Prices versus Quantities for Common Pool Resources[1]

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Abstract

In Weitzman (1974) the choice between price and quantity regulation under imperfect information is analysed. It is shown that the choice between the two regulatory instruments depends on the sign of the sum of the curvatures of the cost and benefit functions. If the marginal benefit function is steep and the marginal cost function is flat quantity regulation is preferred over price regulation, while price regulation is preferred over quantity regulation if the marginal benefit function is flat and the marginal cost function is steep. The results in Weitzman (1974) are sometimes quoted in studies of fisheries management. In this paper an analysis of conditions for generalising the Weitzman result to fisheries economics is presented. It is shown that the result can be generalised if the cost function is additively separable in stock size and catches. This leads to the conclusion that the results hold for a schooling fishery. However, for a search fishery the condition that the cost function must be additively separable is seldom fulfilled and quotation of the classical article is therefore not reasonable. A further result is that for a schooling fishery, taxes are likely to be preferred over individual transferable quotas in the case where there is imperfect information about costs. The reason is that the marginal cost function is likely to be steeper than the demand function. In the light of this result, the fact that individual quotas regulate over 55 fisheries while taxes regulate none is surprising.

Keywords: Fisheries Management, Imperfect Information, Taxes, Individual Transferable Quotas.

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1. 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 problems are often mentioned as a problem that obscures reaching a first-best optimum (see Copes (1986)), while taxes have been criticized for posing too big 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 Baumol and Oates (1988)) as well as in the fisheries economic literature (see 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 the choice between price and quantity regulation depends on the sign of the sum of the curvatures of the benefit and 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. In this paper a brief overview of the pollution control literature is given.

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 the work of Colin W. Clark. Clark (1982) writes:

> *"The relationship between taxes and quota market prices might be clarified in the stochastic setting by modelling the quota market, but we shall not pursue the study here (see Weitzman (1974))".*

From this it is seen that Colin W. Clark seems to think that the classic analysis by Weitzman can be generalised for fisheries economics. Therefore, the purpose of this paper is to analyse conditions for such generalisation to be possible. It is shown that it is only possible to generalise Weitzman's results for fisheries economics if there is no interaction in the cost function between stock size and catches (the cost function is additive separable in stock size and catches).

Within fisheries economics there is a distinction between schooling fisheries and search fisheries, see Neher (1990). A schooling fishery can be defined, as a fishery for which the fish stock size does not influence the cost of fishing. 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 fishery and cod is typically spread over a fishery area. For a schooling fishery the condition that the cost function must be additively separable in stock size and catches is clearly fulfilled and therefore the quotation of Weitzman is correct. However, for a search fishery the cost function is not likely to be additively separable in stock size and catches. Therefore, it is not possible to generalise Weitzman's analysis for a search fishery. These results will be shown in section 4 of this paper.

For a schooling fishery prices tends to be constant, while the marginal cost function tends to have a positive slope. Because Weitzman's result do generalise for schooling fisheries, the implication is that 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 and Gissurarson (1999). This fact is, as argued in section 4, surprising in the light of the analysis in this paper.

In one analysis of the choice between price and quantity regulation under imperfect information for fisheries, Weitzman (2000) studies imperfect information about the stock-recruitment relation and shows that taxes are preferred over

ITQs in this case.[2] With a tax it is possible to reach the desired escapement level for recruiters, while there is no guarantee for this with quantity regulation. Weitzman (2000) calls imperfect information about the stock-recruitment relation "ecological uncertainty". In this paper economic uncertainty is analysed. Economic uncertainty can be defined as uncertainty about the profit function and Weitzman (2000) writes:

> *"Pure economic uncertainty is a typical "price-vs-quantity type" mixed situation".*

This implies that the curvatures of the cost and benefit function are important for the choice between price and quantity regulation. The result in this paper shows that this statement by Weitzman (2000) is imprecise for two reasons. Firstly, Weitzman (2000) overlooks that for a search fishery, nothing definite can be said about the choice between price and quantity regulation. Secondly, for schooling fisheries the demand function tends to be flat, while the marginal cost function tends to be steep. Therefore, taxes are likely to be preferred over ITQs.

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 for the result from Weitzman (1974) to hold for fisheries. Section 5 concludes the paper.

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2 Others that have worked with the choice between price and quantity regulation under uncertainty include Anderson (1986) and Androkovich and Stollery (1991). However, their approach 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 is taken ex post (after the realisation of a random variable), while decisions is taken ex ante (before the realisation of a random variable) in Anderson (1986) and Androkovich and Stollery (1991). Furthermore, the two authors assume a very simple, linear growth function. Even with this growth function the solution becomes very complicated.

2. The pollution control literature

Let us start by sketching the results in Weitzman (1974) for pollution. Weitzman reaches four main conclusions. Firstly, under full information it does not matter whether taxes or individual permits are used. Both instruments secure a first-best optimum. Secondly, an error in estimating the benefit function has adverse effects on the 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. Thirdly, if there is uncertainty about costs, price regulation is preferred over quantity regulation if the marginal costs are steeper than the marginal benefit function. Fourthly, 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:

$$\nabla = \frac{\sigma^2 (B'' + C'')}{2C''^2} \tag{1}$$

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 (the curvature of the total cost function). It is assumed that $C'' > 0$.
>
> B'' is the slope of a linear marginal benefit function (the curvature of the benefit function). It is assumed that $B'' < 0$.

An interpretation of (1) is given in section 4 where conditions for generalising the Weitzman results for fisheries are discussed.
Some recent research extends the work by Weitzman (1974) to a dynamic setting.[3] Baldurson and Fehr (1997) show that an assumption about irreversibility investments in new technology improves the performance of taxes. Nevertheless, irreversible decisions do not fundamentally change Weitzman's results. Hoel and Karp (1997) 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. Newell and Pizer (2000) present a similar model, where the damage depends on the stock of pollution. As in Hoel and Karp (1997) the curvature of cost and benefit functions is important. However, adjustments must be made for the correlations of cost shocks across time, discounting, the stock decay rate and the rate of benefit growth.

It could be argued that the analysis in this paper should depart from the work of Hoel and Karp (1997) and Newell and Pizer (2000), instead of Weitzman (1974), since these articles consider the case where stock effects are included. However, Newell and Pizer (2000) and Hoel and Karp (1997) assume that the cost function is related to the flow of pollution, while the benefit function is related to the stock of pollution. In other words the following problem is set up:

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3 Subsequent work on the issue of price versus quantity regulation in the 70s mostly departs from Weitzman (1974). Ireland (1977) argues that instead of a single price, an ideal price schedule should be considered. This ideal price should be a schedule contingent on the realised state of the world (a contingent message). Indeed, much work in the pollution control literature focuses on such a message, since a principal-agent approach is applied; see for example Jebjerg and Lando (1997). However, a contingent schedule is a complicated procedure, and the second-best problem of choosing between a single price and quantity in discussions of practical regulation is clearly relevant. Yohe (1978) extends Weitzman's analysis, so that quantity regulation does not automatically yield the output chosen under quantity regulation. In other words output is governed by a random variable. The choice between price and quantity regulation still depends on the curvature of cost and benefit functions, but additionally the relative size of variances under the two types of regulation influence the choice between them.

$$\text{Max}\left(\int_{t=0}^{\infty} (B_t(x) - C_t(q))e^{-\ell t}dt\right) \tag{2}$$

s.t.

$$\dot{x} = F(q) \tag{3}$$

where:

$\dot{x}$ is the development in the stock of pollution over time.
x is the stock of pollution.
q is the emission reduction (pollution).
B(x) is the benefit of pollution (the environmental damage that can be avoided by reducing emission).
F(q) is a function relating the stock of pollution to the flow of pollution.
ℓ is the discount rate.
t is time.
C(q) is the cost of pollution.

Even though the structure of the fisheries problem is the same, costs are related to both the stock and flow variables for a search fishery (C(q, x) where x is the fisheries stock and q is catches), while benefits are related to the flow variable (the benefits are the total revenue and B(q)). For a schooling fishery benefits and costs are only related to the flow variables (C(q) and B(q)). This explains why the Weitzman results do not apply to the case of a search fishery, but only to a schooling fishery. Furthermore, it is useful to depart directly from Weitzman (1974), because the purpose of this paper is to analyse conditions for generalising the Weitzman result. Therefore, a Weitzman model is now developed for the fisheries.

3. A Weitzman model for fisheries

Assume that the fishing fleet is homogeneous and that entry and exit to the industry can be excluded. The basic welfare economic problem that arises is that each individual fisherman disregards the effect that catches has on the stock size (the resource restriction is excluded from the maximisation problem). This corresponds to perfect competition. In order to correct this market failure society faces two opportunities if a first-best solution is to be obtained under full information. Firstly, it can set a total quota and allocate the quota to the fishermen by means of a system of ITQs.[4] Secondly, it can tax catches.[5] Since fishermen are homogeneous this amounts to selecting a uniform price on harvest.[6]

Let q be the aggregated catches from a fishery and let x be the stock size. Furthermore, let C(q, x) be the cost function and B(q) the benefit of catches (the total revenue). B(q) – C(q, x) is the long-run economic yield and this economic yield is maximised.[7] 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] A normal assumption within fisheries is that prices are constant such that $B_{qq}(q) = 0$. Empirical analysis (for example Arnason *et al* (2000)) confirms the assumption of constant prices. In section 4 the implication of $B_{qq}(q) = 0$ is discussed, but in order to keep the analysis as general as possible, it is assumed that $B_{qq}(q) \leq 0$.

- For any stock size, marginal costs are increasing in catches ($C_{qq}(q, x) > 0$). Empirical analysis (for example Arnason *et al* (2000)) confirms this result.

4 This solution requires perfectly functioning markets for ITQs.
5 With perfect information this is equivalent to taxing fisheries effort.
6 Clearly, the information requirements of such a system are large.
7 Discounting is disregarded by maximisation of long-run economic yield. Even though it is customary to include discounting in treatments of fisheries (see for example Conrad and Clark (1991) it is excluded in this paper. This is explained by the fact that the purpose of this paper is to analyse conditions for generalising the results in Weitzman (1974). Therefore, the simplest possible model is selected. However, incorporating discounting is a promising future research area.
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 ∇ section 4 approximates the marginal costs and benefits functions with linear curves.

- The costs of catches do not rise in stock size. In other words it is not more expensive to catch from a larger stock than from a smaller stock ($C_x(q, x) \leq 0$).

- 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 secure that an optimum is reached. Under full information the maximization problem for society is to find q* and x* such that:

$$\mathrm{Max}(B(q) - C(q, x)) \tag{4}$$

s.t.

$$F(x) - q = 0 \tag{5}$$

where F(x) is the natural growth. One implication of (5) is that the interest is in a steady-state equilibrium, where the natural growth is equal to catches.[9]

On the basis of (4) and (5) a Lagrange function can be set up. Call 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:

$$B_q(q^*) - C_q(q^*, x^*) - \lambda^* = 0 \tag{6}$$

9 With the assumed non-linearity of the objective function a gradual adjustment toward steady state is optimal. Here a feed-back rule can be used and a promising research path is to be found in Sandal and Steinshamn (1997), since their approach makes it easy to calculate q*. 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 is a promising future research area.

(6) says 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:

$$p^* = B_q(q^*) = C_q(q^*, x^*) + \lambda \tag{7}$$

(7) expresses that society selects the optimal price such that it equals the marginal social cost and now it makes no difference whether society announces the optimal catches or 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. 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. 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 from the fishery as the fishermen.[10]

When selecting the optimal quantity or price, society maximises expected social welfare. It is necessary to choose prices and catches before μ and θ is known. This corresponds to the ex ante solution. The actual welfare loss is determined after θ and μ is known. When θ and μ can be observed an ex post situation arises.

First, quantity regulation is discussed. The optimal quantity instrument under imperfect information about cost and benefits is the quantity that maximises:

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

$$\mathrm{Max}(E(B(q,\mu)-C(q,x,\theta))) \tag{8}$$

s.t.

$$F(x)-q=0 \tag{9}$$

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

$$E(B_q(\hat{q},\mu)) = E(C_q(\hat{q},\hat{x},\theta)+\hat{\lambda}) \tag{10}$$

In analogy with full information, expected marginal benefits equal expected marginal social costs for $\hat{q}$. Note that (10) corresponds to an ex ante selection of a quantity.

Now consider price regulation. Since the price is selected such that an ex ante social optimum occurs, fishermen's catches will respond to prices. The supply response function, $q = h(p,\theta)$, expresses that, and can be found from the fishermen's maximisation problems. θ is included in h(p, θ) because it is the supply response function as perceived by society that is of interest. Since the fishermen are homogenous, it is enough to let one fisherman select aggregate catches. As previously mentioned, the problem is that the fishermen disregard the resource restriction, so the fisherman's maximisation problem may be written as:

$$\mathrm{Max}(ph(p,\theta)-C(h(p,\theta),x,\theta)) \tag{11}$$

The first order condition for h(p, θ) is:

$$p = C_h(h(p,\theta),x,\theta) \tag{12}$$

The interpretation of (12) is that marginal benefit (p) equals marginal costs ($C_h(h(p,\theta), x, \theta)$).

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

$$\text{Max}(E(B(h(p,\theta),\mu) - C(h(p,\theta), x, \theta))) \tag{13}$$

s.t.

$$F(x) - h(p,\theta) = 0 \tag{14}$$

The first order condition for the price satisfies:

$$E(B_h(h(\tilde{p},\theta),\mu)h_p(\tilde{p},\theta)) = E(C_h(h(\tilde{p},\theta),\tilde{x},\theta)h_p(\tilde{p},\theta) + \tilde{\lambda}h_p(\tilde{p},\theta)) \tag{15}$$

$h_p(\tilde{p},\theta)$ is the response of catches to a marginal change in prices, and (15) expresses that the expected benefit from a marginal change in price ($E(B_h(h(\tilde{p},\theta),\mu)h_p(\tilde{p},\theta))$) must be equal to the expected social cost of a marginal price change ($E(C_h(h(\tilde{p},\theta),\tilde{x},\theta)h_p(\tilde{p},\theta) + \hat{\lambda}h_p(\tilde{p},\theta))$). (12) may be rearranged to find the optimal ex ante price, $\tilde{p}$. From (12) it is obtained that $\tilde{p} = C_h(h(\tilde{p},\theta),\tilde{x},\theta)$. By inserting this into (15), and rearranging it is obtained that:

$$\tilde{p} = \frac{E(B_h(h(\tilde{p},\theta),\mu) - \tilde{\lambda})h_p(\tilde{p},\theta))}{E(h_p(\tilde{p},\theta))} \tag{16}$$

The optimal ex ante price is therefore the expected 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 found as $\tilde{q}(\theta) = h(\tilde{p},\theta)$.

Even though both the quantity and price regulations analysed above yield an optimum ex ante, none of the instruments probably 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.

4. Conditions for the Weitzman result to hold

Now 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:

$$\nabla = E(B(\tilde{q}(\theta),\mu) - C(\tilde{q}(\theta),\tilde{x},\theta) - (B(\hat{q},\mu) - C(\hat{q},\hat{x},\theta))) \tag{17}$$

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.

Assume first that the fishery is a schooling fishery. In this case stock effects do not matter on the cost side, so $C(q, \theta)$. In order to say something about (17), more structure on the problem is necessary. Therefore, a second order Taylor approximation of costs and benefits is used. 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 is measured in relation to the costs and benefits under quantity regulation. Let $\approx$ denote a local approximation. Then:

$$C(q,\theta) \approx a(\theta) + (C'+\alpha(\theta))(q-\hat{q}) + \frac{C''}{2}(q-\hat{q})^2 \tag{18}$$

$$B(q,\mu) \approx b(\mu) + (B'+\beta(\mu))(q-\hat{q}) + \frac{B''}{2}(q-\hat{q})^2 \tag{19}$$

Five assumptions and observations are worth mentioning with respect to cost and benefit functions. Firstly, $a(\theta)$ 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 $b(\mu)$ 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. Secondly, it is assumed that $\alpha(\theta)$ and $\beta(\mu)$ is standardised and independently distributed. This implies that $E(\alpha(\theta)) = E(\beta(\mu)) = 0$ and $E(\alpha(\theta)\beta(\mu)) = 0$. Thirdly, the marginal costs and marginal benefits may be found. Differentiating (18) and (19) yields:

$$C_q(q, \theta) \approx C' + \alpha(\theta) + C''(q - \hat{q}) \tag{20}$$

$$B_q(q, \mu) \approx B' + \beta(\mu) + B''(q - \hat{q}) \tag{21}$$

Fourthly, the fixed coefficients in (18) and (19) can be analysed. 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 $B'' \leq 0 < C''$. Lastly, the implication of the assumed cost and benefit functions are that $\alpha(\theta)$ and $\beta(\mu)$ represent pure unbiased shifts in the marginal costs and benefit functions. The variances are by definition the mean square of errors in marginal costs and benefits:

$$\sigma^2 = E(C_q(q, \theta) - E(C_q(q, \theta)) \approx E(\alpha(\theta)^2) \tag{22}$$

$$\pi^2 = E(B_q(q, \mu)) - E(B_q(q, \mu)) \approx E(\beta(\mu)^2) \tag{23}$$

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

$$\nabla = \frac{\sigma^2 B''}{2C''^2} + \frac{\sigma^2}{2C''} \tag{24}$$

It is seen that (24) is exactly the same formula as expressed in (1). So for a schooling fishery there is nothing wrong with quoting Weitzman's results. Five conclusions may be drawn. Firstly, imperfect information about benefits does not enter in (24). The reason is that with a second order approximation it affects price and quantity regulation equally.[11] Secondly, ∇ depends linearly on σ^2. As σ^2 -> 0 the perfect information case is arrived at, while increasing σ^2 magnifies the expected loss of employing a regulatory instrument. Thirdly, ∇ depends critically on the curvature of the costs and benefit functions. The sign of ∇ is simply the sign of $C'' + B''$. Fourthly, 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. Fifthly, 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, constant prices and positive marginal costs, price regulation is preferred over quantity regulation if society is unsure about marginal costs. As mentioned in the introduction these properties characterise a schooling fishery, and among schooling fisheries the herring fishery in Iceland is managed by ITQs. This fact is surprising in the light of the analysis in this paper. Furthermore, the statement by Weitzman (2000) on economic uncertainty, presented in the introduction, is imprecise for a schooling fishery. The reason for this is that Weitzman is unaware of the actual magnitude of the slope of the marginal profit function.

Assume instead that the fishery is a search fishery. Assume also that the cost function is additively separable such that $C(q,x,\theta) = C(q,\theta) + C(x)$ and that C_{xx} = 0.[12] A second order approximation around $\hat{q}$ and $\hat{x}$ yields:

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11 A similar conclusion is mentioned in Andersen (1982). Andersen (1982) analyse price uncertainty and shows that a tax on catch 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:

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

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

$$C(q, x, \theta) \approx a(\theta) + (C' + \alpha(\theta))(q - \hat{q}) + \frac{C''}{2}(q - \hat{q})^2 - \eta(x - \hat{x}) \qquad (25)$$

where η is the marginal cost reduction associated with stock size. Retaining all the assumptions and notation from above it is in appendix shown that:

$$\nabla = \frac{\sigma^2 B''}{2C''^2} + \frac{\sigma^2}{2C''} + \eta(\tilde{x} - \hat{x}) \qquad (26)$$

The only difference between this formula and (1) is that the difference in cost reduction due to increased stock sizes is reflected in the formula. Therefore, if the cost function is additively separable in stock size and catches there is nothing wrong with quoting the analysis by Weitzman (1974) for a search fishery, and an additively separable cost function is a sufficient condition for generalising the Weitzman result for fisheries. Indeed, a schooling fishery also corresponds to a case where the cost function is additively separable in stock size and catches, but it is a special case because $\eta = 0$.

However, for a search fishery the cost function is not additively separable in stock size and catches and the second order approximation around $\hat{q}$ and $\hat{x}$ of 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 be-

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

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

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 $\tilde{\lambda}$.

tween 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 is no easy way to extend the analysis of Weitzman to a search fishery.

This conclusion can be related to the models in Hoel and Karp (1997) and Newell and Pizer (2000). These authors describe, as mentioned in the introduction, 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 generalise the Weitzman results. The reason for this is that the articles are in effect describing a schooling fishery, since the cost effect of the stock is zero.

5. Conclusion

In this paper prices versus quantities for common pool resources have been analysed. The analysis shows that a sufficient condition for generalising Weitzman's analysis for fisheries is that the cost function is additively separable in stock size and catches. For this reason it is therefore not right to quote Weitzman (1974) in connection with analysis of fisheries management for a search fishery, as done in Clark (1985). A further result is related to schooling fisheries. Here it is shown that it is likely that taxes are preferred over ITQs. Therefore, the application of ITQs for the herring fishery in Iceland is surprising.

These conclusions are shown with two simplifying assumptions. Firstly, a steady-state equilibrium model is developed. Secondly, long-run economic yield is maximised. 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.

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.

Even though the analysis in this paper shows that taxes are preferred over ITQs for common pool resources without stock effects on the cost side, other arguments can be put forward in favour 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 of ITQs. However, even if this argument is accepted as correct, the analysis in this paper shows that efficiency can be one argument for preferring taxes.

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Appendix

For both schooling fisheries and search fisheries with additive separable cost functions 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:

$$\hat{p} = C' + \alpha(\theta) + C''(q - \hat{q}) \tag{1}$$

(1) implies that:

$$h(\tilde{p},\theta) = \hat{q} + \frac{p - C' - \alpha(\theta)}{C''} \tag{2}$$

Differentiating (2) gives:

$$h_p(\tilde{p},\theta) = \frac{1}{C''} \tag{3}$$

From the price formula in the text and (3) it follows that:

$$\tilde{p} = E(B_q(q(\theta),\mu) - \tilde{\lambda}) \tag{4}$$

Inserting (2) in the definition of the benefit function, taking the expectations and using (4) yields:

$$\tilde{p} = B' + \frac{B''(\tilde{p} - C')}{C''} - E(\tilde{\lambda}) \tag{5}$$

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

$$\tilde{p} = C' + B'' \frac{(\tilde{p} - C')}{C''} \tag{6}$$

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

$$\tilde{p} = C' \tag{7}$$

From (7) and (2) it follows that:

$$h(p, \theta) = \hat{q} - \frac{\alpha(\theta)}{C''} \tag{8}$$

Inserting (8) in the expression for the comparative advantage yields the expression in the text.

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