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# Economics without Free-Disposal: The Problem of Quota-induced Discarding in Heterogenous Fisheries

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**Abstract**

*Individual quota (IQ) programs are a promising and increasingly common means of regulating fisheries. This paper examines how profit maximizing fishers respond to different types of IQ programs in fisheries where many types of fish are harvested simultaneously. The paper first specifies a joint production function for the fishery. Using this technology, the responses of profit maximizing fishers to different IQ programs are analysed. This analysis shows first that the most common types of individual quota program can induce discarding, and second that of all possible individual quota programs, only those that regulate the value of harvest never induce discarding. Since discarded fish have a high mortality rate, "value-based" individual quota programs are superior to their more conventional counterparts in that they waste fewer fish. These results are driven by the fact that the fishing technology examined here does not satisfy a "free-disposal" assumption. Since this free disposal assumption is ubiquitous in production theory, and not obviously true, the framework developed herein is useful for analyzing a broad class of problems involving joint production.* JEL Classifications: Q22, K32, D24

## 1. Introduction

In an open access fishery profit maximizing fishers over-exploit the stock relative to the social optimum (Gordon 1956). [1] This means that welfare maximizing fisheries managers face the problem of reducing market harvests. Individual quota (IQ) programs are a promising approach to the problem and one beginning to be widely used in North America and abroad (Muse 1991). The chief aim of this paper is to examine how profit maximizing fishers respond to different types of IQ programs in a fishery where many types of fish are harvested simultaneously. To accomplish this goal, the paper first specifies a joint production fishing technology. Using this technology, the responses of profit maximizing fishers to different IQ programs are analysed. This analysis shows first that the most common types of individual quota program can induce discarding, and second that of all possible individual quota programs, only those that regulate the value of harvest never induce discarding. Since discarded fish have a high mortality rate, "value-based" individual quota programs are superior to their more conventional counterparts in that they waste less fish. These results are driven by the fact that the fishing technology does not satisfy a "free-disposal" assumption. Since this assumption is ubiquitous in production theory (e.g. Debreu 1959, Diewert 1973, Sakai 1974), and not obviously true, the framework developed herein should find applications to a broad class of problems involving joint production.

The paper also analyses the usefulness of value-based individual quota programs as regulatory tools. Under a value-based quota program, the weight of fish that may be legally harvested depends on prices. If these prices are uncertain at the time quotas are issued then the harvest weight associated with a particular value-based quota program is also uncertain. Although this is undesirable, it is not obviously worse than uncertainty about harvest weights under conventional quota programs when unobserved discarding occurs. Thus value-based individual quota programs are clearly better than their conventional counterparts in that they never induce discarding, and are not obviously worse because they introduce uncertainty about the final harvest weight. The paper concludes that value-based individual quota programs deserve serious consideration in fisheries where a planner wants to reduce or prevent quota-induced discarding.

While there are many ways of distributing quotas and administering individual quota programs, the fact that a fisher may only bring fish to market if he holds enough quota for the amount of fish he intends to sell is definitional. Since shipboard monitoring is prohibitively expensive, individual quota programs do not generally regulate the amount of fish that is harvested, but rather the amount that is landed and brought to market. Therefore, if a fisher discards fish before landing, the planner will not observe the amount. Such discarding may occur for a variety of reasons: the hold may be full, the fish may have no market value, the market value of the fish may not cover costs of shipboard processing and transportation to market. Anderson

[1] I am grateful to Ralph Winter, Michael Smart, Steve Kohlhagen, Sue Bremner, and seminar participants at the Universty of Toronto for helpful comments. Remaining errors are entirely my own. This research was partly supported by the Woods Hole Oceanographic Institution. Comments welcome.

(1994a) and Arnason (1994) treat this technologically induced discarding in detail, and find that it may be efficient. But, as the following paragraph suggests, individual quota programs may provide an incentive to discard fish that would otherwise be brought to market.

The two most common types of individual quota program are "aggregated" and "disaggregated". In an aggregated individual quota program, a planner issues quotas that permit fishers to land a particular weight of fish regardless of type. If different types of fish have different prices, then there may be an incentive to "highgrade"; that is, to discard fish of the least valuable type in order to meet a quota. In disaggregated individual quota programs a planner issues a quota entitling a fisher to catch up to a certain weight of each particular type of fish. If a fisher fills his quota of one type before another, there may be an incentive to continue fishing to fill the quota for other types, and "dump" any over-quota fish of the first type. This "quota-induced" discarding, rather than "technologically-induced" discarding, is the subject of this paper.

Several authors find evidence for the occurrence of quota-induced discarding. Anderson (1994a), Arnason (1994), and Turner (1995) find a theoretical basis to suspect that tradable individual quota programs induce discarding by profit maximizing fishers. Muse and Schelle (1989) provide a detailed description of twelve individual quota programs. Of these twelve, highgrading or dumping is known or suspected in six. In two of the six cases changes in the quota program resulted in changes in the quantity of discards, so it is clear that the quota program is at least partly responsible for discarding. [2] Discarding also appears to be quota-induced in the remaining four quota programs, though there is slightly more room to suspect that discarding is technologically-induced. Muse (1991) provides an updated, but more cursory description of the original 12, along with nearly 40 additional individual quota programs. Of the 40 additional individual quota programs, highgrading or dumping is known or suspected in two. [3] McCloskey (1990 p16) also documents the occurrence of quota-induced dumping. In short, there is considerable evidence that discarding is a common problem in individual quota programs, and that this discarding is at least sometimes induced by the programs themselves.

This introduction describes only two of many possible problems with individual quota programs. A much more exhaustive listing is given in Copes (1986). Of particular interest is the problem of "quota-busting," called "smuggling" in Muse and Schelle (1989). As the name suggests, this problem occurs when a planner does not observe all landings; under individual quota programs, it is a crime. Thus, managing smuggling in an individual quota program is an enforcement problem, and may be

[2]Muse and Schelle (1989). A change in stock composition in the Lake Erie Walleye fishery led to highgrading under an aggregated IQ program; managers switched to a disaggregated program and the incidence of discarding declined, p43. In a Wisconsin Trout fishery a switch from an IQ program based on numbers of fish to one based on pounds of fish has increased the incidence of discarding, 63.

[3]This second survey devotes much less attention to enforcement problems than its predecessor, and probably under-represents the incidence of problems.

solved by appropriately adjusting monitoring effort and penalties. While one might also regard dumping and highgrading as enforcement problems, this investigation regards smuggling and quota-induced discarding as separate problems, and assumes that the planner has already solved the problem of smuggling. In addition to being convenient analytically, this reflects the fact that the problem of smuggling has been treated in the literature on poaching, e.g. , Furlong (1991), Sutinen (1985). If one regards the problem of discarding as an enforcement problem then these earlier authors have solved the problem. The object of this investigation is to consider another type of solution.

## 2. A Fishing Technology without Free-Disposal

The function of an individual quota program is to reduce the total harvest (one fisher at a time), in a particular time period, from open access levels. If the time period in question is sufficiently short, then the stock level of fish may be treated as fixed. In this case, it is appropriate to examine the response to different individual quota programs in the context of a static model. This section develops such a static model of harvest technologies in heterogenous fisheries. The following section uses this model to examine how fishers respond to various individual quota programs.

In an individual quota program, planners must also decide how much of the total harvest to allocate to each particular fisher. The analysis that follows assumes that a planner has already made this decision and apportioned quotas to the various fishers. It then examines the way that a fisher responds to different types of IQ program. Thus, while a fishery is understood to consist of many fishers, for current purposes it is enough to look at only one.

Since this analysis examines the behaviour of only a single fisher, it does not matter how quotas are distributed to other fishers. It follows that this analysis is invariant to different distributions of quota. This suggests that the analysis should be interpreted as beginning after the quota distribution mechanism has done its work, and that it does not matter whether the quota is distibuted by a market, lottery, or handed out by a planner. Thus the analysis herein applies to the special case of individual tradable quota programs and generalizes earlier results on quota-induced discarding in tradable individual quota programs, e.g., Turner 1995, Anderson 1994b, Arnason 1994.

For current purposes, the defining characteristic of a heterogenous fishery is that more than one type of fish may come up on the same line or in the same net or trap. [4] Economists often represent the harvest technology in a heterogenous fishery as a joint production function in which each different type of fish makes up a fixed proportion of the harvest, Clark (1990, Ch. 10) , Anderson (1994a,b), Arnason (1994). While this means of describing a harvesting technology is particularly tractable, and allows

[4] Muse (1991) gives several examples of fisheries where this occurs. Squires (1986) examines the New England trawler fleet and find evidence that several species of fish are produced jointly. McCloskey (1990) and Warner (1983) describe their experiences aboard commercial fishing vessels in different fisheries with a variety of gear, and in almost every case describe a mixed harvest. In short, heterogenous fisheries appear to be the norm rather than the exception.

different types to be harvested simultaneously, as Anderson (1994b) observes, it fails to allow certain types of observed behaviour. In particular, there is considerable evidence that fishers can, within limits, affect the composition of their harvests by choice of time, place, or technique (McCloskey 1990 p16, Muse and Schelle 1989, Muse 1991, Squires 1986, Warner 1983).

To construct a model of a fishery where fishers have limited control over the composition of their harvests, imagine that the stock of fish is finite and consists of $m$-types of fish. Each "type" is a distinct market class, distinguishable from the other types and with its own price. As such, a type may either be a particular species, or a size class of a species. A harvest is a vector $h \in R^m_+$, where $h_i$ is the harvest weight of type $i$ fish. [5] Assume that there is only one input into the production technology, fishing effort $x \in R^1_+$. This simplifying assumption lightens notation and allows the analysis to concentrate on the choice of outputs rather than the choice of inputs. Fishing effort may be purchased at the market price $w \in R^1_{++}$. This will be a static analysis so the stock level may be taken as fixed and omitted. To allow for the possibility of discarding, distinguish between landings $y \in R^m_+$, which may be sold at the market price $p \in R^m_{++}$ and harvests $h$. In the absence of discarding $y = h$, and it will sometimes be convenient to refer to $y$ as the harvest as well. Define a set $T$ to be the set of all technologically feasible combinations of fishing effort and harvests. Say that landings $y$ are "feasible" if and only if there exists a pair $(-x, h) \in T$ such that $y \leq h$. To avoid the possibility of technologically-induced discarding, all harvested fish are assumed to be marketable. Alternately, the set $T$ specifies the harvest of marketable fish after technologically-induced discarding has occurred.

Suppose that $T$ has the following properties.

**A1.** $T \subset R^1_- \times R^m_+$ is the set of technologically feasible pairs $(-x, h)$.

(1) $(0, 0) \in T$. (possibility of inaction)

(2) $T \bigcap R^{m+1}_+ \subseteq \{0\}$. (no free harvesting)

(3) $T$ is closed.

(4) There exists $h^*$, $\|h^*\| < \infty$, such that $T \subset R^1_- \times [0, h^*]$. (Fish stocks are finite )

(5) If $(-x, h) \in T$ then $(-x - \alpha, h) \in T$ for all $\alpha \geq 0$. (monotonicity)

(6) Let $B_\varepsilon(-x, h)$ denote an $m+1$ dimensional ball of radius $\varepsilon$ with center $(-x, h)$. Given $(x, h), (x', h')$, and $\alpha \in (0, 1)$, let $(x'', h'') = \alpha(x, h) + (1 - \alpha)(x', h')$. If $(-x, h), (-x', h') \in T$, then for some $\varepsilon > 0$, $B_\varepsilon(-x'', h'') \bigcap \{R^1_- \times R^m_+\} \subset T$.

Conditions A1.1-3 are standard. A1.4 requires that harvests be bounded above for all levels of effort. This is consistent with the notion that the fisher in question

[5] $R^m_+$, $(R^m_-)$ denotes the non-negative (non-positive) orthant in $R^m$. $R^m_{++}$ denotes the interior of $R^m_+$, the set of vectors that are strictly positive in all elements. $A \times B$ denotes the Cartesian product of $A$, and $B$.

is harvesting from finite stocks. A1.5 may be regarded as requiring non-negative returns to effort. Condition A1.6 is a convexity condition. It requires that $T$ be convex everywhere, and strictly convex everywhere except the boundaries of $R^1_- \times R^m_+$. Together with A1.1, A1.6 implies that the harvest technology exhibits decreasing returns to scale in effort. Since harvesting also depends on the implicitly fixed level of the fish stocks, this is simply decreasing returns to a fixed factor.

Typically a specification of technology associates a unique output bundle with each input bundle. The technologically feasible set described by (A1) may be such that each input bundle is associated with many output bundles. In effect, (A1) defines production correspondences rather than production functions. This additional complexity of the technologically feasible set is intended to describe a fisher's ability to alter catch composition, for given inputs of effort, by varying quantities like time of day/year, tide, technique, or location, which may be difficult to observe or quantify, and which may not affect production costs.

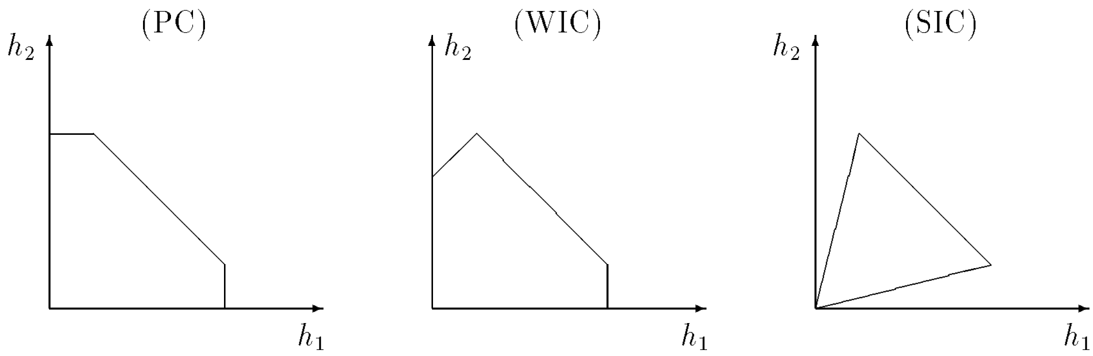
Given this specification of the harvest technology, we can define a harvest correspondence that maps the set of inputs onto the set of technologically feasible harvests. It will often be convenient to work with this correspondence, $\mathcal{H}(x)$, rather than with the technologically feasible set $T$. Define

$$\mathcal{H}(x) = \{h|(-x, h) \in T\}.$$

It is straight forward to show that if A1 holds then: (1) $\{0\} = \mathcal{H}(0)$. (2) $\mathcal{H}(x) \supset \{0\}$ for all $x > 0$. (3) $\mathcal{H}(x)$ is closed and bounded for all $x$. (4) $\mathcal{H}(x') \supseteq \mathcal{H}(x)$ for all $x' \geq x$. (5) $\mathcal{H}(x)$ strictly convex, except along boundaries of $R^m_+$.

Note that A1 does not place any restrictions on harvest compositions that are feasible, and figure 4 illustrates possible forms of $\mathcal{H}(x)$ that are consistent with A1.1-5. A1.6 is not satisfied, since the figures are convex rather than strictly convex.

Figure 1.




In the leftmost figure, any composition of catch is possible at the given effort level. A fisher may catch only type 1, only type 2, or some of both. The ability to perfectly control catch composition is formalized below.

(PC) If $(-x, h) \in T$ then for all $0 \leq h' \leq h$, $(-x, h') \in T$.

This condition is simply a free disposal condition, and together A1 and PC specify substantially the same sorts of technologies as those treated in Diewert 1973, Sakai

1974, and Debreu 1959. While free-disposal, here called PC, is a standard assumption, it is not appropriate to a discusion of quota-induced discarding for three reasons. First, in order to examine the conditions under which disposal occurs, it is necessary to partition technologically feasible sets into subsets that can and cannot be achieved without discarding. Under condition PC, all technologically feasible outcomes can be achieved without discarding. Second, it will be established in Proposition 4 that when A1 and PC hold, discarding is never profit maximizing. This means that if A1 and PC hold, and a profit maximizing fishery is faced with a landing restriction, it will not choose to discard, it will choose to produce less. If we accept that fishers are profit maximizers and that quotas do cause discarding, then we have to reject either A1 or PC. Finally, PC appears to contradict the evidence of imperfect control over harvest composition cited earlier.

For these reasons, this paper will address fishing technologies that do not allow perfect control over catch composition. The inability to perfectly control of catch composition is formalized by the following definition of "strictly imperfect control of catch compostion".

(SIC) $T \subset R^1_- \times \{R^m_{++} \bigcup \{0\}\ \}$ for all $x$.

This assumption requires that fishers always harvest every species or type. The only way to drive the harvest of any particular species to zero is to drive the harvest of all species to zero. Note that SIC is the converse of the free disposal condition, PC. Free-disposal requires that if a particular harvest is feasible then all smaller harvests are feasible. SIC requires that this not be true. Heuristically, the SIC assumption necessitates a more complete specification of technology in that production must be decomposed into separate production and disposal technologies. With this said, this analysis makes the simplifying assumption that disposal technologies are costless. While costly disposal technologies would make the analysis more complete, it adds complexity and little additonal insight. The reader interested in the implications of a non-trivial disposal technology is referred to Anderson (1994a,b), Arnason (1994), or Turner (1995), each of whom consider costly disposal together with a fixed proportions joint production technology .

Although developed in the context of a fishery, technologies characterized by A1 and SIC may also be appropriate in many other cases involving joint production: a producer of beef and hides may be able to choose fat or thin cows to alter the alter the proportions of beef and hides produced; a producer of effluent may not be able to exercise significant control over the proportions of different pollutants in the effluent. Thus this framework should lead to new insights about joint production processes that are neither fixed proportions, which allows no control over output proportions, nor free-disposal, which allows complete control over output proportions.

For completeness, note that weakly imperfect control of catch composition is also possible.

(WIC) $T$ does not satisfy SIC or PC.

Examples of harvest correspondences satisfying PC, SIC, and WIC are illustrated (for $x$ fixed) in figure 1.

While an assumption of strictly imperfect control of harvest composition allows a more accurate description of certain technologies, it imposes a cost in notation. To understand this, consider again figure 1. Under strict convexity and free disposal, or PC, given inputs $x$ and $h_1$, there is a unique value of $h_2$ on the frontier of $T$. This means that the technological frontier can be described as a function, and we can proceed to analyse this "production function", rather than the more primitive technology set (e.g. Diewert 1973). With SIC this is not possible. Given $x$ and $h_1$ there are usually two values of $h_2$ on the frontier of $T$. This type of frontier, by definition, cannot be described by a function and we are compelled to continue with a set theoretic description of the technology.

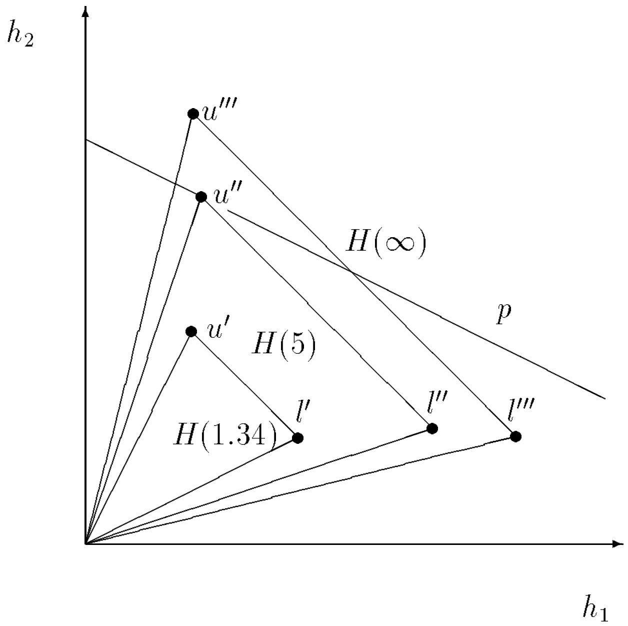
In addition to other phenomena, the technology given above can also describe a fishery where many types of fish are harvested jointly and where a fisher has only imperfect control over the composition of his harvest. This is illustrated in example one. The technology described in the example satisfies SIC and A1.1-5, but while it is convex, it does not satisfy A1.6.

**Example 1** *(No Regulation) Consider a fishery that consists of two types of fish, type 1 and type 2, and let $h_1, h_2$ denote the amount of each type harvested. Let $y_1 \leq h_1, y_2 \leq h_2$ denote the amount of each type landed. $\mathcal{H} : R^1_+ \mapsto R^2_+$ is the harvest correspondence given by*

$$\begin{aligned}\mathcal{H}(x) \quad = \quad & \left\{(h_1, h_2)|h_2 \geq \frac{x+1}{4x+2}h_1\right\} \bigcap \\ & \left\{(h_1, h_2)|h_2 \leq \frac{4x+1}{x+2}h_1\right\} \bigcap \\ & \left\{(h_1, h_2)|h_2 + h_1 \leq \frac{x}{x+1}\right\}.\end{aligned}$$

*For $x > 0$, $\mathcal{H}(x)$ is a triangle with its apex at the origin. When $x = 0$, $\mathcal{H}(x) = \{(0,0)\}$. As $x \to \infty$, $\mathcal{H}(x)$ asymptotically approaches a triangle with vertices $(0,0)$, $(\frac{1}{5}, \frac{4}{5})$, $(\frac{4}{5}, \frac{1}{5})$. Denote this triangle $\mathcal{H}(\infty)$. The first set in the above definition defines a half plane whose boundary is the "lower" leg of a triangle. The second and third sets respectively define the "upper" leg and base of the triangle. Figure 2 illustrates $\mathcal{H}(x)$ for different values of $x$. Note that the technology described here has the intuitively appealing property that it allows more control of harvest composition as effort increases.*

Figure 2.




*Let $u(x) = [u_1(x), u_2(x)]$ be the locus of points on the upper corner of $\mathcal{H}(x)$, and let $l(x) = [l_1(x), l_2(x)]$ be the corresponding locus of points on the lower corner. Points on these loci are indicated in figure 1 by $u', u'', u'''$, and $l', l'', l'''$. Solving for the u and l loci gives;*

$$[u_1(x), u_2(x)] = \left[\frac{x^2+2x}{5x^2+8x+3}, \frac{4x^2+x}{5x^2+8x+3}\right],$$
$$[l_1(x), l_2(x)] = \left[\frac{4x^2+2x}{5x^2+8x+3}, \frac{x^2+x}{5x^2+8x+3}\right].$$

*If $p_1 > p_2$ then the fisher maximizes profits by harvesting $u(x)$ at that point on $u(x)$ where $p_1\frac{du_1}{dx} + p_2\frac{du_2}{dx} = w$, and by landing the entire harvest (i.e. $y = h$). If $p_2 < p_1$ the fisher maximizes profits at that point on $l(x)$ where $p_1\frac{dl_1}{dx} + p_2\frac{dl_2}{dx} = w$. If $p_1 = p_2$ the two conditions are identical, and the fisher maximizes profits anywhere on the straight line connecting $u(x)$ to $l(x)$.*□

## 3. Necessary and Sufficient Conditions for Quota-induced Discarding

The next step in the analysis is to describe an individual quota program. Suppose that a planner can specify any quota set $Q$ of legal landings, provided that $Q$ has the following properties.

**A2.** The Quota set $Q \subset R^m_+$ is the set of harvests that may be legally landed.

(1) $Q$ is closed, bounded, non-empty.

(2) If $y \in Q$ then $y$ is feasible.

(3) If $y \in Q$ and $y' \in [0, y]$ then $y' \in Q$.

A2.1 is a regularity condition. A2.2 requires that the quota set contain only feasible landings. Since infeasible landings are never reached, this requirement does not affect behaviour, and eases notation. A2.3 requires that a planner permit fishers to land any amount less than or equal to the legal maximum. Given such a representation of an individual quota program, we can easily represent the three types of quota in which this investigation is interested: aggregated, disaggregated, and value-based.

In an aggregated quota program, a planner issues a fisher a quota that entitles him to land and bring to market up to weight $W$ of fish regardless of type. The quota set associated with this sort of quota program is given by $Q = \{y | \sum_{I=1}^{m} y_i \leq W\}$. While one can imagine such a quota program occurring in a fishery where the different types of fish are different species, [6] it is more common for the two types to be different sizes of the same species. [7] The National Marine Fisheries Service tracks prices and landings for 9 market categories of Cod, 35 market categories of flounder, 22 of Tuna, and so on. [8] This suggests that quota programs in which one type of quota is issued for each species are very often aggregated programs.

In a disaggregated program a planner issues a fisher quota for each of the $m$ types of fish. Thus the quota set associated with this type of quota program is given by $Q = \{y | y \leq q\}$, where $q \in R_+^m$ is the vector of maximum allowable harvest weights for each type, and also the vector that describes the quota issued. In a value-based quota program, a planner issues a quota allowing a fisher to land up $V$ dollars worth of fish. The quota set associated with this is given by $Q = \{y | py \leq V\}$. Although this sort of quota is little known in the economics literature; the possibility of value-based quota is mentioned in Copes (1986), the possibility of value-based quota in a tradable individual quota program is analysed in Turner (1995), and finally, Muse and Schelle (1989) describe a value-based quota program in operation in Iceland.

Example 2 demonstrates that disaggregated quota programs can induce discarding. In the example it is assumed that a planner is interested in the harvest level of both species. It is also possible to construct examples in which disaggregated quotas on only one type induce discarding of the other.

**Example 2** *(Weight-Based Quota on both types) Consider again the fisher of example one, and suppose that a planner would like to regulate a fisher's harvest of both types of fish, and sets a quota of* $(q_1, q_2) = (0.125, 0.375)$*, prohibiting all landings in excess of this amount. Since* $(q_1, q_2) \in \mathcal{H}(x)$ *for all* $x \geq 5$ *it is feasible for the fisher to produce his quota without discarding.*

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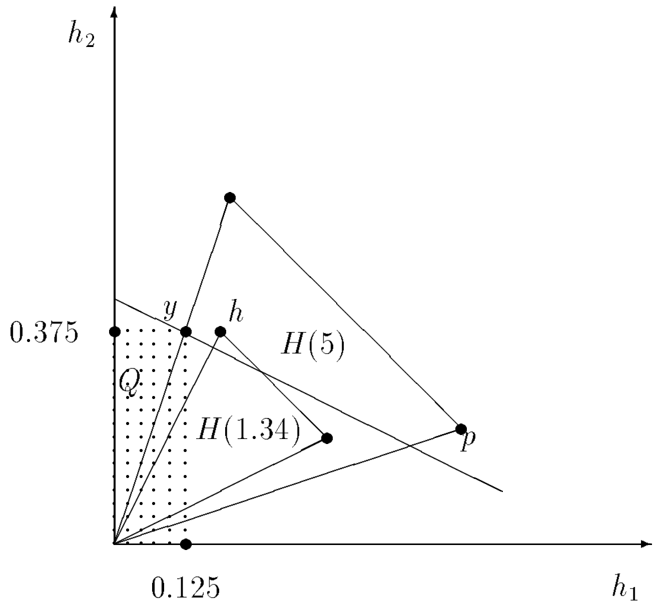
[6] This occurs on Lake Winnipeg in Manitoba. The total landings of pickerel, sauger, and whitefish are regulated, but there is no quota on the landings of each species, Muse (1991).

[7] Muse (1991) records only one case in about 50 in which different sizes of the same species are subject to different quotas, the Walleye fishery in western Lake Erie.

[8] Documentation for Weighout Detail Trip record (WODETT) database, of the National Marine Fisheries Service in Woods Hole, Massachusetts.

*However, even if factor and output prices are such that the quota is binding on both types of fish, choosing* $(h_1, h_2) = (0.125, 0.375)$ *is not profit maximizing. When* $x = 1.337$, *the harvest* $(h_1, h_2) = [u_1(1.337), u_2(1.337)] = (0.1975, 0.375)$ *is feasible, despite that fact that* $(h_1, h_2) = (0.125, 0.375) \notin \mathcal{H}(x)$ *for all* $x < 5$. *Assuming that the quota is binding, so landings are* $(y_1, y_2) = (0.125, 0.375)$, *the fisher maximizes profits by choosing the smallest* $x$ *such that* $h \geq (0.125, 0.375)$ *is feasible. This cost minimizing value of* $x$ *is 1.337, so profit maximization under this particular individual quota requires that the fisher discard .075 units of type 1 fish. Such a choice of inputs, outputs, and discarding is optimal whenever* $p_2 \frac{du_2}{dx}\Big|_{1.33} - w \geq 0$, *or, rearranging and evaluating the derivative, whenever* $\frac{w}{p_2} \leq 0.274$.□

Figure 3.



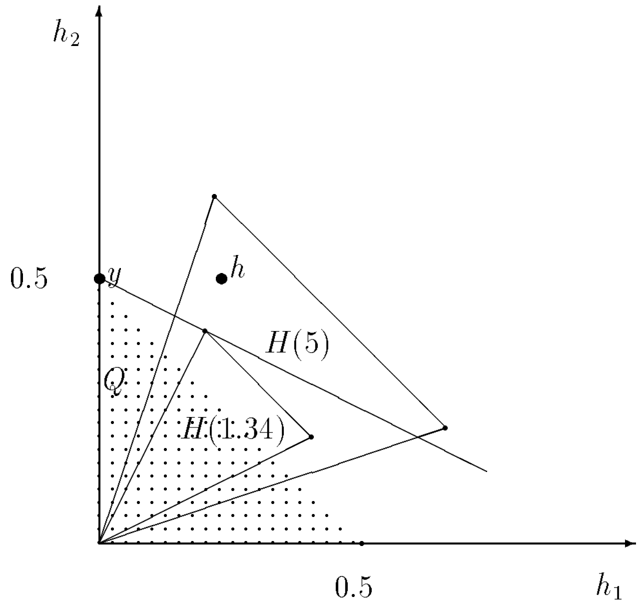

If a planner chooses a quota that is not in $\mathcal{H}(\infty)$ then either it is not binding, or it can only be achieved with discarding. In example two a profit maximizing fisher chooses to over-harvest and discard rather than produce the exact amount of a quota that is in the interior of $\mathcal{H}(\infty)$. This occurs because for certain harvest levels and compositions, it requires less input to over-harvest and discard than it does to harvest the precise amount.

Example 3 demonstrates that aggregated individual quota programs can induce discarding. This extends the intuition developed in Anderson(1994b), Arnason (1994), and Turner (1995) to this more general model.

**Example 3** *(Aggregated Quota) Consider again the fisher described in example one, and suppose that a planner wants to limit the harvest of types 1 and 2 fish to one half. In this case the quota set is given by* $Q = \{(h_1, h_2) | h_1 + h_2 \leq \frac{1}{2}\}$. *Suppose that* $p_2 > p_1$. *From the definition of* $\mathcal{H}(x)$, *the quota is binding whenever* $x \geq 1$. *For* $x = 1$ *and* $p_2 > p_1$, *revenue is maximized at* $[u_1(1), u_2(1)] = [\frac{3}{16}, \frac{5}{16}]$. *This choice of* $x$ *maximizes profits when* $p_2 \frac{du_2}{dx}\Big|_{x=1} + p_1 \frac{du_1}{dx}\Big|_{x=1} = w$.

*The marginal return from increasing $x$ above 1 is $(p_2-p_1)\frac{du_2}{dx}-w$. That is, for each additional unit of type 2 fish landed, the inputs to harvest the additional unit must be paid for, and equal weight of type 1 fish discarded. Thus discarding is profitable whenever $(p_2-p_1)\frac{du_2}{dx}\Big|_{x=1} \geq w$.*$\square$

<ins>Figure 4.</ins>




The preceding examples show that for a particular harvest technology, discarding may be a profit maximizing response to the two most common types of individual quota program, disaggregated and aggregated. Given a technology satisfying the assumptions of A1, the remainder of this section finds necessary and sufficient conditions on quota sets for quota-induced discarding to be profit maximizing. As a first step in this direction, define $\mathcal{H}^E$ to be the set of all technologically efficient harvests. That is, $\mathcal{H}^E$ is the set of all harvests such that for some $x$, no larger harvest is possible. More formally,

$$\mathcal{H}^E = \{h | \text{ for some } x, (-x,h) \in T \text{ and } (-x, h+\varepsilon) \notin T \text{ for all } \varepsilon > 0\}.$$

For the examples above, $\mathcal{H}^E$ is the union over $x$ of all the line segments connecting $u(x)$ to $l(x)$, so that $\mathcal{H}^E$ is a proper subset of the set of technologically feasible harvests.

Let $f(x,h) = x$. Define the conditional input and harvest correspondences to be the pair $[x(y), h(y)]$ that solves

$$\begin{aligned}[x(y), h(y)] &= \text{argmin } f(x,h) \\ &\quad \text{s.t. } (-x,h) \in T \text{ and } h \geq y.\end{aligned}$$

**Proposition. 1** *If A1 holds and $y$ is feasible, then;*

*(1) $[x(y), h(y)]$ exists and is single valued.*

*(2)* $h(y) \in \mathcal{H}^E$.

*(3)* $h(y) > y$ *if and only if* $y \notin \mathcal{H}^E$.

A cost function $c(w, y)$ is, by definition, the least costly way to produce $y$ at input prices $w$. In this instance, $c(w, y) = wx(y)$. Prop. 1 allows us to make the following statements. A cost function exists and is single valued. Cost minimization always requires a harvest in the technologically efficient set. Discarding is consistent with cost minimization if and only if $y$ is not in the technologically efficient set.

Given $Q$ and $\mathcal{H}^E$, partition the quota set into those legal harvests that are technologically efficient, and those that are not. More formally, let

$$\begin{aligned} Q^E &= Q \bigcap \mathcal{H}^E \\ Q^{notE} &= Q - Q^E. \end{aligned}$$

The following proposition gives a condition under which quota-induced discarding is not profit maximizing. The proof of this, and subsequent propositions, may be found in the appendix.

**Proposition. 2** *If A1 and A2 hold, and if there exists* $\bar{y} \in Q^E$ *such that* $p\bar{y} \geq py$ *for all* $y \in Q$ *then discarding is never profit maximizing.*

Proposition 2 states that subject to the quota set $Q$, if revenue is maximized by a technologically efficient harvest, then discarding is never profit maximizing. In light of Proposition 1, the intuition behind this result is fairly clear. All else equal, landings in the technologically efficient set are produced at less cost. If revenue generated by technologically efficient landings is at least equal to that generated by inefficient landings, then profits are maximized by technologically efficient landings. Proposition 3 is a partial converse of proposition 2.

**Proposition. 3** *If A1 and A2 hold, and if there exists* $\underline{y} \in Q^{\text{notE}}$ *such that* $p\underline{y} > py$ *for all* $y \in Q^E$*, then for* $w$ *small enough, discarding is profit maximizing.*

Proposition 3 states that if the revenue maximizing legal landings are not in the technologically efficient set, then discarding may be profit maximizing. By Proposition 1, the cost minimizing way to produce landings not in the technologically efficient set is to over-harvest and discard. It follows that if the revenue maximizing legal harvest is not technologically efficient, then as $w \to 0$, at some point these landings must become profit maximizing.

Proposition 2 establishes that a necessary condition for profit maximizing discarding is that there be a legal harvest that maximizes revenue and is not technologically efficient. Proposition 3 establishes that this necessary condition is also sufficient if input prices are low enough.

Thus far, no use has been made of the assumptions about a fisher's ability to control catch composition. As the following proposition shows, these conditions can be very important determinants of whether discarding is profit maximizing.

**Proposition. 4** *(1) If A1, A2 and PC hold then* $Q^{\mathrm{notE}} = \phi$. *(2) If A1, A2 and SIC hold then* $Q^{\mathrm{notE}} \neq \phi$.

Under perfect control of catch composition, the necessary condition of Proposition 2 never holds, so that discarding is never profit maximizing. Conversely under SIC, profit maximizing discarding may be possible. Under WIC, one can construct examples where $Q^{notE} = \phi$ or $Q^{notE} \neq \phi$. Hence there may or may not be conditions under which discarding is profit maximizing.

## 4. Value-Based Quota

Propositions 2 and 3 state that the way to prevent quota-induced discarding is to ensure that the revenue maximizing legal harvest is in the technologically efficient set, i.e., there exists $\bar{y} \in Q^E$ such that $p\bar{y} \geq py$ for all $y \in Q^{notE}$. If a planner knows a particular $y^* \in \mathcal{H}^E$, then choosing $Q = \{y|0 \leq y \leq y^*\}$ solves this problem. Alternately, a planner might specify the quota set such that only technologically efficient harvests are legal, i.e. $Q \subset \mathcal{H}^E$. In this case $Q^{notE} = \phi$, and $Q^E = Q$, so the necessary condition of Proposition 2 is never satisfied. The first approach is simply a disaggregated quota program where the planner picks a technologically efficient quota. The second approach corresponds to landing restrictions or supplemental taxes discussed in Anderson (1994b). In this second approach, a planer issues aggregated or disaggregated quotas, and also prohibits or sanctions (taxes) landings that would not have been produced without discarding by a profit maximizing fisher (i.e. are not in the technologically efficient set). These sorts of landing restrictions are under consideration in several fisheries (Muse 1991). It should be clear that such solutions to quota-induced discarding are information intensive. In particular, both require that a planner be able to determine whether particular landings are or are not technologically efficient. This will generally require a planner to occasionally observe discarding, and to distinguish between technologically- and quota-induced discarding.

Propositions 2 and 3 also suggest a third approach to the problem of quota-induced discarding. In particular, suppose that a planner issues $V$ dollars of value-based quota, each unit of which entitles a holder to land one dollar's worth of fish regardless of type. In this case, the quota set is given by $Q = \{y|py \leq V\}$, and corollary 1 establishes that quota-induced discarding is never profit maximizing.

**Corollary. 1** *If A1 and A2 hold, and if* $Q = \{y|py \leq V\}$ *for some* $V \in R_+$, *then discarding is never profit maximizing.*

The intuition behind this result is fairly straight forward. By construction, under a value-based quota program, the boundary of the quota set is an iso-revenue line. Assuming that the quota set is binding, this means that a fisher will maximize profits by choosing the cost minimizing way of producing landings on the boundary of the quota set. By proposition 1, these landings are produced without discarding.

On its face, administering such a quota program appears to be very complex. In fact, all that is required is that a planner issue a fisher a vector of disaggregated quota

$q^*$, and then allow the fisher to convert one unit of quota for type $i$ fish into $\frac{p_i}{p_j}$ units of quota for type $j$ fish. The resulting quota set is given by

$$Q = \{y | py \leq pq^*\}, \tag{1}$$

which is the same as is considered in corollary 1. Evidence that value-based quota programs are possible is given by Muse and Schelle (1989). These authors describe an Icelandic fishery in which

> ... operators are allowed to trade quota in one species for quota in another with the fisheries ministry. They may convert 5% of their quota in other species to Cod, and make unlimited trades from Cod to other species. These tradeoff ratios, based on relative fish prices are published in the regulations.(p54)

This quota program corresponds very closely to the one describe by equation (1). While value-based quota programs are probably more difficult to administer than their conventional counterparts, the Icelandic example demonstrates their feasibility. Moreover, value-based quota programs are probably less difficult to administer than conventional IQ programs with a system of landings restrictions or taxes to combat discarding.

By definition, value-based quota programs regulate harvest *value*, whereas planners are most likely to be interested in harvest *weight*. This means that if prices are unknown at the time $V$ is selected, then the weight of the fish that may be legally harvested under this quota is unknown. While this uncertainty is undesirable, if a planner knows relative fish prices, but not the price level, then the problem is easily solved. Suppose that $p = \alpha p^*$, where $p^*$ is the known vector of relative fish prices, and $\alpha$ is the price level, which is unknown until after quotas are distributed. If a planner issues $V$ dollars worth of quota, then the size of the quota set varies with $\alpha$. On the other hand, if a planner picks a particular harvest $q^*$ and issues quota that allows fishers to make any landing $y$ such that $py \leq pq^*$, then the quota set is invariant to changes in $\alpha$. That is, $Q = \{y|py \leq pq^*\}$. This means that the size of the value-based quota set need not vary with price level.

Although this method of administering a value-based quota program makes the quota set invariant to changes in the price level, the size and shape of the quota set will vary with changes in relative fish prices. Since a planner cannot know relative fish prices with certainty until after the fish market clears, a planner must issue a value-based quota when relative prices are still uncertain. Hence, under a value-based quota program the weight of fish that may be legally landed is more or less uncertain as relative fish prices are more or less volatile.

While this uncertainty is clearly undesirable, it is not necessarily worse than the uncertainty that exists under disaggregated and aggregated individual quota programs. In a disaggregated or aggregated individual quota program, a planner knows with certainty whether a particular bundle of fish may be legally landed, without knowing relative prices. But unless a planner knows prices and a great deal about the shape of the fisher's technologically feasible set, he cannot know *a priori* the amount of discarding that a particular disaggregated or aggregated quota set will induce. Even if a planner is able to observe discards, the question remains unanswerable unless the planner can distinguish between technologically- and quota-induced discarding. While landings can be known with certainty under conventional programs, if discarding is unobserved then harvest weight must be uncertain.

Thus the choice between value-based and disaggregated or aggregated individual quota programs boils down to the following. Under a value-based individual quota program planners are uncertain about the size and shape of quota sets until after fishing has begun and market prices are known. However, given corollary 1, planners are certain that the quota program does not induce any discarding. Under disaggregated or aggregated quota programs, planners know with certainty the weight of fish that may be legally landed, but are uncertain about the quantity of discarding induced by quota programs, and hence are uncertain about the total harvest weight. In short, value-based individual quotas are better than their conventional counterparts in that they do not induce discarding. Furthermore, value-based quota programs are not necesarily worse than their more conventional counterparts because they induce uncertainty about the final harvest weight. This suggests that value-based individual quota programs should be given serious consideration in any fishery where a planner wants to reduce or prevent quota-induced discarding.

## 4. Conclusion

Extant remedies for quota-induced discarding include landing restrictions and a type specific system of landing taxes on top of the quota program. Both are information intensive in that they require a planner to identify harvest bundles that are and are not technologically efficient. This paper presents a new analytical framework in which the shape of quota sets is treated as a control variable. In this context it is shown first that quota-induced discarding may be profit maximizing under conventional disaggregated and aggregated individual quota programs, and second, that quota-induced discarding is never profit maximizing in a value-based individual quota program. Value-based individual quota programs have the additional advantage that they do not require a planner to know whether any particular harvest is or is not technically efficient, information that is required by other extant solutions to quota-induced discarding.

While value-based quota programs remove an incentive to discard, the size and shape of the quota set depends on relative fish prices. This means that planners cannot know with certainty the size and shape of quota sets that results from a particular issue of value-based quota until after the quota has been distributed and market prices revealed. While this is undesirable, a similar problem occurs under disaggregated and aggregated individual quota programs. Under these types of programs, planners know with certainty the size and shape of the quota set associated with a particular issue of quota, but are uncertain about the amount of discarding induced by the quota program.

While it is not clear that value-based quota dominates other types of quota as a management tool, this paper has established under general conditions that value-based quota can solve the problems of quota-induced highgrading and dumping that may occur under other types of quota program. This suggests that value-based quota should be considered as a policy option, at least in fisheries where a planer wants to reduce quota-induced discarding.

These results are encouraging in that they suggest a new solution to the problem of quota-induced discarding. Perhaps more importantly, these results indicate the importance of the nearly ubiquitous free disposal assumption, and provide a framework in which this assumption can be relaxed. There are however, many unanswered questions. Economists often argue for taxes as a solution to overexploitation in fisheries. These arguments are typically based on technologies satisfying free disposal. Are arguments in favor of taxes robust to a relaxation of free-disposal? How do fishers respond to taxes? Should taxes be preferred to IQ programs in a heterogenous fishery? The analysis does not explicitly model uncertainty about prices or technology. How should a planner choose IQ programs when this uncertainty is explicit? What if fishing technologies are stochastic and not merely unknown to a planner? All of these questions are subjects for future research.

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## Appendix: Proofs

**Proposition. 1** *If A1 holds and $y$ is feasible, then*

*(1)* $[h(y), x(y)]$ *exists and is single valued.*

*(2)* $h(y) \in \mathcal{H}^E$.

*(3)* $h(y) > y$ *if and only if* $y \notin \mathcal{H}^E$.

Proof: (1) ($x > 0$) Since $y$ is feasible, there exists $(-x', h') \in T$ such that $h' \geq y$. Define $T(y) = \{(-x, h) \in T | h \geq y, x \leq x'\}$. $T(y)$ closed follows from A1.3. $T(y)$ bounded follows from A1.4 and $T \subset R^1_- \times R^m_+$. Thus $T(y)$ is compact, so $min_{T(y)} f(x, h)$ exists. Since $min_{T(y)} f(x, h) = min_T f(x, h)$, it follows that $[h(y), x(y)]$ exists. Since $x(y) \in R^1$, it must be single valued. Suppose $h(y) = \{h, h'\}$. Let $h'' = \alpha h + (1 - \alpha)h'$. By A1.6, for $\alpha \in (0, 1)$, there exists $\varepsilon > 0$ such that $B_\varepsilon(-x(y), h'') \bigcap \{R^1_- \times R^m_+\} \subset T$. If $x > 0$ this means that for some $\varepsilon' \leq \varepsilon$, $(-x(y) + \varepsilon', h'') \in T$, contradicting the minimality of $x(y)$. If $x = 0$ then by A1.2 $\{h | (0, h) \in T\} = \{0\}$, so that $h(0)$ is single valued.

(2) Suppose not, then there exists $h' > h(y)$ such that $(-x(y), h') \in T$ with $h' \geq y$ and $h' \neq h(y)$. This contradicts (1).

(3) (ONLY IF) If $y \notin \mathcal{H}^E$ then it follows from (2) that $y \neq h(y)$. Since $y$ is feasible, $h(y) > y$ follows. (IF) By definition of $x(y)$, if $x < x(y)$ then $\{(x, h) \in T | h \geq y\} = \phi$. By hypothesis, and A1.5, $(-x(y) - \alpha, h(y)) \in T$ for all $\alpha \geq 0$. It follows that there is

no $x$ such that $(-x, y) \in T$ and for all $\varepsilon > 0$, $(-x, y+\varepsilon) \notin T$. Thus $y \notin \mathcal{H}^E$. $\square$

**Proposition. 2** *If A1 and A2 hold, and if there exists $\bar{y} \in Q^E$ such that $p\bar{y} \geq py$ for all $y \in Q$ then discarding is never profit maximizing.*

Proof: Suppose that the following condition holds. (a) For every $\underline{y} \in Q^{notE}$ there exists $h^* \in Q^E$ such that (I) $p\underline{y} = ph^*$ and (ii) $ph^* \geq ph$ for every $h$ such that $(-x(h^*), h) \in T$. By Prop 1.3, and the definition of $Q^{notE}$, $\underline{y} < h(\underline{y})$ so that $ph(\underline{y}) > p\underline{y} = ph^*$. By (ii) above, $(-x(h^*), h(\underline{y})) \notin T$. By A1.3, $x(\underline{y}) > x(h^*)$. Thus, $ph^* - wx(h^*) > p\underline{y} - wx(\underline{y})$. It follows that if condition (a) holds, it is never profit maximizing to choose $\underline{y} \in Q^{notE}$. By Proposition 1.3, discarding is never profit maximizing for $y \in Q^E$; it follows that discarding is not profit maximizing if (a) holds.

Thus it is sufficient to show that if for some $\bar{y} \in Q^E$, $p\bar{y} \geq py$ for all $y \in Q$, then condition (a) holds.

By hypothesis, there exists $\bar{y} \in Q^E$ such that $p\bar{y} \geq py$ for all $y \in Q^{notE}$. For arbitrary $\underline{y} \in Q^{notE}$ let $x^*$ denote the smallest $x$ such that $T(\underline{y}) = \{(-x, h) \in T | h \in Q, ph \geq p\underline{y}\} \neq \phi$. The proof that $x^*$ exists and is unique is very similar to the proof of Prop 1.1. Note that by A1.2, $\Pi_{Q^{notE}}(p, w) > 0$ implies that $x^* > 0$. Suppose (ii) does not hold so that for some $h$, $ph > ph^*$ and $(-x^*, h) \in T$. Then by A1.6 and A1.1, there exists $\alpha \in (0,1)$ such that $(-\alpha x^*, \alpha h) \in T$ with $p\alpha h \geq p\underline{y}$, and $\alpha x^* < x^*$. This contradicts the minimality of $x^*$. Therefore (ii) holds. Suppose (I) does not hold, so that $ph^* > p\underline{y}$. By A1.6 and A1.1 there exists $\alpha \in (0,1)$ such that $(-\alpha x^*, \alpha h) \in T$ with $p\alpha h \geq p\underline{y}$, and $\alpha x^* < x^*$. This contradicts the minimality of $x^*$. Therefore (I) holds. $\square$

**Proposition. 3** *If A1 and A2 hold, and if there exists $\underline{y} \in Q^{\mathrm{notE}}$ such that $p\underline{y} > py$ for all $y \in Q^E$, then for $w$ small enough, discarding is profit maximizing.*

Proof: Let $\bar{y} \in Q^E$ be an arbitrary legal and technologically efficient landing. By hypothesis $p\underline{y} > p\bar{y}$. Let $w^* = \frac{p\underline{y} - p\bar{y}}{x(\underline{y})}$. Then for all $w < w^*$, $p\underline{y} - wx(\underline{y}) > p\bar{y} - wx(\bar{y})$. Since $\bar{y}$ is arbitrary, this is true for all $\bar{y} \in Q^E$. By prop 1.3, $\underline{y} < h(\underline{y})$. Thus discarding is profit maximizing for $w$ sufficiently small. $\square$

**Proposition. 4** *(1) If A1 and PC hold then $Q^{\mathrm{notE}} = \phi$. (2) If A1 and SIC hold then $Q^{\mathrm{notE}} \neq \phi$.*

Proof: (1) Let $y \in Q$. It is sufficient to show that $y \in \mathcal{H}^E$. By Prop 1.3, it is sufficient to show that $h(y) = y$. Suppose $h(y) > y$; then by PC, there exists $x$ such that $(-x(y), y) \in T$. By A1.6 for $\alpha \in (0,1)$ there exists $\varepsilon > 0$ such that $B_\varepsilon(-x(y), \alpha y + (1-\alpha)h(y)) \subset T$. By A1.2 if $y > 0$, then $x(y) > 0$ so for some $\varepsilon' < \varepsilon$, $(-x(y) + \varepsilon', \alpha y + (1-\alpha)h(y)) \in T$ and $\alpha y + (1-\alpha)h(y) > y$. This contradicts the minimality of $x(y)$. (2) Trivial. $\square$

**Corollary. 1** *If A1 and A2 hold, and if* $Q = \{y|py \leq V\}$ *for some* $V \in R_+$ *then discarding is never profit maximizing.*

Proof: By Proposition 2, it is sufficient to show that there exists $\bar{y} \in Q^E$ such that $p\bar{y} = V$. Let $T(V) = \{(-x, h) \in T|ph \geq V\}$. If $T(V) = \phi$ then the quota is not binding and does not induce discarding. Suppose $(-x', h') \in T(V)$ and let $T^*(V) = \{(-x, h) \in T|ph \geq V, x \leq x'\}$. Then $T^*(V)$ is compact and non-empty. Let $f(x, h) = x$. Since $f$ is continuous, by the Wierstrauss Theorem, $f$ reaches a minimum $x^*$ on $T^*(V)$. Since $\min_{T^*(V)} f = \min_{T(V)} f$, it follows that $x^*$ is the smallest effort level such that for some $h^*$, $(-x^*, h^*) \in T(V)$. Using A1.6 it is easy to show that $ph^* = V$, and $h^* \in \mathcal{H}^E$. It follows that $h^* \in Q^E$. $\square$