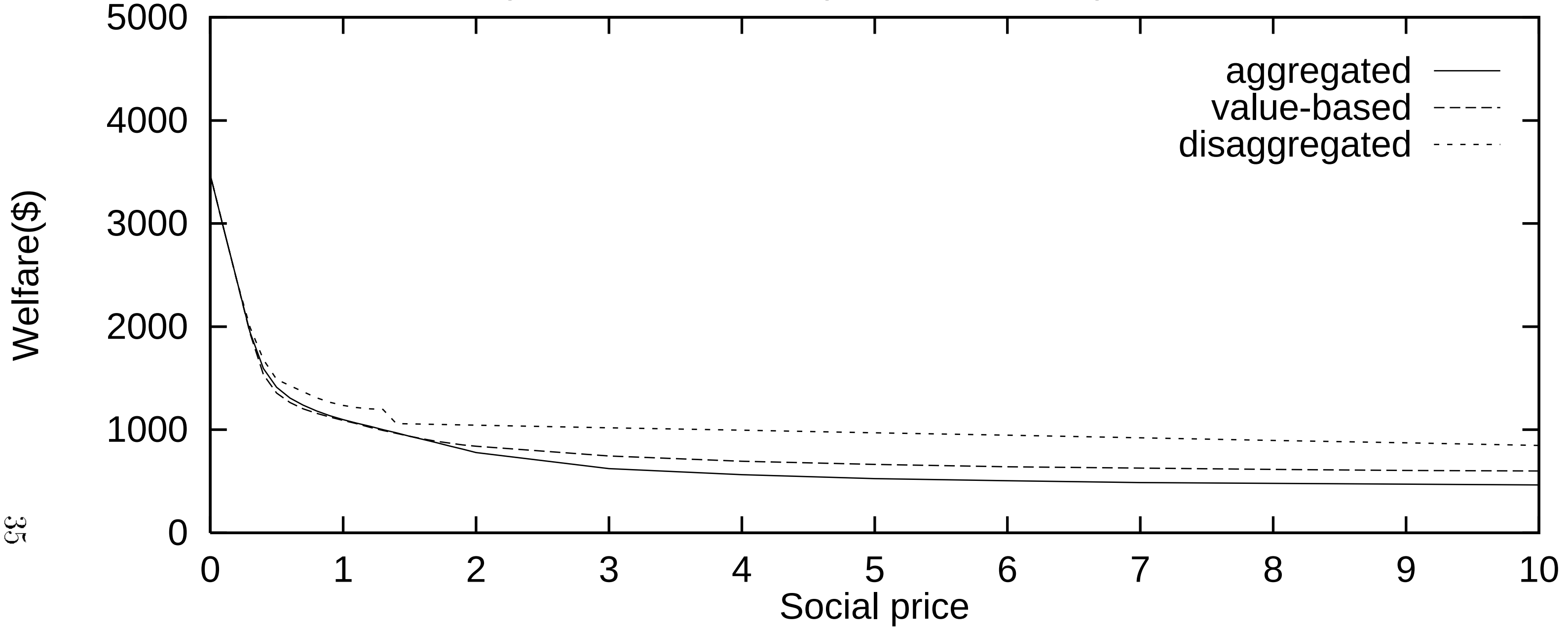


Fig.6a Leontief h=(5697,1443,5125) more concave

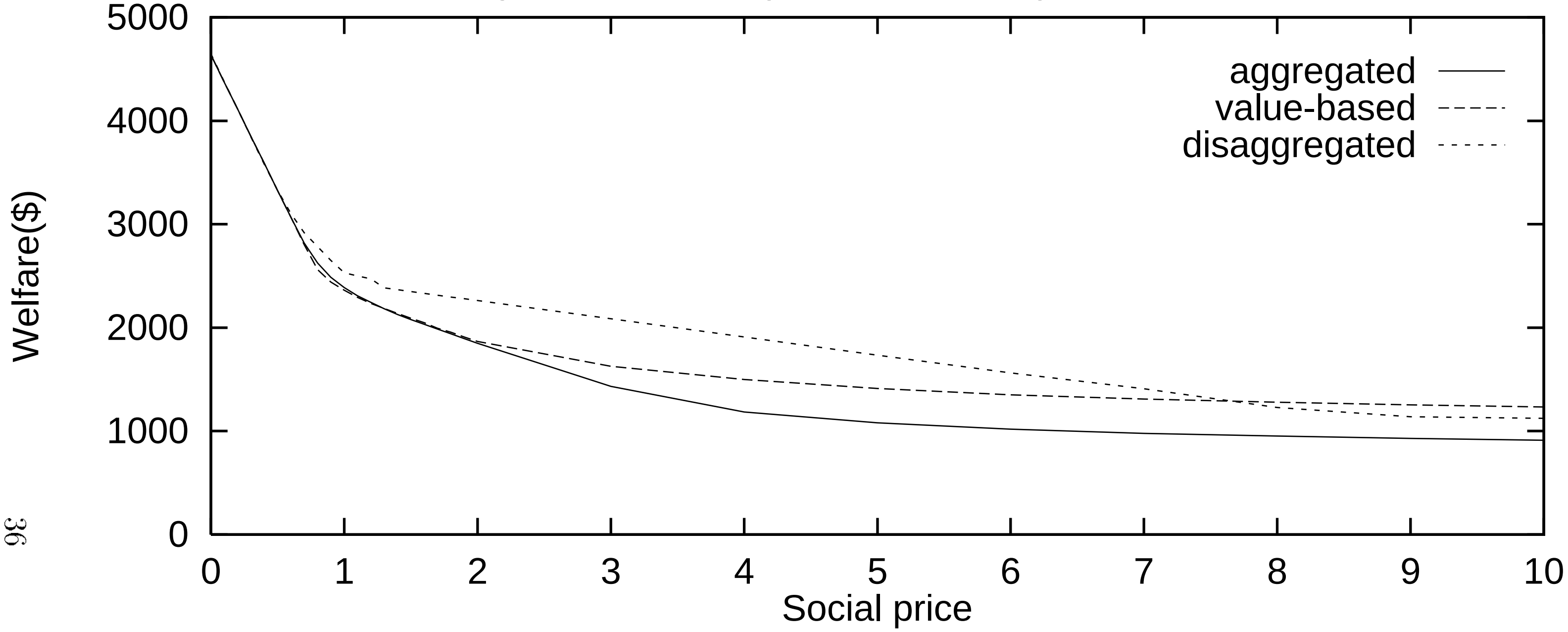


Fig.6b Substitutes h=(5697,1443,5125) more concave

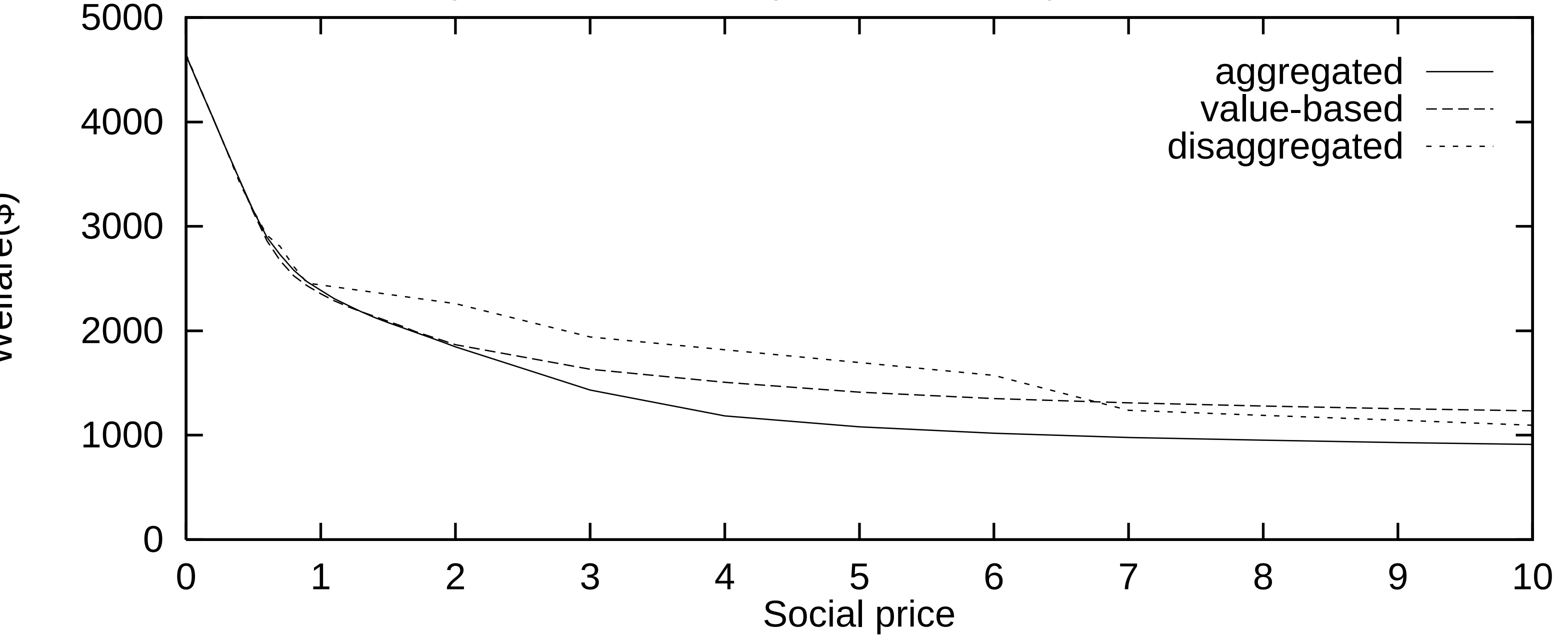


Fig.7a Expected harvests: Substitutes h=(5697,1443,5125)

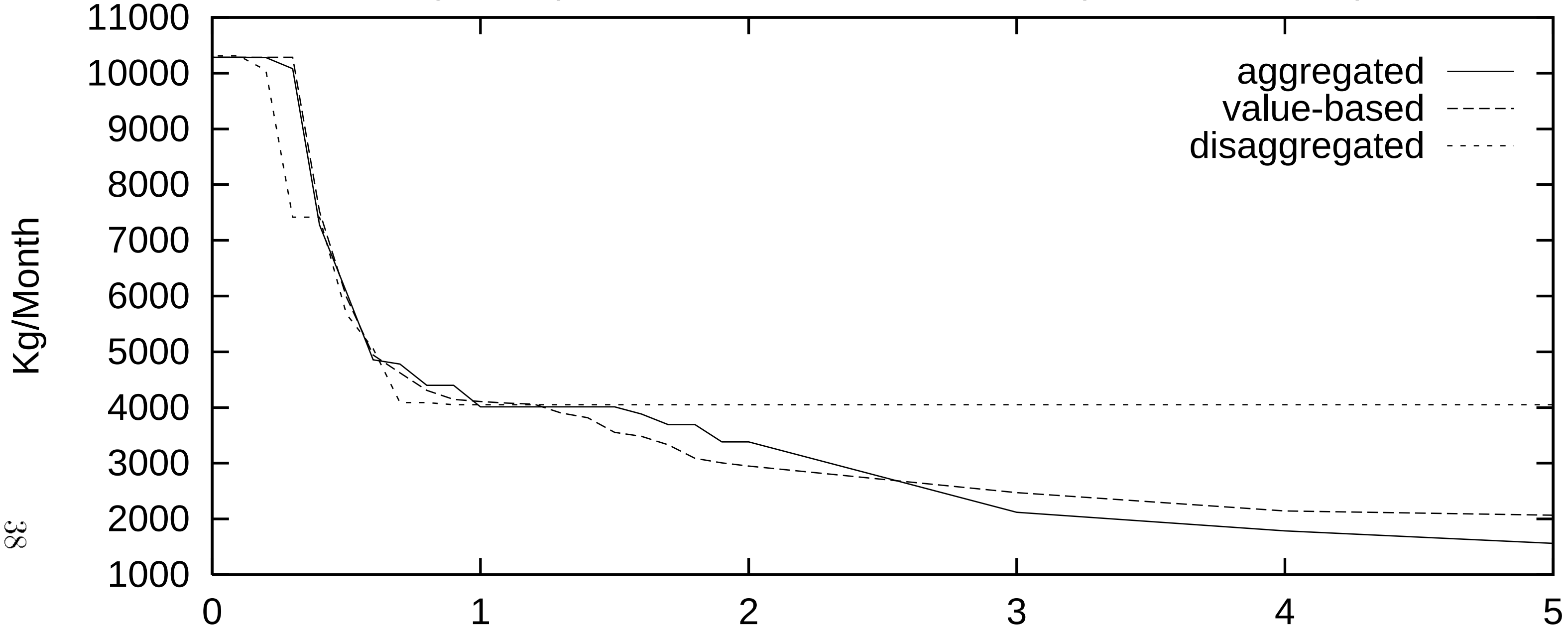


Fig.7b Harvest SD: Substitutes h=(5697,1443,5125)

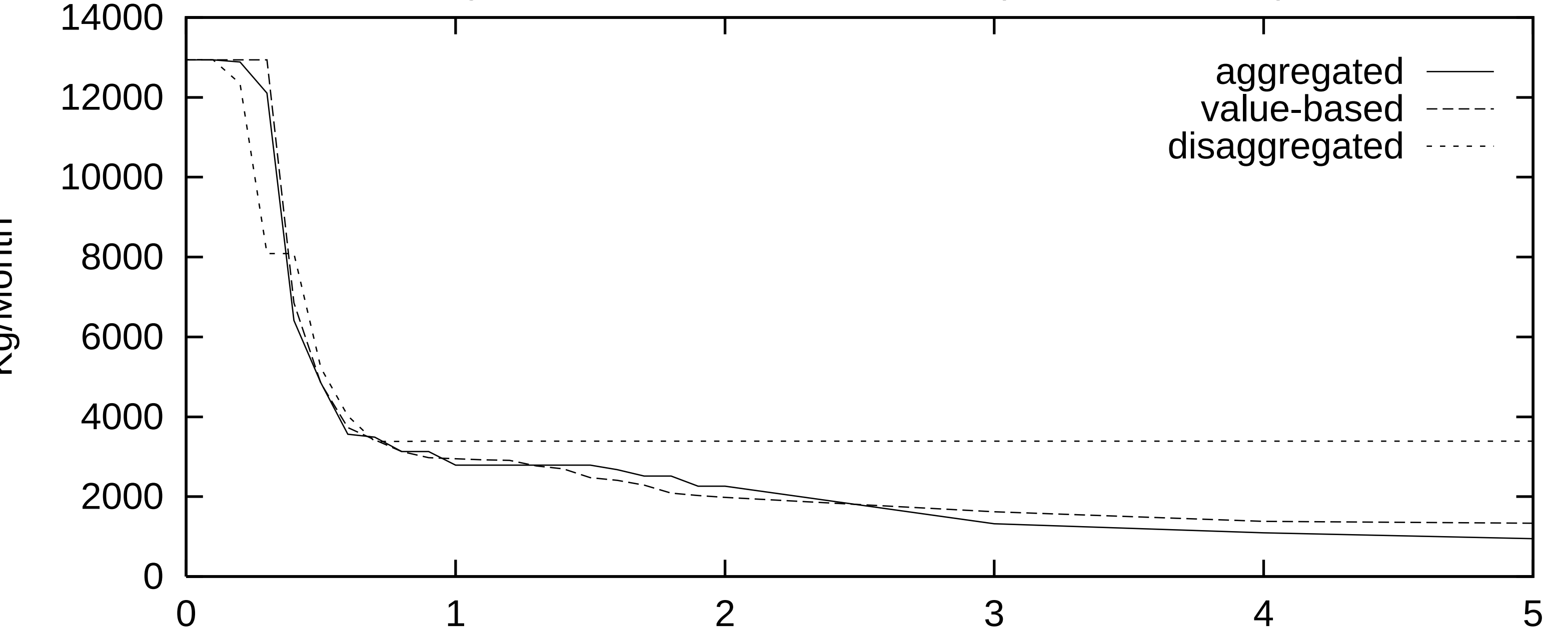


Fig 7c Expected discarding: Substitutes h=(5697,1443,5125)

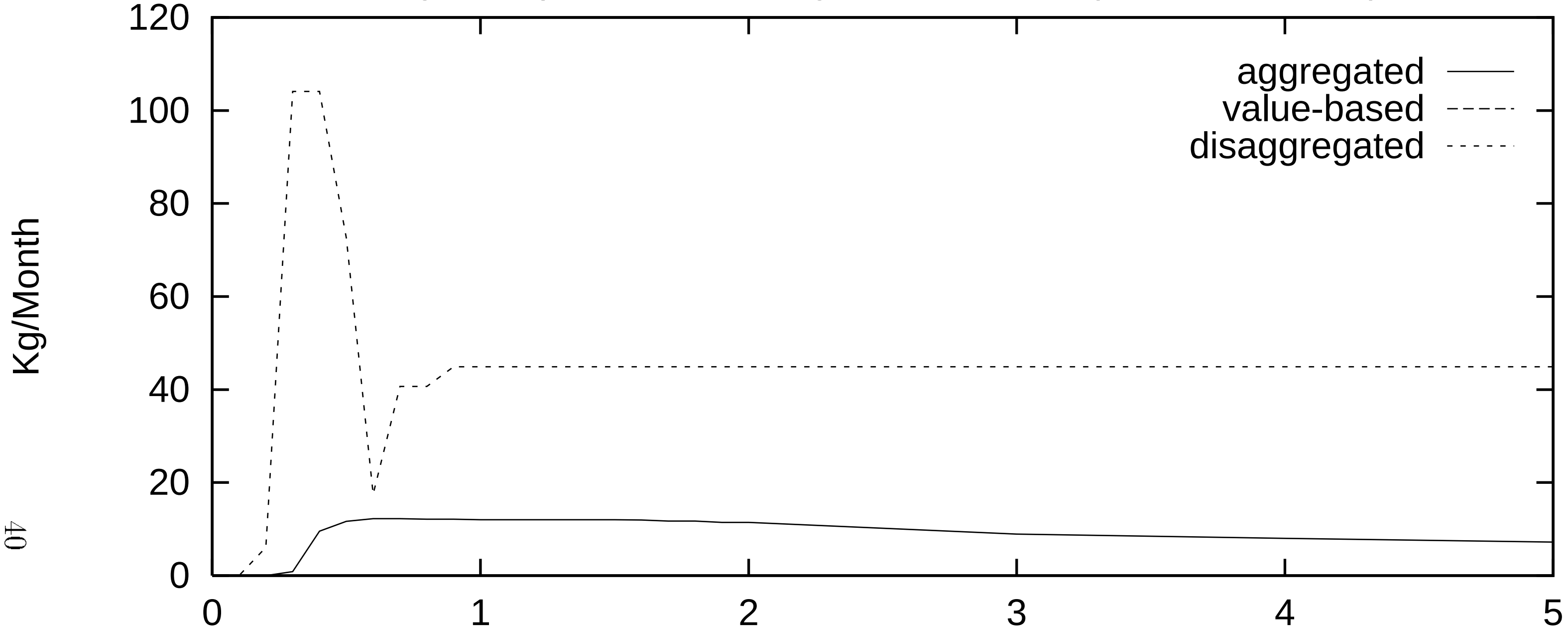


Fig 7d SD of discarding: Substitutes h=(5697,1443,5125)

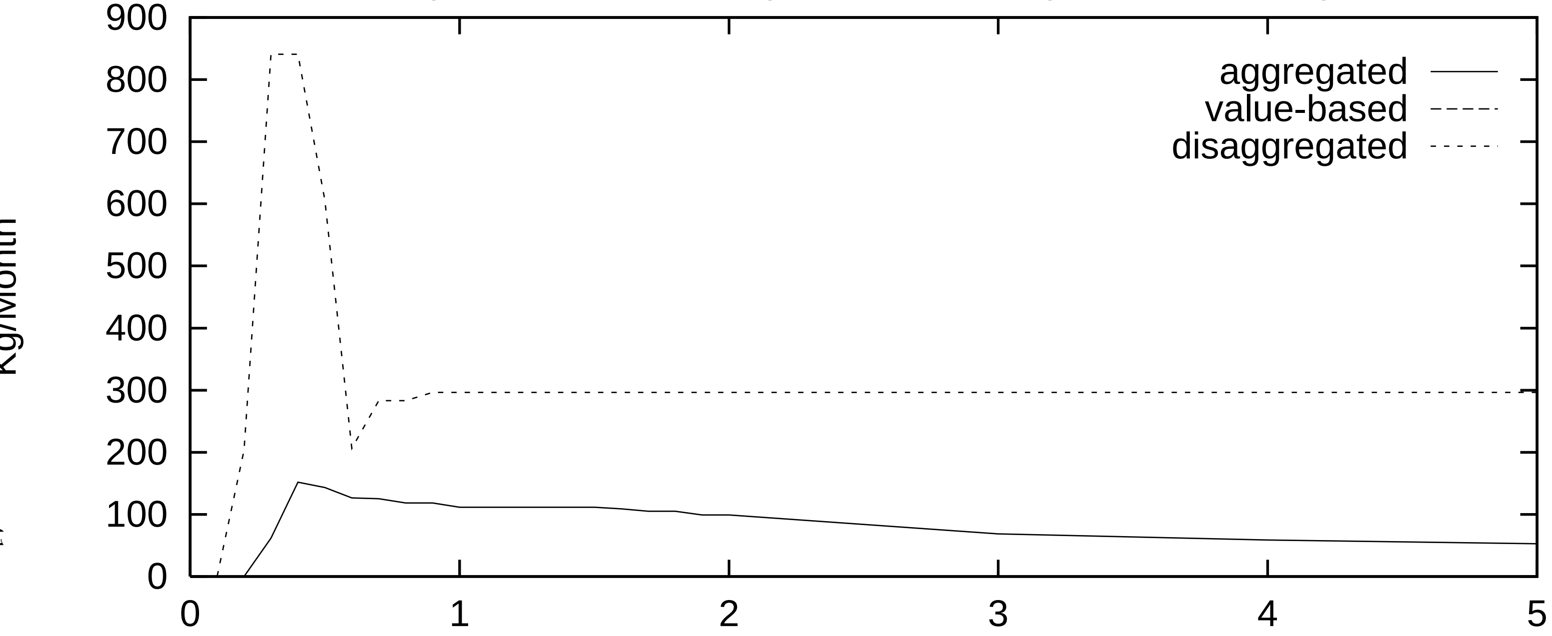
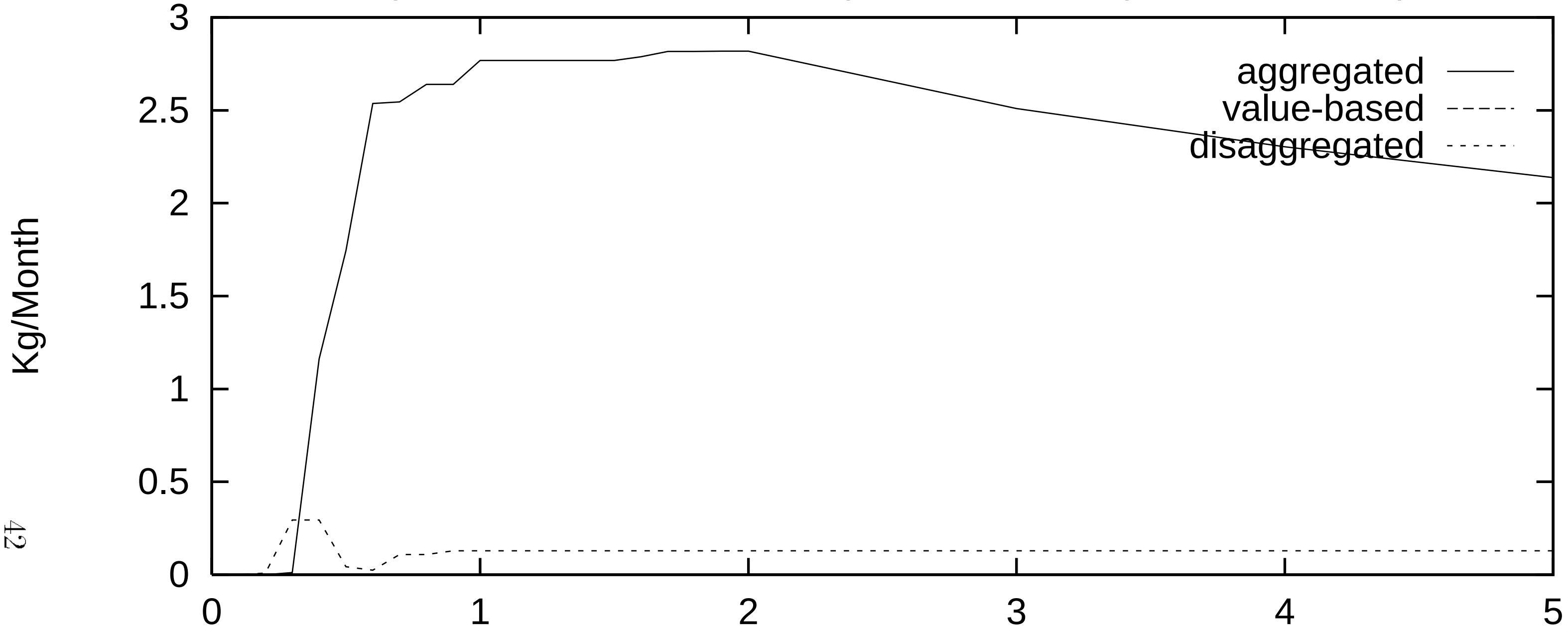


Fig.8 Ex Post SD of discarding: Substitutes h=(5697,1443,5125)



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7 Appendix 1: Analytical solutions to fisher's problem

7.1 Value-based quota

In a value-based quota program, a planner chooses vector of weights, one for Cod, Haddock, and Pollock, and then allows a fisher to land any bundle of equal or lesser value. Thus a fisher's problem is to choose effort, composition, and discarding to solve:

$$\begin{aligned}
\max_{x,d,\boldsymbol{\theta}} \quad & \Pi = \mathbf{p}\left(\boldsymbol{\theta}(A_0 x + \frac{A_1}{2}x^2) - \mathbf{d}\right) - cx \\
& \text{s.t. } \mathbf{p}\left[\boldsymbol{\theta}(A_0 x + A_1 x^2) - \mathbf{d}\right] \leq \mathbf{pq} \\
& \theta_c \in \left[\underline{\theta_c}, \overline{\theta_c}\right] \\
& \theta_h \in \left[\underline{\theta_h}, \overline{\theta_h}\right] \\
& \theta_p \in \left[\underline{\theta_p}, \overline{\theta_p}\right] \\
& \theta_c + \theta_h + \theta_p = 1 \\
& x, \mathbf{d} \geq 0,
\end{aligned}$$

where A_0, A_1, $\overline{\boldsymbol{\theta}}$, and $\underline{\boldsymbol{\theta}}$, are the estimated values from Section 6.1. Solving this problem with standard techniques shows that a fisher's profit maximizing choices of effort and discarding are given by:

$$\begin{aligned} x^v(\mathbf{A}, \boldsymbol{\theta}^0, \mathbf{p}, \mathbf{q}) &= \begin{cases} \frac{c}{\boldsymbol{\theta}\mathbf{p}A_1} - \frac{A_0}{A_1} & \text{if } \mathbf{pq} \geq \mathbf{p}\boldsymbol{\theta}F\left(\frac{c}{\boldsymbol{\theta}\mathbf{p}A_1} - \frac{A_0}{A_1}\right) \\ -\left(\frac{A_0^2}{A_1^2} + \frac{2\mathbf{pq}}{\mathbf{p}\boldsymbol{\theta}\mathbf{A}_1}\right)^{\frac{1}{2}} - \frac{A_0}{A_1} & \text{if } \mathbf{pq} < \mathbf{p}\boldsymbol{\theta}F\left(\frac{c}{\boldsymbol{\theta}\mathbf{p}A_1} - \frac{A_0}{A_1}\right) \end{cases} \\ \mathbf{d}^v(\mathbf{A}, \boldsymbol{\theta}^0, \mathbf{p}, \mathbf{q}) &= \mathbf{0}. \end{aligned}$$

The choice of $\boldsymbol{\theta}$ is made as follows. If $p_i \geq p_j \geq p_k$, then $\theta_k = \underline{\theta}_k$, $\theta_i = \overline{\theta}_i$, and $\theta_j = 1 - \underline{\theta}_k - \overline{\theta}_i$

7.2 Aggregated quota

In an aggregated quota program, a planner chooses an aggregate weight of Cod, Haddock, and Pollock, and then allows a fisher to land any bundle of equal or lesser weight. A fisher's problem is to choose effort, composition, and discarding to solve:

$$\begin{aligned} \max_{x, \mathbf{d}, \boldsymbol{\theta}} \quad & \Pi = \mathbf{p}\left(\boldsymbol{\theta}(A_0 x + \frac{A_1}{2}x^2) - \mathbf{d}\right) - cx \\ & \text{s.t. } (A_0 x + \frac{A_1}{2}x^2) - d_1 - d_h - d_p \leq W \\ & \theta_c \in \left[\underline{\theta_c}, \overline{\theta_c}\right] \\ & \theta_h \in \left[\underline{\theta_h}, \overline{\theta_h}\right] \\ & \theta_p \in \left[\underline{\theta_p}, \overline{\theta_p}\right] \\ & \theta_c + \theta_h + \theta_p = 1 \\ & x, \mathbf{d} \geq 0, \end{aligned}$$

where A_0, A_1, $\overline{\boldsymbol{\theta}}$, and $\underline{\boldsymbol{\theta}}$, are the estimated values from Section 6.1. If $p_k \geq p_j \geq p_i$, then solving this problem with standard techniques gives a fisher's profit maximizing choices of effort and discarding:

$$
x^a(\mathbf{A}, \boldsymbol{\theta}^0, \mathbf{p}, \mathbf{q}) = \begin{cases}
\frac{c}{\boldsymbol{\theta}\mathbf{p}A_1} - \frac{A_0}{A_1} & \text{if} \quad W \geq F\left(\frac{c}{\boldsymbol{\theta}\mathbf{p}A_1} - \frac{A_0}{A_1}\right) \\
-\left(\frac{A_0^2}{A_1^2} + \frac{2W}{A_1}\right)^{\frac{1}{2}} - \frac{A_0}{A_1} & \text{if} \quad W \geq F\left(\frac{c}{(\boldsymbol{\theta}\mathbf{p}-\mathbf{p}_i)A_1} - \frac{A_0}{A_1}\right) \\
& \text{and} \quad W < F\left(\frac{c}{\boldsymbol{\theta}\mathbf{p}A_1} - \frac{A_0}{A_1}\right) \\
\frac{c}{(\boldsymbol{\theta}\mathbf{p}-\mathbf{p}_i)A_1} - \frac{A_0}{A_1} & \text{if} \quad W \geq (1-\theta_i)F\left(\frac{c}{(\boldsymbol{\theta}\mathbf{p}-\mathbf{p}_i)A_1} - \frac{A_0}{A_1}\right) \\
& \text{and} \quad W < F\left(\frac{c}{(\boldsymbol{\theta}\mathbf{p}-\mathbf{p}_i)A_1} - \frac{A_0}{A_1}\right) \\
-\left(\frac{A_0^2}{A_1^2} + \frac{2W}{(1-\theta_i)A_1}\right)^{\frac{1}{2}} - \frac{A_0}{A_1} & \text{if} \quad W \geq (1-\theta_i)F\left(\frac{c}{\theta_k(p_k-p_j)A_1} - \frac{A_0}{A_1}\right) \\
& \text{and} \quad W < (1-\theta_i)F\left(\frac{c}{(\boldsymbol{\theta}\mathbf{p}-\mathbf{p}_i)A_1} - \frac{A_0}{A_1}\right) \\
\frac{c}{\theta_k(p_k-p_j)A_1} - \frac{A_0}{A_1} & \text{if} \quad W \geq \theta_k F\left(\frac{c}{\theta_k(p_k-p_j)A_1} - \frac{A_0}{A_1}\right) \\
& \text{and} \quad W < (1-\theta_i)F\left(\frac{c}{\theta_k(p_k-p_j)A_1} - \frac{A_0}{A_1}\right) \\
-\left(\frac{A_0^2}{A_1^2} + \frac{2W}{\theta_k A_1}\right)^{\frac{1}{2}} - \frac{A_0}{A_1} & \text{if} \quad W < \theta_k F\left(\frac{c}{\theta_k(p_k-p_j)A_1} - \frac{A_0}{A_1}\right)
\end{cases}
$$

$$
d_i^a(\mathbf{A}, \boldsymbol{\theta}^0, \mathbf{p}, \mathbf{q}) = \begin{cases}
0 & \text{if} \quad W \geq F\left(\frac{c}{(\boldsymbol{\theta}\mathbf{p}-\mathbf{p}_i)A_1} - \frac{A_0}{A_1}\right) \\
F\left(\frac{c}{(\boldsymbol{\theta}\mathbf{p}-\mathbf{p}_i)A_1} - \frac{A_0}{A_1}\right) - W & \text{if} \quad W \geq (1-\theta_i)F\left(\frac{c}{(\boldsymbol{\theta}\mathbf{p}-\mathbf{p}_i)A_1} - \frac{A_0}{A_1}\right) \\
& \text{and} \quad W < F\left(\frac{c}{(\boldsymbol{\theta}\mathbf{p}-\mathbf{p}_i)A_1} - \frac{A_0}{A_1}\right) \\
\frac{\theta_i}{1-\theta_i}W & \text{if} \quad W \geq (1-\theta_i)F\left(\frac{c}{(\boldsymbol{\theta}\mathbf{p}-\mathbf{p}_i)A_1} - \frac{A_0}{A_1}\right) \\
& \text{and} \quad W < (1-\theta_i)F\left(\frac{c}{\theta_k(p_k-p_j)A_1} - \frac{A_0}{A_1}\right) \\
\theta_i F\left(\frac{c}{\theta_k(p_k-p_j)A_1} - \frac{A_0}{A_1}\right) & \text{if} \quad W \geq \theta_k F\left(\frac{c}{\theta_k(p_k-p_j)A_1} - \frac{A_0}{A_1}\right) \\
& \text{and} \quad W < (1-\theta_i)F\left(\frac{c}{\theta_k(p_k-p_j)A_1} - \frac{A_0}{A_1}\right) \\
\frac{\theta_i}{\theta_k}W & \text{if} \quad W < \theta_k F\left(\frac{c}{\theta_k(p_k-p_j)A_1} - \frac{A_0}{A_1}\right)
\end{cases}
$$

$$
d_j^a(c, \mathbf{A}, \boldsymbol{\theta}^0, \mathbf{p}, \mathbf{q}) = \begin{cases}
0 & \text{if} \quad W \geq (1-\theta_i)F\left(\frac{c}{(\boldsymbol{\theta}\mathbf{p}-\mathbf{p}_i)A_1} - \frac{A_0}{A_1}\right) \\
(1-\theta_i)F\left(\frac{c}{\theta_k(p_k-p_j)A_1} - \frac{A_0}{A_1}\right) - W & \text{if} \quad W \geq \theta_k F\left(\frac{c}{\theta_k(p_k-p_j)A_1} - \frac{A_0}{A_1}\right) \\
& \text{and} \quad W < (1-\theta_i)F\left(\frac{c}{\theta_k(p_k-p_j)A_1} - \frac{A_0}{A_1}\right) \\
\frac{\theta_j}{\theta_k}W & \text{if} \quad W < \theta_k F\left(\frac{c}{\theta_k(p_k-p_j)A_1} - \frac{A_0}{A_1}\right)
\end{cases}
$$

$$
d_k^a(c, \mathbf{A}, \boldsymbol{\theta}^0, \mathbf{p}, \mathbf{q}) = 0
$$

The choice of $\boldsymbol{\theta}$ is made in exactly the same way as under value-based quota. If $p_i \geq p_j \geq p_k$,then $\theta_k = \underline{\theta}_k$, $\theta_i = \overline{\theta}_i$, and $\theta_j = 1 - \theta_j - \theta_k$.

7.3 Disaggregated quota

In a disaggregated quota program, a planner chooses target harvests for each of Cod, Haddock, and Pollock, and then allows a fisher to land any bundle that does not exceed any of the targets. A fisher's problem is to choose effort, composition, and discarding to solve:

$$
\begin{aligned}
\max_{x,d,\boldsymbol{\theta}} \quad & \Pi = \mathbf{p}\left(\boldsymbol{\theta}(A_0 x + \frac{A_1}{2}x^2) - \mathbf{d}\right) - cx \\
& \text{s.t. } \boldsymbol{\theta}(A_0 x + \frac{A_1}{2}x^2) - \mathbf{d} \leq \mathbf{q} \\
& \theta_c \in \left[\underline{\theta_c}, \overline{\theta_c}\right] \\
& \theta_h \in \left[\underline{\theta_h}, \overline{\theta_h}\right] \\
& \theta_p \in \left[\underline{\theta_p}, \overline{\theta_p}\right] \\
& \theta_c + \theta_h + \theta_p = 1 \\
& x, \mathbf{d} \geq 0,
\end{aligned}
$$

where A_0, A_1, $\overline{\boldsymbol{\theta}}$, and $\underline{\boldsymbol{\theta}}$, are the estimated values from Section 6.1. This problem is very complex so I solve it in two stages. In the first a fisher chooses effort and discarding, conditional on a choice of $\boldsymbol{\theta}$, and in the second he chooses $\boldsymbol{\theta}$. This first stage problem is,

$$
\begin{aligned}
\max_{x,\mathbf{d}} \quad & \Pi = \mathbf{p}\left(\boldsymbol{\theta}(A_0 x + \frac{A_1}{2}x^2) - \mathbf{d}\right) - cx \\
& \text{s.t. } \boldsymbol{\theta}(A_0 x + \frac{A_1}{2}x^2) - \mathbf{d} \leq \mathbf{q} \\
& x, \mathbf{d} \geq 0.
\end{aligned}
$$

If $\frac{q_k}{\theta_k} \geq \frac{q_j}{\theta_j} \geq \frac{q_i}{\theta_i}$, then solving this problem with standard techniques gives a fisher's profit maximizing choices of effort and discarding:

$$x^d(\mathbf{A},\mathbf{p},\mathbf{q}|\boldsymbol{\theta}) = \begin{cases} \frac{c}{\boldsymbol{\theta}\mathbf{p}A_1} - \frac{A_0}{A_1} & \text{if} \quad \mathbf{q} \geq \boldsymbol{\theta} F\left(\frac{c}{\boldsymbol{\theta}\mathbf{p}A_1} - \frac{A_0}{A_1}\right) \\ -\left(\frac{A_0^2}{A_1^2} + \frac{2q_i}{A_1\theta_i}\right)^{\frac{1}{2}} - \frac{A_0}{A_1} & \text{if} \quad q_i < \theta_i F\left(\frac{c}{\boldsymbol{\theta}\mathbf{p}A_1} - \frac{A_0}{A_1}\right) \\ & \text{and} \quad q_i \geq \theta_i F\left(\frac{c}{(\boldsymbol{\theta}_j p_j + \theta_k p_k)A_1} - \frac{A_0}{A_1}\right) \\ \frac{c}{(\boldsymbol{\theta}_j p_j + \theta_k p_k)A_1} - \frac{A_0}{A_1} & \text{if} \quad q_i < \theta_i F\left(\frac{c}{(\boldsymbol{\theta}_j p_j + \theta_k p_k)A_1} - \frac{A_0}{A_1}\right) \\ & \text{and} \quad q_j \geq \theta_j F\left(\frac{c}{(\boldsymbol{\theta}_j p_j + \theta_k p_k)A_1} - \frac{A_0}{A_1}\right) \\ & \text{and} \quad q_k \geq \theta_k F\left(\frac{c}{(\boldsymbol{\theta}_j p_j + \theta_k p_k)A_1} - \frac{A_0}{A_1}\right) \\ -\left(\frac{A_0^2}{A_1^2} + \frac{2q_j}{A_1\theta_j}\right)^{\frac{1}{2}} - \frac{A_0}{A_1} & \text{if} \quad q_j < \theta_j F\left(\frac{c}{(\boldsymbol{\theta}_j p_j + \theta_k p_k)A_1} - \frac{A_0}{A_1}\right) \\ & \text{and} \quad q_j \geq \theta_j F\left(\frac{c}{\theta_k p_k A_1} - \frac{A_0}{A_1}\right) \\ \frac{c}{\theta_k p_k A_1} - \frac{A_0}{A_1} & \text{if} \quad q_j < \theta_j F\left(\frac{c}{\theta_k p_k A_1} - \frac{A_0}{A_1}\right) \\ & \text{and} \quad q_k \geq \theta_k F\left(\frac{c}{\theta_k p_k A_1} - \frac{A_0}{A_1}\right) \\ -\left(\frac{A_0^2}{A_1^2} + \frac{2q_k}{A_1\theta_k}\right)^{\frac{1}{2}} - \frac{A_0}{A_1} & \text{if} \quad q_k < \theta_k F\left(\frac{c}{\theta_k p_k A_1} - \frac{A_0}{A_1}\right) \end{cases}$$

$$d_i^d(\mathbf{A},\mathbf{p},\mathbf{q}|\boldsymbol{\theta}) = \begin{cases} 0 & \text{if} \quad q_i \geq \theta_i F\left(\frac{c}{(\boldsymbol{\theta}_j p_j + \theta_k p_k)A_1} - \frac{A_0}{A_1}\right) \\ \theta_i F\left(\frac{c}{(\boldsymbol{\theta}_j p_j + \theta_k p_k)A_1} - \frac{A_0}{A_1}\right) - q_i & \text{if} \quad q_i < \theta_i F\left(\frac{c}{(\boldsymbol{\theta}_j p_j + \theta_k p_k)A_1} - \frac{A_0}{A_1}\right) \\ & \text{and} \quad q_j \geq \theta_j F\left(\frac{c}{(\boldsymbol{\theta}_j p_j + \theta_k p_k)A_1} - \frac{A_0}{A_1}\right) \\ & \text{and} \quad q_k \geq \theta_k F\left(\frac{c}{(\boldsymbol{\theta}_j p_j + \theta_k p_k)A_1} - \frac{A_0}{A_1}\right) \\ \frac{\theta_i q_j}{\theta_j} - q_i & \text{if} \quad q_j < \theta_j F\left(\frac{c}{(\boldsymbol{\theta}_j p_j + \theta_k p_k)A_1} - \frac{A_0}{A_1}\right) \\ & \text{and} \quad q_j \geq \theta_j F\left(\frac{c}{\theta_k p_k A_1} - \frac{A_0}{A_1}\right) \\ \theta_i F\left(\frac{c}{\theta_k p_k A_1} - \frac{A_0}{A_1}\right) - q_i & \text{if} \quad q_j < \theta_j F\left(\frac{c}{\theta_k p_k A_1} - \frac{A_0}{A_1}\right) \\ & \text{and} \quad q_k \geq \theta_k F\left(\frac{c}{\theta_k p_k A_1} - \frac{A_0}{A_1}\right) \\ \frac{\theta_i q_k}{\theta_k} - q_i & \text{if} \quad q_k < \theta_k F\left(\frac{c}{\theta_k p_k A_1} - \frac{A_0}{A_1}\right) \end{cases}$$

$$d_j^d(\mathbf{A},\mathbf{p},\mathbf{q}|\boldsymbol{\theta}) = \begin{cases} 0 & \text{if} \quad q_j \geq \theta_j F\left(\frac{c}{\theta_k p_k A_1} - \frac{A_0}{A_1}\right) \\ \theta_j F\left(\frac{c}{\theta_k p_k A_1} - \frac{A_0}{A_1}\right) - q_j & \text{if} \quad q_j < \theta_j F\left(\frac{c}{\theta_k p_k A_1} - \frac{A_0}{A_1}\right) \\ & \text{and} \quad q_k \geq \theta_k F\left(\frac{c}{\theta_k p_k A_1} - \frac{A_0}{A_1}\right) \\ \frac{\theta_j q_k}{\theta_k} - q_j & \text{if} \quad q_k < \theta_k F\left(\frac{c}{\theta_k p_k A_1} - \frac{A_0}{A_1}\right) \end{cases}$$

$$d_k^d(\mathbf{A},\mathbf{p},\mathbf{q}|\boldsymbol{\theta}) = 0$$

8 Appendix 2: Data and estimation

8.1 Fish prices

Ex-vessel fish prices are constructed from DFO records of trip by trip landings for mobile gear vessels in 1991. More specifically, monthly prices for Cod, Haddock, and Pollock are each month's average price. Annual means (standard deviations) follow: Cod \$1.24 (0.03), Haddock \$1.66 (0.12), Pollock \$0.77 (0.04). The data contain twelve observations of monthly prices. Put another way, the data describe twelve equi-probable price states given in the definition of g_p.

8.2 Production function

Evaluating a planner's problem also requires that we estimate the harvest technology. There are two common ways to conduct this estimation. (1) Estimate the profit/cost/revenue function from price and output data, or (2), estimate the production function directly from data on inputs and outputs. The dual approach is attractive because there is a well developed set of flexible functional forms for dual functions and because prices can usually be taken as exogenous. However, estimation of a dual function relies on Shephard's lemma to generate a system of supply functions which are also estimated. This lemma does not apply at "corners" where one of many outputs is zero—the dual function is not generally differentiable at these corners. Since about 26% of the 1146 specialist vessel/months report a zero harvest of Cod, Haddock, or Pollock, the dual approach is probably not a correct specification of the problem. Given this I rely on a direct estimation of parameters of the production function.[17]

Landings data is disaggregated to the daily level. Since vessels do not generally stay out overnight, they make one or zero trips per day. Since details about the length of trips or number of times nets were towed are not available, I aggregate and use trips per month as a measure of effort. Landings are assumed quadratic in trips. To correct for the endogeneity of Trips, it is replaced with, $\widehat{\text{Trips}}$, a value predicted by regressing Trips on the prices of all species. This effectively converts the landings function into a supply function. The resulting coefficients and standard errors are reported in table 8.1.

The R^2 for this regression is 0.52 and $N = 1142$. Note that the coefficients have "correct signs". All else equal, more trips increase production at a decreasing rate. Although the second derivative of this production function is negative, the coefficient is significant only at the 12% level. I tried a number of different specifications, e.g.

[17] I estimated a system of supply equations based on a generalized Leontief revenue function anyhow. The results were consistent with those that I present.

Total Landings (Kg./mo.) =	$A_0\widehat{\text{Trips}}$	$+\frac{A_1}{2}\widehat{\text{Trips}}^2$
Coefficient	1208	-20
S.E.	253	13.2

Table 2: Quadratic technology coefficients

including interaction terms like, $\widehat{\text{Trips}}*$vessel characteristics, or using actual rather than predicted trips. As expected, actual trips perform better than predicted trips. Including interaction terms does not generally affect signs of coefficients, but does reduce the statistical significance of the second order term. Including interaction terms like, $\widehat{\text{Trips}}^2*$vessel characteristics, causes a loss of significance of all second order terms.

Solving **??** or **??** also requires density functions for A_0 and A_1. While the normal distribution is a natural candidate, it assigns positive probabilities to negative values of A_0 and A_1, which may cause the solutions to a fisher's problem to be undefined. In addition, the normal distribution is too time consuming to integrate. To get around these problems, the densities of A_0 and A_1 are assumed to be the result of a sum of Bernoulli trials with appropriate mean and variances. This results in densities that "look like" a normal density (and converges to a normal density), and is easy to integrate. For most of the subsequent analysis I suppose that A_0 is the sum of seven draws from the Bernoulli pdf,

$$B(A_0) = \begin{cases} \frac{1208+4\times 253}{7} & \text{with probabability} \quad \frac{1}{2} \\ \frac{1208-4\times 253}{7} & \text{with probabability} \quad \frac{1}{2} \end{cases}.$$

The resulting density is g_{A_0} with mean 1208 and standard deviation 253.

Similarly, I suppose that A_1 is the sum of seven Bernoulli trials,

$$B(\frac{A_1}{2}) = \begin{cases} \frac{-20-4\times 13.2}{7} & \text{with probabability} \quad \frac{1}{2} \\ \frac{-20+4\times 13.2}{7} & \text{with probabability} \quad \frac{1}{2} \end{cases}.$$

Since my prior is that A_1 must be negative, I disregard negative realizations of A_1 and distribute the probability mass equally over other realizations. Imposing this prior on A_1 gives $g_{A_1}$with mean 27.6.

It remains to characterize the extent to which fishers control harvest proportions. To measure the extent of this control perform the following regressions,

$$\text{Proportion type}_i = A \times \text{prices} + B \times \text{ Vessels Characteristics } + \varepsilon.$$

Results are reported in table 4.3. Pollock coefficients are computed from the other two regressions. Intercepts sum to one, other coefficients sum to 0.

	Proportion Cod	**Proportion haddock**	**Proportion Pollock**
Sample mean	0.51	0.19	0.30
$\mathbf{R}^2$	0.09	0.05	
Root MSE	0.27	0.22	
Constant	-2.25	1.16	2.09
	0.38	0.31	
Price Cod	2.86	-0.23	-2.63
	0.29	0.24	
Price haddock	-0.05	-0.27	0.32
	0.07	0.05	
Price Pollock	-0.85	-0.11	0.96
	0.25	0.21	
Ves. Wt.	-0.001	-0.001	0.002
	0.001	0.001	
Ves. Length	0.0007	-0.0006	0.0001
	0.002	0.002	
Horsepower	0.0000	-0.0001	0.0000
	0.223	0.0001	

Table 3: Relationship between prices and proportions

While proportions are sensitive to changes in prices, they are not very sensitive. If we allow all prices to vary within one standard deviation of their respective means, proportions stay in the following intervals: Proportion Cod$\in [0.49, 0.58]$, Proportion Haddock$\in [0.17, 0.26]$, Proportion Pollock$\in [0.25, 0.25]$.

Two comments about these results are appropriate. First, the quadratic technology function implicitly assumes input-output separability. Table 4.3 confirms this assumption. Vessel characteristics have almost no measurable impact on the composition of the landings. Second, these regressions explain very little of the observed variance in harvest composition. This suggests that fishers exercise relatively little control over harvest composition. Most of the variance is random, and presumably driven by the presence or absence of different types of fish. This is not what we would expect to find if fishers were discarding large fractions of their harvests in response to changes in prices.

To solve **??** or **??** we need an estimate of Θ and its dependence on the state of nature $\boldsymbol{\theta}^0$. Since Θ is intended to reflect the extent to which fishers control harvest proportions, let

$$\boldsymbol{\Theta}(\boldsymbol{\theta}^0) = \left(\left[\theta_c^0 - C_c, \theta_c^0 + C_c\right] \times \left[\theta_h^0 - C_h, \theta_h^0 + C_h\right] \times \left[\theta_p^0 - C_p, \theta_p^0 + C_p\right]\right) \cap \left(0.0\overline{3}, 0.9\overline{3}\right)^3 \cap S_+^3,$$

where the C_i are half the amount of variance induced in harvest proportions by a one standard deviation in prices: $C_c = (0.58 - 0.49)/2, C_h = (0.26 - 0.17)/2, C_p = (0.25 - 0.25)/2$. This assumption is ad hoc and I will check how sensitive results are to changes in this assumption.

The $\boldsymbol{\theta}^0$ are the random component of proportions choice and are assumed to be distributed jointly in exactly the same way as the raw proportions data. To describe the density of the raw proportions data, i.e. the density of $\boldsymbol{\theta}^0$, note that it is sufficient to examine just the distribution of Cod and Haddock proportions. To do this, divide the unit square into a 10 by ten grid, and count the proportion of times that the (Prop. Cod, Prop. Had) falls in each square. Assign this probability mass to the midpoint of the grid to get the pdf for (Prop. Cod, Prop. Had.). This joint density is g_θ.