Prices versus Quantities in Fisheries Models

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ABSTRACT. *This paper discusses the conditions for generalizing the analysis in Weitzman (1974) to fisheries. It is shown that it is straightforward to generalize the analysis if the cost function is direct additively separable in stock size and catches. This leads to the conclusion that the analysis holds for a schooling fishery with and without search costs, but it might not hold for a search fishery. A further result is that for a schooling fishery without search costs, where the marginal cost function is steeper than the marginal benefit function, taxes are likely to be preferred over individual transferable quotas.* (JEL Q22)

I. INTRODUCTION

Fisheries economists usually recommend the use of a system of individual transferable quotas (ITQs) or taxes as the regulatory instruments that secure economic efficiency, (see Clark 1985). With regard to ITQs, compliance is often mentioned as a problem that prevents a first-best optimum from being reached (see Copes 1986), while taxes have been criticized for posing excessive information requirements, (see Arnason 1990).

The equivalence of transferable permits or quotas and taxes in terms of economic efficiency under full information has been shown repeatedly in the pollution control literature (see, e.g., Baumol and Oates 1988) as well as in the fisheries economic literature (see, e.g., Moloney and Pearse 1979). Furthermore, within the pollution control literature, there are many analyses of the choice between price and quantity regulation under imperfect information. The classic article within this area is Weitzman (1974), where it is shown that, within this particular setting, the choice between price and quantity regulation depends on the sign of the sum of the slopes of the marginal benefit and marginal cost functions. If the marginal benefit function is flat and the marginal cost function is steep, price regulation is preferred over quantity regulation, while quantity regulation is preferred over price regulation if the marginal benefit function is steep and the marginal cost function is flat.

Even though it is well documented in the pollution control literature that the equivalence between price and quantity regulation does not hold in the presence of imperfect information, it is often not well understood in the literature of fisheries management. This can be illustrated by quoting Clark (1985), "The relationship between taxes and quota market prices might be clarified in the stochastic setting by modeling the quota market, but we shall not pursue the study here (see Weitzman 1974)."

Weitzman (2002) studies imperfect information about the stock-recruitment relation and shows that taxes are preferred over ITQs in this case. With a tax it is possible to let a desired quantity of recruiters escape, while there is no guarantee of this with quantity regulation. Weitzman (2002) calls imperfect information about the stock-recruitment relation "ecological uncertainty". He also defines economic uncertainty as uncertainty about the profit function and writes, "Pure economic uncertainty is a typical 'price-vs-quantity type' mixed situation."

This implies that the slope of the marginal

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cost and marginal benefit function are important for the choice between price and quantity regulation. Others that have worked with the choice between price and quantity regulation under uncertainty include Anderson (1986) and Androkovich and Stollery (1991). However, their approaches differ from the approach taken in this paper (the Weitzman approach), with respect to the timing of decisions taken by the fishermen. In the Weitzman approach, decisions are taken ex post (after the realization of a random variable), while decisions are taken ex ante (before the realization of a random variable) in Anderson (1986) and Androkovich and Stollery (1991). Furthermore, these authors assume a very simple, linear growth function. Even with this growth function the solution becomes very complicated.

The purpose of this paper is to analyze conditions for generalizing the results in Weitzman (1974) on economic uncertainty to fisheries economics.[1] In other words, we examine whether the statements by Weitzman (2002) and Clark (1985) quoted above, are correct. In order to discuss this issue, it is useful to give a brief introduction to the pollution control literature.

It turns out that an important determinant of conditions for generalizing the Weitzman result is the cost function. Assume that q is the catch, x is the stock and θ is a random variable. A cost function is directly additive separable in catches and stock size if the marginal cost of catches does not depend on stock size. Therefore, directly additive separability can be expressed as $C(q, x, \theta) = C(q, \theta) + C(x)$.[2]

The discussion of direct additive separability can be related to the discussion of schooling and search fisheries. Neher (1990) defines a schooling fishery as a fishery for which the fish stock size does not influence the cost of fishing ($C(q)$). The herring fishery is an example of such a fishery, and herring is typically found in shoals. A search fishery is defined as a fishery where the fish stock influences the cost of fishing. Cod is an example of such a fish stock, and cod is typically spread over a fishery area ($C(q, x)$). Clark (1985) defines a schooling fishery with search costs and specifies $C(q) = c_q q + c_s$, where c_q is the marginal catch costs and c_s is the search costs. An alternative formulation of the schooling fishery with search costs will be $C(q, x) = c_q q + c_s x$, which could capture that stock size influences the costs incurred to identify shoals. This could be the case for herring. Based on Neher (1990) and Clark (1985) three different kinds of fisheries can, therefore, be identified:

- A schooling fishery without search costs ($C(q, \theta)$). In this case costs are independent of stock size.
- A schooling fishery with search costs ($C(q, x, \theta) = C(q, \theta) + C(x)$). Now costs are directly additive separable in catches and stock size.
- A search fishery ($C(q, x, \theta)$ with $C_{xq} \neq 0$). There is interaction in the cost function between stock size and catches.

The two schooling cases do not rule out density or age as important determinants for landings. However, an adequate characterization of stock characteristics cannot be given and therefore fisheries economics usually relies on resource levels. Another aspect that requires attention is the issue of variable versus fixed costs. Under a search fishery, the stock size is treated as a variable production factor, while search costs are treated as a fixed cost in a schooling fishery without search costs. This case may be thought of as unrealistically. As the stock size becomes larger, the schools become denser, or more schools are formed. In this case, search costs become an inverse function of stock size. However, typically there is a range of stocks for which landings do not change. Then, the stocks drop so low that landings and costs do change. In other words, a shifting factor is created in the cost specification and this may justify why $C(q, \theta)$.

In this paper it is shown that the results in Weitzman (1974) hold for fisheries in the

[1] Note that in the discussion of conditions for generalizing the result in Weitzman (1974), ecological uncertainty is assumed away.

[2] As pointed out by one of the referees, Theil (1977) classify the technology as being independent if the cost function can be decomposed into separate components. With the cost function in this paper, the technology is independent if $C(q, x, \theta) = C(q, \theta) + C(x)$.

two schooling fisheries but not for a search fishery. Therefore, the statements by Weitzman (2002) and Clark (1985) are imprecise, because Weitzman's results only hold for schooling fisheries, with and without search costs.

For a schooling fishery, where the marginal cost function is steeper than the marginal benefit function, taxes are preferred over ITQs in terms of economic efficiency if the regulatory authority (society) is unsure about marginal costs. However, Wilen (2000) mentions that individual quotas regulate about 55 fisheries, while taxes regulate none. Among schooling fisheries the herring fishery in Iceland is managed by ITQs, see Arnason (1993). These facts are, as argued in Section 4, surprising, in light of the analysis in this paper.

The paper is organized as follows. The pollution control literature on the choice between price and quantity regulation is further discussed in Section 2. In Section 3, the model from Weitzman (1974) is developed for fisheries, while Section 4 analyses conditions required for the result from Weitzman (1974) to hold for fisheries. Section 5 concludes the paper.

II. THE POLLUTION CONTROL LITERATURE

Let us start by sketching the results in Weitzman (1974) for pollution. Weitzman reaches four main conclusions. First, under full information it does not matter whether taxes or individual permits are used. Both instruments secure a first-best optimum. The use of the word first-best optimum may be questioned.[3] In a general model, the first-best optimum requires that all sectors in the economy are maximizing net benefits to society. Moreover, Layard and Walters (1978) illustrate that the first-best solution requires that there are no substitutes or complements in consumption, production of goods or factors of production. However, as used in this paper, the term first-best optimum is consistent with a partial model. In other words, it is assumed that the rest of the economy is in equilibrium in this paper. Second, an error in estimating the benefit function has adverse effects on welfare, but the welfare loss does not differ between price and quantity regulation. In other words, it does not matter for the choice between taxes and transferable permits if there is imperfect information about benefits. Third, if there is uncertainty about costs, price regulation is preferred over quantity regulation if the marginal costs are steeper than the marginal benefit function. Fourth, transferable permits are preferred over taxes in the case of imperfect information about costs if the marginal benefit function is steeper than the marginal cost function.

Indeed, Weitzman (1974) arrives at the following formula for the choice between price and quantity regulation:

$$\nabla = \frac{\sigma^2(B'' + C'')}{2C''^2}, \qquad [1]$$

where:

∇ is the relative advantage of price over quantity regulation measured in terms of welfare. If $\nabla > 0$, price regulation is preferred over quantity regulation, while $\nabla < 0$ implies that quantity regulation is preferred over price regulation;

σ^2 is the variance of the error in marginal costs;

C'' is the slope of a linear marginal cost function. It is assumed that $C'' > 0$;

B'' is the slope of a linear marginal benefit function. It is assumed that $B'' < 0$.

An interpretation of [1] is given in Section 4 where conditions for generalizing the Weitzman results for fisheries are discussed.

Hoel and Karp (2001) consider the case where environmental damage depends on the stock of pollution. As in Weitzman (1974), the curvature of cost and benefit functions is important. However, now the discount rate, the stock's decay rate, and society's ability to make adjustments will also influence the choice between price and quantity regulation under imperfect information.

Even though the model structure of the fisheries problem is the same, costs are re-

[3] One anonymous referee pointed this out.

lated to both the stock and flow variables for a search fishery ($C(q, x)$), while benefits are related to the flow variable.

III. A WEITZMAN MODEL FOR FISHERIES

The basic welfare economics problem that arises under open access is that each individual fisherman disregards the effect that catches have on the stock size (the resource restriction is excluded from the maximization problem). In order to correct this market failure, society faces two choices if a first-best solution is to be obtained under full information. First, it can set a total quota and allocate the quota to the fishermen by means of a system of ITQs. Second, it can tax catches. The notion of a first-best solution may also be questioned here. Scott (1993) discusses how ITQs (or output taxes) on the resource flow rather than the resource stock are not a complete first-best solution. Some technological stock externality remains. An alternative could be to use transferable effort rights or effort taxes. Danielson (2002) studies the choice between effort quotas and catch quotas under uncertainty about the stock relation and catch per unit of effort (CPUE). It is shown that if the uncertainty in the stock relation is large, effort management is preferred, while catch quotas are preferred if the uncertainty in CPUE is large. However, the approach taken in this paper differs from the approach in Danielson (2002) because the choice between price and quantity regulation is analyzed under economic uncertainty and in this case a first-best solution is not arrived at with effort regulation because the effort is a multi-dimensional variable that cannot be measured with accuracy (Dupont 1991).[4]

Let $C(q, x)$ be the cost function[5] and $B(q)$ be the benefit of catches.[6] $B(q) - C(q, x)$ is the economic yield and this economic yield is maximized.[7] By maximizing economic yield, discounting is disregarded. Even though it is customary to include discounting in studies of fisheries (see, e.g., Conrad and Clark 1991), it is excluded in this paper because the purpose of this paper is to analyze conditions for generalizing the analysis in Weitzman (1974). Therefore, the simplest possible model is selected. Nonetheless, including discounting does not change the fundamental results. Another critique that can be raised of the chosen welfare measure is that fisheries involve multiple markets. The fishing industry is composed of dockside sales, processing, retail and final consumption. When the issue of price versus quantity regulation shall be clarified, the effects on the whole industry must be considered. However, this critique is not necessary correct. Just and Hueth (1979) shows that the area behind a supply curve in an intermediate market not only measures the rents in that market but also rents for all producers selling in more basic markets plus initial producers surplus. Thus, by defining welfare as long-run economic yield, the rents of, for example, the processing industry is also captured.

The following assumptions are made with regard to the cost and benefit functions:

- Marginal benefits are non-increasing. ($B_{qq}(q) \leq 0$, where the subscript denotes partial derivatives).[8]

[4] Note also that ad valorum and lump sum taxes are not used. Grafton (1994) combines ITQs and various tax systems under price uncertainty and shows that, for example, ad valorum taxes can be used for rent capturing. However, the approach taken in this paper is different because the single choice between price and quantity regulation is studied. In this case, it is well known within welfare economics that ad valorum taxes and lump sum taxes will not secure a first-best optimum (Boadway and Wildasin 1984).

[5] The cost function is defined in terms of opportunity costs. However, the rest of the economy is in equilibrium so the schooling and search specifications from the introduction hold when costs are defined as opportunity costs.

[6] Benefits are defined as the sum of producers and consumers surplus; see Boadway and Wildasin (1984).

[7] By defining the welfare function in this way it is implicitly assumed that the regulatory costs are zero or the same for price and quantity regulation. In theory, the regulatory costs of the two regulatory instruments must be included if a selection between price and quantity regulation is to be made. However, the assumption about identical regulatory costs is useful, because it keeps the analysis focused.

[8] In order to keep the analysis as general as possible, it is useful to change notation and let subscripts denote partial derivatives. The reason for this is that the general model allows for non-linear marginal costs and benefits, while the derivation of ∇ in Section 4 approximates the marginal costs and benefits functions with linear curves.

- For any stock size, marginal costs are increasing in catches ($C_{qq}(q, x) > 0$).
- The costs of catches do not rise with stock size. In other words, as the stock goes up, the costs go down ($C_x(q, x) \leq 0$).
- It is always profitable to catch some of the stock ($B_q(0) > C_q(0, x)$).
- Above some catch level, the marginal benefits are lower than the marginal costs ($B_q(q) < C_q(q, x)$ for $q > q^*$).

These assumptions ensure that an optimum is reached. Under full information, the maximization problem for society is to find q^* and x^* such that:

$$\underset{q,x}{Max}\, B(q) - C(q, x), \qquad [2]$$

s.t.

$$F(x) - q = 0, \qquad [3]$$

where $F(x)$ is the natural growth. An implication of [3] is that a steady-state equilibrium is analyzed. With the assumed non-linearity of the objective function, a gradual adjustment toward the steady-state is optimal and a feed-back rule can be used. In this paper, the focus is on steady-state equilibrium since this is the simplest possible assumption. However, studies of choices between regulatory instruments under gradual adjustment toward equilibrium are a promising future research area, but the fundamental results in this paper are not changed by analyzing adjustments toward equilibrium.[9]

On the basis of [2] and [3], a Lagrange function can be set up. Denote the optimal solutions q^*, x^* and λ^*, where $\lambda > 0$ is a Lagrange multiplier and a measure of the marginal user costs of the fisheries stock. The first-order condition for catches satisfies:

$$B_q(q^*) - C_q(q^*, x^*) - \lambda^* = 0. \qquad [4]$$

Equation [4] states that society selects catches where marginal benefits, ($B_q(q^*)$), equal marginal social costs, ($C_q(q^*, x^*) + \lambda^*$).

Now something can be said about the choice between price and quantity regulation. Call the optimal price of catches p^* and set this price such that:

$$p^* = B_q(q^*) = C_q(q^*, x^*) + \lambda^*). \qquad [5]$$

Equation [5] says that society selects the optimal price such that it equals the marginal social cost and it makes no difference whether society announces the optimal size of catches or the price. With perfect information both price and quantity regulation secures a first-best optimum. This result is also shown in, for example, Moloney and Pearse (1979).

One reason for the break down of the equivalence between price and quantity regulation can be asymmetric information between society and the fishermen, see Hoel and Karp (2001). Assume, therefore, that society has imperfect information about costs. Formally, this may be written as $C(q, x\ \theta)$, where θ is a random variable which measures the information gap. In other words, θ captures that society is not as well informed about the fishermen's costs as the fishermen themselves. An example of θ could be imperfect information about an exogenous cost parameter. Assume also that a random variable, μ, governs the benefit function such that $B(q, \mu)$. Again μ measures an information gap and, as above, μ captures that society is not as well informed about the benefit of the fishery as the fishermen. An example of μ could be imperfect information about prices.[10]

When selecting the optimal quantity or price, society maximizes expected social welfare. It is necessary to choose prices and catches before the values of μ and θ is known. The actual welfare loss is determined after the values of θ and μ is known. Now the imperfect information model is analyzed for quantity regulation and price regulation.

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[9] Assume that discounting and adjustments toward equilibrium are allowed. Now a present value Hamiltonian can be set up. However, the first order condition with respect to catches remains the same and therefore, the expression for ∇ is unchanged in steady-state.

[10] For the purpose of this section, it is not necessary to describe the properties of θ and μ.

Quantity Regulation

The optimal quantity instrument under imperfect information about costs and benefits is the quantity that maximizes:

$$\underset{x,q}{Max}\, E(B(q, \mu) - C(q, x, \theta)), \qquad [6]$$

s.t.

$$F(x) - q = 0, \qquad [7]$$

where E is an expectation operator. Again, a Lagrange function can be set up. Call the optimal solutions to the model $\hat{q}$, $\hat{x}$, and $\hat{\lambda}$. The first-order condition for catches satisfies:

$$E(B_q(\hat{q}, \mu)) = E(C_q(\hat{q}, \hat{x}, \theta)) + \hat{\lambda}. \qquad [8]$$

In analogy with full information, expected marginal benefits equal expected marginal social costs for $\hat{q}$. Note that [8] corresponds to an ex ante selection of both a quantity and a stock size with the first-order condition for stock and the restriction.

Price Regulation

Now consider price regulation. The supply response function, $q = h(p, \theta, x)$, expresses how the fishermen respond to price changes, and can be found from the fishermen's maximization problems. θ is included in $h(p, \theta, x)$ because it is the supply response function as perceived by society that is of interest. As previously mentioned, the externality problem is that the fishermen disregard the effects that catches have on stock size, so the fisherman's maximization problem may be written as:

$$\underset{h(\cdot)}{Max}\, ph(p, \theta, x) - C(h(p, \theta, x), x, \theta). \qquad [9]$$

Equation [9] corresponds to letting one fisherman select aggregated catches.

The first-order condition for $h(p, \theta, x)$ is:

$$p = C_h(h(p, \theta, x), x, \theta). \qquad [10]$$

The interpretation of [10] is that the marginal benefit, (p), equals marginal private costs, $(C_h(h(p, \theta, x), x, \theta))$.

Now the interest is in finding the optimal ex-ante solution for price regulation given the fishermen's response function, $(h(p, \theta, x))$. Call these $\tilde{p}$, $\tilde{\lambda}$ and $\tilde{x}$. Society will choose the variables according to the following maximization problem:

$$\underset{p,x}{Max}\, E(B(h(p, \theta, x), \mu) - C(h(p, \theta, x), x, \theta)), \qquad [11]$$

s.t.

$$F(x) - h(p, \theta, x) = 0. \qquad [12]$$

The first-order condition with respect to the price satisfies:

$$E(B_h(h(\tilde{p}, \theta, \tilde{x}), \mu)h_p(\tilde{p}, \theta, \tilde{x})) = E(C_h(h(\tilde{p}, \theta, \tilde{x}), \tilde{x}, \theta) h_p(\tilde{p}, \theta, \tilde{x})) + \tilde{\lambda}E(h_p(\tilde{p}, \theta, \tilde{x})) \qquad [13]$$

where $h_p(\tilde{p}, \theta, \tilde{x})$ is the response of catches to a marginal change in prices, and [13] expresses that the expected benefit from a marginal change in price, $(E(B_h(h(\tilde{p}, \theta, \tilde{x}), \mu)h_p(\tilde{p}, \theta, \tilde{x})))$, must be equal to the expected social cost of a marginal price change $E(C_h(h(\tilde{p}, \theta, \tilde{x}), \tilde{x}, \theta)h_p(\tilde{p}, \theta, \tilde{x})) = \tilde{\lambda}E(h_p(\tilde{p}, \theta, \tilde{x})))$. From [10], the fisherman's selection of price may be expressed as $\tilde{p} = C_h(h(\tilde{p}, \theta, \tilde{x}), \tilde{x}, \theta)$. By inserting this into [13], and rearranging, it is obtained that:

$$\tilde{p} = \frac{E(B_h(h(\tilde{p}, \theta, \tilde{x}), \mu)) - \tilde{\lambda}E(h_p(\tilde{p}, \theta, \tilde{x}))}{E(h_p(\tilde{p}, \theta, \tilde{x}))}. \qquad [14]$$

The optimal ex ante price is, therefore, the expected marginal benefit minus the user costs of a marginal price change, divided by the expected response of catches to a marginal price change. Corresponding to an ex ante optimal price is an ex post catch level, which may be expressed as $\tilde{q}(\theta) = h(\tilde{p}, \theta, \tilde{x})$.

Even though both of the quantity and price regulations analyzed above yield an optimum ex ante, it is unlikely that any of the instruments will yield an optimum ex post, since, in all likelihood, it will be the case that $B_q(\hat{q}, \mu) \neq C_q(\hat{q}, \hat{x}, \theta) + \hat{\lambda}$ and $B_q(\tilde{q}(\theta), \mu) \neq C_q(\tilde{q}(\theta), \tilde{x}, \theta) + \tilde{\lambda}$. The relevant question is, therefore, which regulatory instrument secures the highest welfare ex post. This is the question to which attention is now turned.

IV. PRICES VERSUS QUANTITIES FOR FISHERIES

In this section, the issue of prices versus quantities for fisheries is discussed. The comparative advantage of prices over quantities can be defined as the total net benefit under price regulation minus the total net benefit under quantity regulation:

$$\nabla = E(B(\tilde{q}(\theta), \mu) - C(\tilde{q}(\theta), \tilde{x}, \theta) - B(\hat{q}, \mu) - C(\hat{q}, \hat{x}, \theta))) \quad [15]$$

If $\nabla > 0$, price regulation is preferred over quantity regulation, because the net benefits associated with quantity regulation are smaller than those of price regulation. $\nabla < 0$ implies that quantity regulation is preferred over price regulation. The choice between price and quantity regulation for a schooling fishery without search costs, a schooling fishery with search costs, and a search fishery are now examined.

A Schooling Fishery without Search Costs

Assume first that the fishery is a schooling fishery without search costs. In this case, stock effects do not matter on the cost side, so the cost function may be written as $C(q, \theta)$. In order to ease the interpretation of [15], it needs to be simplified. Therefore, a second-order Taylor approximation of costs and benefits is used; see Weitzman (1974). In this formulation, cost and benefits vary within the range of the optimal catch under price regulation around the optimal catch under quantity control. In other words, the costs and benefits under price regulation are measured in relation to the costs and benefits under quantity regulation. Let $\approx$ denote a local approximation. Then:

$$C(q, \theta) \approx a(\theta) + (C' + \alpha(\theta))(q - \hat{q}) + \frac{C''}{2}(q - \hat{q})^2. \quad [16]$$

and

$$B(q, \mu) \approx b(\mu) + (B' + \beta(\mu))(q - \hat{q}) + \frac{B''}{2}(q - \hat{q})^2. \quad [17]$$

Five assumptions and observations are worth mentioning with respect to cost and benefit functions. First, $a(\theta)$ and $b(\mu)$ translate different values of μ and θ into pure vertical shifts of the cost and benefit functions. Furthermore, $a(\theta) = C(\hat{q}, \theta)$ and $b(\mu) = B(\hat{q}, \mu)$. In other words, $a(\theta)$ corresponds to the total cost of catches under quantity control and $b(\mu)$ is the total benefit under quantity control. From this fact it follows that it is enough to concentrate on finding the optimal catches under price regulation. Second, it is assumed that $\alpha(\theta)$ and $\beta(\mu)$ are independently distributed. This implies that $E(\alpha(\theta)) = E(\beta(\mu)) = 0$ and $E(\alpha(\theta)\beta(\mu)) = 0$. Third, the marginal costs and marginal benefits can be identified. Differentiating [16] and [17] yields:

$$C_q(q, \theta) \approx C' + \alpha(\theta) + C''(q - \hat{q}), \quad [18]$$

and

$$B_q(q, \mu) \approx B' + \beta(\mu) + B''(q - \hat{q}) \quad [19]$$

Fourth, the fixed coefficients in [16] and [17] can be analyzed. Since $E(q) = \hat{q}$ and $E(\alpha(\theta)) = E(\beta(\theta)) = 0$, $C' \approx E(C_q(q, \theta))$ and $B' \approx E(B_q(q, \mu))$. Therefore, C' is the expected marginal cost of catches and B' is the expected marginal benefit. Furthermore, $C'' \approx C_{qq}(q, \theta)$ and $B'' \approx B_{qq}(q, \mu)$ (C'' is the curvature of the cost function, and B'' is the curvature of the benefit function). From the assumptions in Section 3, it follows that $B'' \leq 0 < C''$. Finally, the implication of the assumed cost and benefit functions are that $\alpha(\theta)$ and $\beta(\mu)$ represent pure unbiased shifts in the marginal cost and benefit functions.

The variances of marginal costs and benefits are, by definition, the mean square of errors in marginal costs and benefits:

$$\sigma^2 = E(C_q(q, \theta) - E(C_q(q, \theta)) \approx E(\alpha(\theta)^2), \quad [20]$$

$$\pi^2 = E(B_q(q, \mu)) - E(B_q(q, \mu)) \approx E(\beta(\mu)^2). \quad [21]$$

Now ∇ can be calculated. In the Appendix it is shown that:

$$\nabla = \frac{\sigma^2(B'' + C'')}{2C''^2}. \qquad [22]$$

Note that [22] is exactly the same formula as expressed in [1]. Thus, for a schooling fishery without search costs there is nothing wrong with quoting Weitzman's analysis. Five conclusions may be drawn. First, imperfect information about benefits does not enter in [22]. The reason is that with a second order approximation price and quantity regulation are affected equally.[11] Second, ∇ depends linearly on σ^2. As $\sigma^2 - >0$ the perfect information case is arrived at, while increasing σ^2 magnifies the expected loss of employing a regulatory instrument. Third, ∇ depends critically on the curvature of the cost and benefit functions. The sign of ∇ is simply the sign of $C'' + B''$. Fourth, quantity regulation is preferred if the benefit function is sharply curved and the cost function is close to linear. In these cases the coefficient of ∇ is negative. Fifth, when the benefit function is close to linear, price regulation is preferred. In this case ∇ is large and positive. For fisheries without stock effects on the cost side where marginal costs are steeper than marginal benefits, price regulation is preferred over quantity regulation if society is unsure about marginal costs. As mentioned in the Introduction, over 55 fisheries are managed with individual quotas while none are managed with taxes. This fact is surprising in light of the analysis in this paper because is seems likely that for some schooling fisheries without search costs, marginal costs are steeper than marginal benefits.

A Schooling Fishery with Search Costs

Assume instead that the fishery is a schooling fishery with search costs. Now $C(q, x, \theta) = C(q, \theta) + C(x)$ and assume that $C_{xx} = 0$.[12] A second-order approximation around $\hat{q}$ and $\hat{x}$ yields:

$$C(q, x, \theta) \approx a(\theta) + (C' + \alpha(\theta))(q - \hat{q}) + \frac{C''}{2}(q - \hat{q})^2 - \eta(x - \hat{x}), \qquad [23]$$

where η is the marginal cost reduction associated with derivations of tock size under price regulation from stock size under quantity regulation. Retaining all the assumptions and notation from above it is shown in appendix that:

$$\nabla = \frac{\sigma^2(B'' + C'')}{2C''^2} + \eta(x - \hat{x}). \qquad [24]$$

The only difference between this formula and [1] is that the difference in cost reductions due to increased stock sizes, between quantity and price regulation is reflected in the formula. If the stock size under price regulation is larger than the stock size under quantity regulation, there will be a tendency to favor price over quantity regulation. However, [24] shows that if the cost function is direct additively separable in stock size and catches, there is nothing wrong with quoting the analysis by Weitzman (1974), and a directly additive separable cost function is a sufficient condition for generalizing the Weitzman result for fisheries.

Search Fishery

For a search fishery, the cost function is not directly additive separable in stock size

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[11] A similar conclusion is mentioned in Andersen (1982), who analyses price uncertainty and shows that a tax on catches and ITQs yields the same results.

[12] The assumption that $C_{xx} = 0$ is by no means critical. Assume instead that $C_{xx} > 0$. In this case a second order approximation around $\hat{q}$ and $\hat{x}$ gives the result that:

$$C(q, x, \theta) \approx \alpha(\theta) + (C' + \alpha(\theta))(q - \hat{q}) + \frac{C''}{2}(q - \hat{q})^2 - \eta'(x - \hat{x}) - \frac{\eta''}{2}(x - \hat{x})^2$$

where η' is the marginal cost reduction associated with an increased stock size and η'' is the curvature of the stock cost function. Now:

$$\nabla = \frac{\sigma^{2\prime}B''}{2C''^2} + \frac{\sigma^2}{2C''} + \eta'(\tilde{x} - \hat{x}) + \frac{\eta''}{2}(\tilde{x} - \hat{x})^2,$$

and the Weitzman results generalize as in the case where $\eta'' = 0$.

and catches and the second-order approximation around andof the cost function becomes complex, because cross partial derivatives ($C_{xq}(q, x, \theta)$) and interactive terms ($(x - \hat{x})(q - \hat{q})$) (are included.[13] In order to say something more about this case, assume that $F(x)$ is given by a second-order approximation around $\hat{x}$.[14] Now the optimal quantity and stock size under price regulation may be found by solving four equations in four unknowns,[15] and the expression for ∇ becomes so complex that it is impossible to say anything about the choice between price and quantity regulation under imperfect information.[16] Indeed, multiplicative terms between the slope of the marginal cost function and the parameters in the natural growth are included in ∇, and there might not be an easy way to extend Weitzman's analysis to a search fishery.

This conclusion can be related to the models in Hoel and Karp (2001). As mentioned in the introduction, these authors describe the case where the benefit of pollution depends on the stock of pollution. However, the costs only depend on the flow of pollution. In such a model it is possible to generalize the Weitzman analysis.

V. CONCLUSION

In this paper the use of prices versus quantities for regulating fisheries have been analyzed. The analysis shows that a sufficient condition for generalizing Weitzman's analysis for fisheries is that the cost function is directly additive separable in stock size and catches. For this reason, it might not be correct to quote Weitzman's analysis in connection with analysis of fisheries management for a search fishery. A further result is related to schooling fisheries without search costs. Here it is shown that taxes are preferred over ITQs if the marginal cost function is steeper than the marginal benefit function.

These conclusions are shown with two simplifying assumptions. First, a steady-state equilibrium model is developed. Second, long-run economic yield is maximized. Promising areas for future research is to study the choice between price and quantity regulation with the inclusion of a discount rate and an adjustment process toward equilibrium. However, the fundamental results in this paper do not change if adjustment toward equilibrium and discounting are included.

Another simplifying assumption is the single species assumption. Under a single species assumption it is shown that there are difficulties in generalizing the Weitzman results for a search fishery. Assume that the cost function must capture economic interaction between two stocks. In this case, the expression for ∇ becomes more complex so it is even more difficult to generalize the Weitzman results to a multi-species setting. Another question that arises is whether all possible cost functions have been examined in this paper. Because the Weitzman results only hold for a directly additive separable cost function, the answer to this question is that all cost functions that are relevant for the analysis in the paper have been examined.

Even though the analysis in this paper shows that taxes are preferred over ITQs for some fisheries without stock effects on the cost side, other arguments can be put forward in favor of ITQs. For example, it can be argued that ITQs have the property that the fishermen collect the resource rent, while society collects the resource rent with taxes. In other words distributional arguments can lead to a recommendation for ITQs. Furthermore, taxes are hard to compute and in many societies taxes are hard to change each year in response to changes in resource stock conditions. However, even if these arguments are accepted as correct, the analysis in this paper shows that for some fisheries the total benefit will be higher with taxes when there is economic uncertainty.

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[13] See Williamson et al. (1972) for the formula of a second order Taylor approximation in two variables.

[14] A second-order approximation must be logical, because such an approximation is conducted on the cost and benefit functions.

[15] The fisherman's first order condition for $h(p, \theta)$ and the optimality conditions for $\tilde{x}$, $\tilde{q}$, and λ.

[16] This conclusion may also be seen from the analysis in Anderson (1986). As mentioned above, Anderson (1986) assumes that the fishermen take decisions before the random variable is realized. Furthermore, the growth function is linear. Even with these simplifying assumptions, the solution becomes very complicated.

APPENDIX

This appendix follows the proof in Weitzman (1974). For schooling fisheries both with and without search costs the proof is the same. In order to find ∇, an expression for $h(\tilde{p}, \theta)$ must be found. From the fishermen's maximization problem under price regulation it follows that:

$$\hat{p} = C' + \alpha(\theta) + C''(q - \hat{q}). \qquad [A1]$$

[A1] implies that:

$$h(\tilde{p}, \theta) = \hat{q} + \frac{p - C' - \alpha(\theta)}{C''}. \qquad [A2]$$

Differentiating [A2] gives:

$$h_p(\tilde{p}, \theta) = \frac{1}{C''}. \qquad [A3]$$

From the price formula in the text and [A3] it follows that:

$$\tilde{p} = E(B_q(q(\theta), \mu) - \tilde{\lambda}). \qquad [A4]$$

Inserting [A2] in the definition of the benefit function, taking the expectations and using [A4] yields:

$$\tilde{p} = B' + \frac{B''(\tilde{p} - C')}{C''} - E(\tilde{\lambda}). \qquad [A5]$$

From the first order condition for society under price regulation, $B' = C' + E(\tilde{\lambda})$. Therefore, it must be the case that:

$$\tilde{p} = C' + B''\frac{(\tilde{p} - C')}{C''}. \qquad [A6]$$

Because $B'' < 0 < C''$, it follows that:

$$\tilde{p} = C'. \qquad [A7]$$

From [A7] and [A2] it follows that:

$$h(p, \theta) = \hat{q} - \frac{\alpha(\theta)}{C''}. \qquad [A8]$$

Inserting [A8] in the following expression for the comparative advantage:

$$\nabla = \frac{\sigma^2 B''}{2C''^2} + \frac{\sigma^2}{2C''}. \qquad [A9]$$

Furthermore, for a schooling fishery with search costs the following expression is reached:

$$\nabla = \frac{\sigma^2 B''}{2C''^2} + \frac{\sigma^2}{2C''} + \eta(\tilde{x} - \hat{x}). \qquad [A10]$$

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