JOURNAL OF ENVIRONMENTAL ECONOMICS AND MANAGEMENT **33,** 186–195 (1997)
ARTICLE NO. EE970985

Quota-Induced Discarding in Heterogeneous Fisheries[1]

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Received March 29, 1996; revised October 23, 1996

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. This analysis shows that the most common types of individual quota programs can induce discarding, and that individual quota programs that regulate the value of harvests 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. The disadvantages of value-based quotas are also examined. Results are driven by the fact that the harvest 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 may be useful for analyzing a broad class of problems involving joint production.

1. INTRODUCTION

While there are many ways of distributing quotas and administering individual quota programs, the fact that a fisher may bring to market only as much fish as his quotas allow is definitional. Since shipboard monitoring is expensive, individual quota programs typically regulate the amount of fish that is landed rather than the amount that is harvested [11, 12].

Absent a shipboard observer, 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, or the market value of the fish may not cover costs of shipboard processing and transportation to market. Anderson [1] and Arnason [3] treat this technologically induced discarding in detail and find that it may be efficient. There is also evidence that individual quota programs can provide an incentive to discard fish that would otherwise be brought to market.[2] Since discarded fish have a high mortality rate, quota-induced discarding involves the following social costs: the market value of the fish is lost, the effort used to harvest the fish is wasted, and the reproductive potential of the fish is

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[1] This research was supported by the Connaught Foundation and the Woods Hole Oceanographic Institution. This paper has the benefit of helpful comments and advice from: Ralph Winter, Michael Smart, Steven Kohlhagen, Jim Kelly, an anonymous referee, and seminar participants at the University of Toronto, the Canadian Public Economics Study Group, and the Toronto–Cornell–Rochester Summer Workshop. All remaining errors are my sole responsibility.

[2] Muse and Schelle [11] provide a detailed description of 12 individual quota programs. Of these 12, quota-induced discarding is known or suspected in 6. McCloskey [10, p. 16] also documents the occurrence of quota-induced dumping. In addition, Anderson [2], Arnason [3], and Turner [17] find a theoretical basis to suspect that *tradable* individual quota programs induce discarding by profit maximizing fishers.

0095-0696/97 $25.00

wasted. Therefore, all else equal, quota programs that induce less discarding are to be desired.

The two most common types of individual quota programs are ‘‘aggregated’’ and ‘‘disaggregated,’’ both of which can cause discarding. 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 meet a quota by ‘‘highgrading’’ and discarding less valuable types of fish. In a disaggregated individual quota program, a planner issues quotas entitling fishers to land 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 quotas for other types, and ‘‘dump’’ any over-quota fish of the first type. ‘‘Quota-induced’’ discarding, rather than ‘‘technologically induced’’ discarding, is the subject of this paper.

Specifically, this paper considers the regulation of heterogeneous fisheries with individual quota programs and establishes the following results. First, while the most common types of quota programs can cause discarding, provided that the planner has enough information about the harvest technology, they need not do so. Second, quota programs that regulate the value of harvested fish never induce discarding. This result is independent of how much the planner knows about the harvest technology. Thus the advantage of value-based quota is that it eliminates the incentive for quota-induced discarding and does not require the planner to have any information about the technology. This feature should make value-based quota programs attractive in fisheries where (1) the technology depends on difficult-to-predict fluctuations in stock size, (2) is subject to rapid technological change, or (3) is badly understood.

Value-based quota programs also have disadvantages. First, since the value of harvest is regulated, rather than the weight, the legal harvest weight may vary with prices. If prices are uncertain this will cause the relationship between quotas issued and the legal harvest weight to be uncertain. This problem may be reduced, but not eliminated, by basing quotas on relative fish prices. Although this uncertainty is an undesirable feature of value-based quota programs, it is not obviously worse than the price-driven uncertainty that occurs with conventional quota programs. Under conventional quota programs, quota-induced discarding, and hence harvest weight, can change with changes in price level and relative prices (although landings can be known with certainty).

The preceding paragraph points out another important difference between value-based and conventional quotas. With value-based quotas the planner knows that landings and harvests coincide. With aggregated or disaggregated quota programs the planner often does not observe the quantity of discarding, and hence, is uncertain about harvest size. Relative to the conventional programs, value-based quota programs allow the planner to have better information about the *ex post* harvest size, in exchange for *ex ante* uncertainty about landings. Since accurate information about harvests is important to stock size assessment, managers may prefer value-based quotas because they reduce *ex post* uncertainty over harvest size.

A second drawback to value-based quota programs is that they offer the planner little control over harvest composition. Under a value-based quota program (if it is binding), a fisher will fill his quotas in the least costly way. It may be that the least costly way to fill the quotas involves concentrating on a single type that has a much higher ‘‘shadow price’’ than other types (e.g., seasonal aggregations of breeding stocks). Thus value-based quota need not provide an incentive for socially optimal harvesting. Note that this problem is not unique to value-based quota programs. Aggregated quota programs also allow fishers to concentrate on types with high shadow prices.

This introduction describes only two of many possible problems with individual quota programs. A much more exhaustive listing is given in Copes [5]. Of particular interest is the problem of ‘‘quota-busting’’ called ‘‘smuggling’’ in Muse and Schelle [11]. As the name suggests, this problem occurs when a fisher commits the crime of concealing landings from the planner. Thus, managing smuggling in an individual quota program is an enforcement problem. While Arnason [3] points out that we can also regard dumping and high-grading 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 literature on poaching (e.g., [8, 14]). If one regards the problem of quota-induced 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.

The results in this paper are driven by the fact that fishers have only imperfect control over the proportions of different types of fish in their harvests. This type of imperfect control of output composition is common among joint production technologies: A farmer may exercise only imperfect control over the proportions of different grades of fruit produced by an orchard; a factory manager may have only limited control over the proportions of different pollutants emitted from a smokestack. Although this paper is primarily concerned with fisheries management, the analysis is really a description of joint production technologies with imperfect control over output composition. Hence the analysis may find applications in this much larger class of problems.

The paper proceeds as follows. The next section describes the fishery and the harvesting technology. The third section presents and discusses the paper’s main conclusions. The analysis conducted here is primarily graphical. Proofs and a more rigorous analysis are contained in an earlier working paper [18].

2. HARVEST TECHNOLOGY

While a fishery is understood to consist of many fishers, the current analysis examines the way that a single fisher responds to an individual quota program. This analysis should therefore be interpreted as beginning after the planner has allocated quotas, whether this allocation takes place by fiat, lottery, or through a quota market.

For current purposes, the defining characteristic of heterogeneous fisheries is that more than one type of fish may come up on the same line or in the same net or trap.[3] Economists often represent the harvest technology in a heterogeneous

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[3] Muse [12] gives several examples of fisheries where this occurs. Squires [13] examines the New England trawler fleet and finds evidence that several species of fish are produced jointly. McCloskey [10] and Warner [18] 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, heterogeneous fisheries appear to be the norm rather than the exception.

fishery as a joint production function in which each type of fish makes up a fixed proportion of the harvest [1, 2, 3, 4 ch. 10]. While this method of describing a harvest technology is particularly tractable, and allows different types to be harvested simultaneously, as Anderson [2] observes, it fails to allow certain types of observed behavior. In particular, there is considerable evidence that fishers can, within limits, affect the composition of their harvests by choice of time, place, or technique [10 p. 16, 11, 12, 13, 19].

To construct a model of a fishery where fishers have limited control over the composition of their harvests, imagine that the stock of fish consists of two types of fish,[4] where each ‘‘type’’ is a distinct market class, distinguishable from the other types and with its own price. As such, a type may be a particular species, or a size class of a species. A harvest is a pair $h = (h_1, h_2) \geq 0$, where h_1 and h_2 are the harvested weights of type 1 and type 2. Assume that ‘‘effort’’ is the only input into the production technology. This is a simplifying assumption that lightens notation and allows the analysis to concentrate on the choice of outputs rather than the choice of inputs. Effort is denoted by x, and may be purchased at the market price $w > 0$. This analysis will be static so that the size of fish stocks is fixed and may be omitted. To allow for the possibility of discarding, distinguish between landings $y = (y_1, y_2) \geq 0$, which may be sold at the market price $p = (p_1, p_2) > 0$ and harvests h that may be landed or discarded. In the absence of discarding $y = h$, and it will sometimes be convenient to refer to y as the harvest as well. To avoid an analysis of technologically induced discarding, all harvested fish are assumed to be marketable. Alternatively, (h_1, h_2) may be regarded as the harvest of marketable fish after technologically induced discarding has occurred.

Say that a harvest technology is ‘‘regular’’ if the set of technologically feasible harvests satisfies the following standard conditions from neoclassical production theory (e.g., [6, 7, 16]). (1) It is closed, bounded, and nonempty. (2) It is convex. (3) No harvests are possible with zero effort. Finally, (4) the set of feasible harvests increases with the amount of effort. The first condition is necessary to ensure that a fisher’s profit-maximization problem has a solution and cannot be contradicted with a finite data set. In addition, boundedness reflects the fact that fish stocks are finite. The second condition is a simplifying assumption—it ensures that there is at most one profit maximizing choice of harvest. The third and fourth conditions are stylized facts. Taken together (2), (3) and (4) imply decreasing returns to harvesting effort. Since the size of the fish stock is implicitly fixed, this is just decreasing returns to a fixed factor.

Figure 1 illustrates two regular harvest technologies. In these figures the axes refer to quantities of each type harvested, while $H(x')$, $H(x'')$, and $H(x''')$ describe the sets of feasible harvests associated with input levels $x''' > x'' > x' > 0$. Consider a fisher with the harvest technology illustrated in Fig. 1a. For such a fisher, for any level of effort, any composition of harvests is possible. He may catch only type 1, only type 2, or some of both. Say that a technology with this property satisfies ‘‘perfect control of harvest composition’’ (PC). More precisely, say that a technology satisfies PC if: whenever a harvest is feasible, every smaller harvest is also feasible with the same amount of effort. Because this condition is satisfied

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[4] All results and intuition extend easily to a fishery with any finite number of types at some cost in notation.

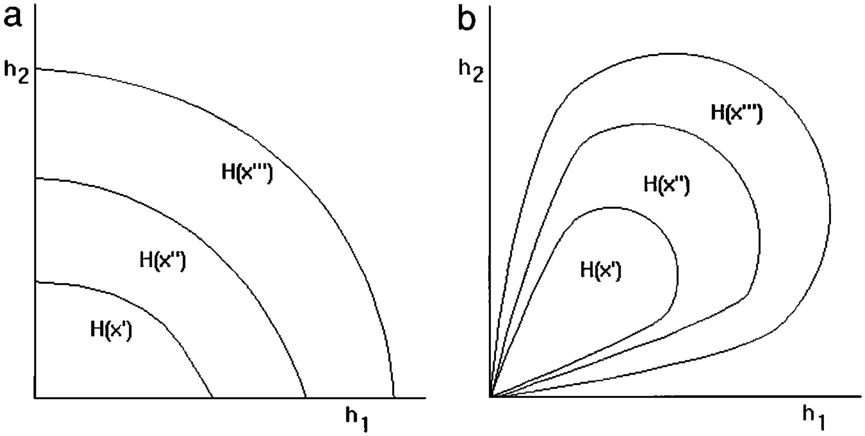

FIGURE 1

whenever it is costless to discard the harvest, it is often called a ‘‘free-disposal’’ condition.

There are two reasons why harvest technologies satisfying free-disposal (here PC) are not appropriate for an analysis of quota-induced discarding. First, perfect control of harvest composition is not consistent with evidence that fishers have only a limited ability to control harvest compositions [10 p. 16, 11, 12, 13, 19]. Second, discarding can never be profit maximizing when fishers have perfect control. To see this, note that in Fig. 1a, for every possible harvest, it requires strictly more effort to produce a larger harvest. As a result, discarding can never be cost minimizing, and it follows immediately that discarding cannot be profit maximizing.[5] Thus if we observe discarding we must reject either PC or the assumption that fishers maximize profits.

For these reasons, this paper will address fishing technologies that do not allow perfect control over harvest composition. Say that a technology exhibits ‘‘imperfect control over harvest composition’’ (IC) if for all effort levels the set of feasible harvests intersects the h_1 and h_2 axes only at the origin.[6] Put another way, IC 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. A harvest technology satisfying IC is illustrated by Fig. 1b.

As argued above, if the harvest technology allows perfect control of harvest composition, then discarding is never profitable and need not be described. However, if imperfect control of harvest composition holds, then we need a more complete specification of the fishery. Landings are the net of separate harvest and disposal technologies, and a complete model of fishing must describe both. Unless this is accomplished we cannot observe the impact of regulation on discarding, an activity that has potentially large social costs. With this said, this analysis makes the simplifying assumption that disposal technologies are costless for the fishermen. As a result, the *landing* technology satisfies free-disposal, though the *harvest* technol-

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[5] A more rigorous proof of this result is available in [18].

[6] For completeness, note that ‘‘weakly imperfect control of catch composition’’ is also is possible and may be defined as the failure to satisfy perfect or imperfect control of harvest composition.

ogy does not. While costly disposal technologies would make the analysis more complete, it adds complexity and little additional insight. The reader interested in the implications of a nontrivial disposal technology is referred to Anderson [1, 2], Arnason [3], or Turner [17], each of whom consider costly disposal together with a fixed proportions joint production technology.

While the condition IC reflects the stylized fact of imperfect control over harvest composition and opens the door to quota-induced discarding, it imposes a cost in notation. To understand this, consider Fig. 1a. Given effort x and h_2, there is a unique value of h_2 on the frontier of $H(x)$. This means that the technological frontier can be described as a function, and we can proceed to analyze this ''production function,'' rather than the more primitive technology set (e.g., [7]). With imperfect control of harvests, this is not possible. Given x and h_1 there are usually two values of h_2 on the frontier of $H(x)$. This is illustrated in Fig. 1b. This type of frontier, by definition, cannot be described by a function and we are compelled to describe the harvest technology with correspondences.

3. REGULATION

The next step in the analysis is to describe an individual quota program and to specify the set of quota programs that we will allow the planner to consider. Suppose that a planner can specify any quota set Q of legal landings, provided that this set has the following properties: (1) Q is closed, bounded, nonempty, and (2), if landings y are legal, then all landings less than y are also legal. The first condition is necessary to ensure that the fisher's profit maximization problem has a solution. The second prevents the planner from setting minimum legal harvests, regulation that is rarely observed. Say that a quota set satisfying these conditions is ''regular.''

We can now describe aggregated, disaggregated, and value-based quota programs. 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 $Q = \{(y_1, y_2) \mid y_1 + y_2 \leq W\}$. 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 $Q = \{(y_1, y_2) \mid (y_1, y_2) \leq (q_1, q_2)\}$, where $(q_1, q_2) \geq 0$ are the maximum legal landing weights for each type.[7] Finally, in a value-based quota program, a planner issues quotas allowing a fisher to land up to V dollars worth of fish. The corresponding quota set is $Q = \{(y_1, y_2) \mid p_1 y_1 + p_2 y_2 \leq V\}$. Although value-based quota programs are little known in the economics literature, they are mentioned in Copes [5], value-based quotas in a tradable individual quota program are analysed in Turner [17], and finally, Muse and Schelle [11] describe a value-based quota program in operation in Iceland.

Having described fishing technologies and individual quota programs, we can now ask how the fisher responds to regulation. Figure 2 illustrates aggregated and disaggregated quota programs along with a harvesting technology. In Fig. 2a the shaded region Q is the set of legal harvests that results when the planner issues

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[7] Aggregated quota programs can be used in a fishery where the different types of fish are different species. However, it is more common for the different types regulated by an aggregated quota program to be different sizes of the same species. Disaggregated quota programs are usually used in multispecies fisheries [12].

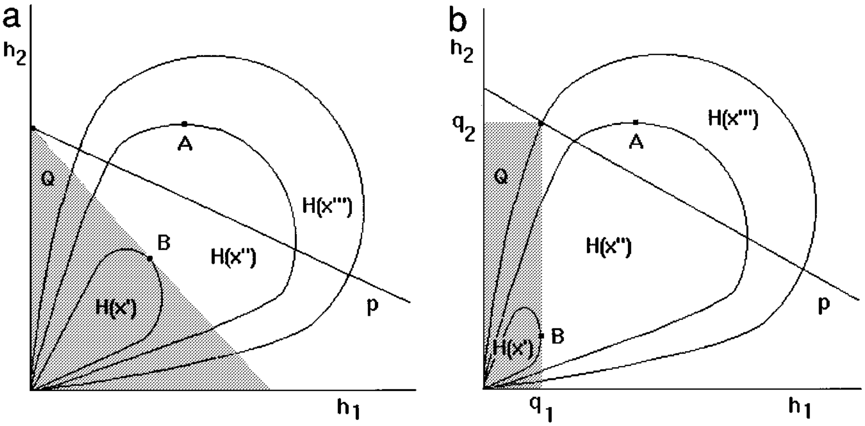

FIGURE 2

aggregated quotas that allow the fisher to land W pounds of fish regardless of type (i.e., $Q = \{(y_1, y_2) \mid y_1 + y_2 \leq W\}$). If the price of type 2 fish is higher than that of type 1 fish, then revenue maximizing legal landings consist only of type 2 fish. Therefore, if the price of effort is low enough the fisher will maximize profits by choosing the harvest labelled A and discarding the entire harvest of type 1 fish. This is high-grading. As the price of effort rises the fisher's profit maximizing harvest will move along the boundary of Q to point B where no discarding occurs. If the price of effort rises further, then the quotas no longer bind.

In Fig. 2b the planner gives the fisher disaggregated quotas that allow landings of up to q_1 pounds of type 1 fish and q_2 pounds of type 2 fish (i.e., $Q = \{(y_1, y_2) \mid (y_1, y_2) \leq (q_1, q_2)\}$). With disaggregated quota, the revenue maximizing legal landings are always $(y_1, y_2) = (q_1, q_2)$, the northeast corner of the quota set. Given the technology in Fig. 2b, if the price of effort is low enough, then the fisher harvests at point A, lands (q_1, q_2), and discards type 1 fish. As the price of effort rises, profit maximizing landings move along the boundary of Q to point B where no quota-induced discarding occurs. If the price of effort increases further than the quotas no longer bind. This type of quota-induced discarding is often called dumping.

The examples illustrated in Fig. 2 show that for a particular harvest technology, discarding may be a profit maximizing response to the two most common types of individual quota programs. Much of the rest of this paper will explore the conditions under which the intuition illustrated by these examples does and does not generalize. As a first step it is necessary to define the set of "technologically efficient" harvests.

Say that a harvest (h_1, h_2) is "technologically efficient" if there exists some level of effort such that (1) this harvest is feasible, and (2) no larger harvest is feasible. Thus the revenue maximizing legal landings in Figs. 2a and 2b are not technologically efficient, while the harvests denoted A and B in Figs. 2a and 2b are technologically efficient. Put a little less formally, a harvest is not technologically efficient if, whenever a harvest is feasible, there is a way to harvest more fish with the same effort. Thus we should expect the discarding is cost-minimizing if and only if the fisher chooses landings that are not technologically efficient. This intuition is formalized by the following proposition.

PROPOSITION 1. *For any regular harvest technology, discarding is a cost minimizing way to produce landings y if and only if y is not technologically efficient.*

Over-harvesting and then discarding is a cost minimizing way to produce particular landings only if those landings are not technologically efficient. This means that individual quota programs can induce discarding only if the quota program provides an incentive to choose landings that are not technologically efficient. That is, a particular quota program can induce discarding only if the revenue maximizing legal landings are not technologically efficient. Note that this exactly the situation illustrated in Figs. 2a and 2b. This intuition is formalized in the following proposition.

PROPOSITION 2. *Given p, a regular quota set, and a regular harvest technology with imperfect control of harvest composition, suppose there is a legal harvest that is not technologically efficient and generates strictly greater revenue than any technologically efficient legal harvest. Then if w is sufficiently small, discarding is profit maximizing.*

Proposition 2 says that for discarding to be profit maximizing, it must be cost minimizing to discard, and the price of effort must be low enough that it is profitable to continue fishing when only a portion of the catch is retained. An interesting implication of this is that quota-induced discarding is more likely to occur in fisheries that are very profitable than in fisheries that are marginally profitable. Proposition 3 is a converse of Proposition 2. The paper's main policy implications follow as corollaries of this proposition.

PROPOSITION 3. *Given p, a regular quota set, and a regular harvest technology, if the revenue maximizing legal landings y are technologically efficient then discarding is not profit maximizing.*

Given Proposition 3, the way to prevent quota-induced discarding is to ensure that the revenue maximizing legal landings are technologically efficient. Since the set of legal landings is under the planner's control, this suggests that the planner control discarding by a judicious choice of the quota set. One of many possible ways to do this is established by the following corrollary.

COROLLARY 1. *Given a regular harvest technology, let q be a technologically efficient harvest. If the planner issues disaggregated quotas q then for all p and w discarding is not profit maximizing.*

The intuition behind Corrollary 1 is as follows. The quota set associated with disaggregated quota q is $Q = \{(y_1, y_2) \mid (y_1, y_2) \leq (q_1, q_2)\}$. For all positive prices, the revenue maximizing element of this set is q. By assumption, q is technologically efficient, so by Proposition 3 discarding is not profit maximizing.

This solution to the problem of quota-induced discarding requires that the planner have a lot of information about the harvest technology. If there is rapid technological progress or unpredictable stock fluctuations then this information may not be available. As the following corrollary shows, value-based quota programs overcome this problem.

COROLLARY 2. *Given a regular harvest technology it is never profitable to discard under a value-based quota program.*

Under a value-based individual quota program, the planner issues a fisher quota allowing V dollars of landings regardless of type. The associated quota set is $Q = \{(y_1, y_2) \mid p_1 y_1 + p_2 y_2 \leq V\}$. By construction the boundary of this quota set is an isorevenue line. Given a regular harvest technology it is always true that this isorevenue line contains a technologically efficient harvest and the corrollary follows from Proposition 3.

Value-based quotas eliminate the incentive to discard and do not require that the planner have any information about the technology. However, since the size and shape of the quota set varies with prices, if prices are uncertain then the relationship between harvest weight and the number of quotas issued is also uncertain. This problem may be partially overcome by using ‘‘relative-value-based’’ quotas. Under such a program the planner issues a vector (q_1, q_2) of disaggregated quotas, and then allows the fishers to convert quotas for one type of fish into quotas for another at a rate determined by their relative prices. The quota set associated with this type of program is given by $Q = \{(y_1, y_2) \mid p_1 y_1 + p_2 y_2 \leq p_1 q_1 + p_2 q_2\}$. Since this quota set is invariant to changes in the price level, this type of quota program reduces price driven uncertainty relative to a nominal value-based quota program. Since this quota set can still change with relative prices, price-driven uncertainty is not eliminated.[8]

Although this uncertainty is an undesirable feature of value-based quota programs, it is not obviously worse than the price-driven uncertainty that occurs with conventional quota programs. Under conventional quota programs, quota-induced discarding, and hence harvest weight, can change with changes in price level and relative prices (although landings can be known with certainty). Since the quantity of quota-induced discarding is not observed, this means that the planner is uncertain about actual harvest weight. Therefore, relative to conventional programs, value-based quota programs allow the planner to have better information about the *ex post* harvest size, in exchange for *ex ante* uncertainty about harvest size.

A second drawback to value-based quota programs is that they offer the planner little control over harvest composition. Under a value-based quota program (if it is binding), a fisher will fill his quota in the least costly way. It may be that the least costly way to fill the quotas involves concentrating on a single type that has a much higher ‘‘shadow price’’ than other types (e.g., seasonal aggregations of breeding stocks). This means that value-based quota programs need not result in socially optimal harvests. This problem can also occur under aggregated quota programs.

4. CONCLUSION

This paper considers the use of individual quota programs to regulate a heterogeneous fishery. It is shown that conventional types of quota programs can induce

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[8] I know of one real-world instance of a value-based quota program, and it is actually a relative-value-based quota program. Muse and Schelle [11 p. 54] describe this Icelandic fishery as follows: ‘‘[O]perators 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.’’

discarding. Two solutions are proposed. The first solution is to issue disaggregated quotas corresponding to a technologically efficient harvest. The disadvantage of this approach is that it is information intensive.

The second solution is to issue value-based quotas. Value-based quotas remove the incentive to discard and do not require the planner to have any information about the technology. The first disadvantage of value-based quota is that, like aggregated quotas, it may provide an incentive to concentrate fishing effort on types of fish with very high shadow prices. The second disadvantage of value-based quota is that, like conventional types of quotas, the relationship between quotas issued and harvest weight is uncertain if prices are not known with certainty.

This analysis supports at least the following conservative conclusions. Value-based individual quota programs should be considered in fisheries where (1) quota-induced discarding is suspected (2), the technology is not very well known, or is difficult to predict, and (3), all types of fish have approximately the same ‘‘shadow price.’’

REFERENCES

1. L. G. Anderson, A note on the economics of discards, *Mar. Resour. Econom.* **9**, 183–186 (1994a).
2. L. G. Anderson, An economic analysis of highgrading in ITQ fisheries regulation programs, *Mar. Resour. Econom.* **9**, 209–226 (1994b).
3. R. Arnason, On catch discarding in fisheries, *Mar. Resour. Econom.* **9**, 189–207 (1994).
4. C. W. Clark, ‘‘Mathematical Bioeconomics: The Optimal Management of Sustainable Resources,’’ Wiley–Interscience, New York (1990).
5. P. Copes, A critical review of the individually transferable quota as a device in fisheries management, *Land Econom.* **62**, 278–291 (1986).
6. G. Debreu, ‘‘Theory of Value,’’ Cowles Foundation monograph (1959).
7. W. E. Diewert, Functional forms for profit and transformation functions, *J. Econom. Theory* **6**, 284–316 (1973).
8. W. J. Furlong, The deterrent effects of regulatory enforcement in the fishery, *Land Econom.* **67**, 116–129 (1991).
9. H. S. Gordon, The economic theory of a common property resource: The fishery, *J. Polit. Econom.* **62**, 124–142 (1954).
10. W. McCloskey, ‘‘Fishdecks: Seafarers of the North Atlantic,’’ Paragon House, New York (1990).
11. B. Muse and K. Schelle, ‘‘Individual Fisherman’s Quotas: A Preliminary Review of Some Recent Programs,’’ Alaska Commercial Fisheries Entry Commission (1989).
12. B. Muse, ‘‘Survey of Individual Quotas Programs,’’ Alaska Commercial Fisheries Entry Commission (1991).
13. D. Squires, ‘‘Public Regulation and the Structure of Production in Multi Product Fisheries: An Application to the New England otter trawl industry,’’ *Rand J. Econom.* **18**(2), 232–247 (1987).
14. J. G. Sutinen, The economics of fisheries law enforcement, *Land Econom.* **61**, 387–397 (1985).
15. Weighout Data Trip database (WODETT) documentation, Nation Marine Fisheries Service, Woods Hole (1995).
16. Y. Sakai, Substitution and expansion effects in production theory: The case of joint production, *J. Econom. Theory* **9**, 255–274 (1974).
17. M. Turner, Value-based ITQ’s, *Mar. Resour. Econom.* **11**, 59–69 (1996).
18. M. Turner, ‘‘Quota-induced Discarding in Heterogeneous Fisheries,’’ University of Toronto, Department of Economics working paper series 95-02 (1996).
19. W. W. Warner, ‘‘Distant Water: The Fate of the North Atlantic Fisherman,’’ Little Brown, Boston (1983).