Prices versus Quantities
– When there is Non-Compliance with Fisheries Regulations

by

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Preface

In recent papers (Weitzman 2002; Jensen and Vestergaard 2003) price regulation (via landing fees) has been compared with quantity regulation (via tradable quotas) under biological and economic uncertainty in the spirit of Weitzman (1974) with mixed results. We attempt to clarify the reasons for this mixture and then introduce into this literature the problem of compliance and enforcement as a potentially more important source of uncertainty and information asymmetry. We adduce evidence that compliance and enforcement problems within fisheries management are widespread and involve substantial portions of total catch. We show that this type of information asymmetry implies that taxes are always more efficient than tradable quotas.

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Contents

1 Introduction

Many managed fisheries are regulated with quantity restrictions. Indeed, Wilen (2000) notes that over 55 countries use quantity regulation while price regulation is not used at all. Until recently fisheries economists have also focused on quantity measures in their research, and recommendations for the use of individual transferable fishing quotas (ITQs) are common (see e.g. Moloney and Pearse (1979) for an original contribution and Grafton et al. (2000) for a recent overview). Tax regulation seems to have been dismissed as a management alternative for at least three reasons. First, it is argued that taxes imply substantial information requirements (see Arnason 1990) making it difficult for a regulatory authority to calculate the optimal tax rates correctly. The optimal tax rate is equal to the user cost of the fish stock, but in a complex, dynamic and non-linear bio-economic setting calculation of the user cost is not a trivial task. Second, public appropriation of all or part of the resource rent through payment of tax revenue may be considered unfair or politically unattractive (see Clark 1990). Third, since the optimal tax rate varies over time with variations in the stock size (see Clark 1990) optimal tax regulation may aggravate income fluctuations of fishermen and, thus, impose extra risk.

These arguments for dismissing taxes may, however, be questioned. First, even though optimal taxes imply substantial information requirements so would an attempt to regulate in an optimal fashion with individually transferable quotas (ITQs). Indeed, essentially, the same information is required by the regulator when calculating the optimal tax rate as when calculating an optimal total quota in an ITQ system (see e.g. Clark and Munro 1978). Second, if public appropriation of all or part of the resource rent seems undesirable the regulator can design a budget-balancing tax system or simply recycle tax revenue back to the fishing industry in a lump-sum manner.[1] Third, although the optimal tax rate varies over time so does the optimal total quota in an ITQ system (see Sandal and Steinshamn 1997). Thus, there is no reason to expect the income fluctuations generated by optimal tax regulation to be greater than the fluctuations generated by an optimal ITQ system.[2] In line with this train of thought, serious consideration of taxes as an instrument for fisheries management was (re)introduced into the fisheries economics literature in a paper by Weitzman (2002). In a follow up paper Jensen and Vestergaard (2003) continued this line of research.

These papers consider a specific structure of the regulator's uncertainty about the cost, benefit and biological functions[3] characterising the industry using arguments in the general spirit of the seminal paper on prices versus quantities by Weitzman (1974). For a fishery where marginal fishing costs only depend on stock size[4], Weitzman (2002) shows that tax regulation performs better than ITQs under ecological uncertainty (i.e. where the regulator is more uncertain than the fishermen about the stock-recruitment relation). Jensen and Vestergaard (2003) study a schooling fishery where marginal fishing costs only depend on harvest[5]. Here quotas are preferred under economic uncertainty (i.e. where the regulator is more uncertain about the cost and benefit functions than the fishermen). However, as we see in the following section, these results have not been generalised to the more common search fishery type where marginal fishing costs depend on both harvest and fish stock[6].

The main purpose of our paper is to introduce into this literature the problem of compliance and enforcement as a potential source of uncertainty and information asymmetry. It seems that compliance and enforcement problems within fisheries management are widespread[7] and we will argue that the uncertainty generated by compliance and enforcement problems constitutes an important (perhaps the most important) source of information asymmetry between the regulator and the fishermen in fisheries regulation. Furthermore, we show that for a search fishery where marginal fishing costs depend on both harvest and fish stock this type of information asymmetry implies that taxes are always more efficient than ITQs.

In chapter 2 the recent literature on price versus quantities instruments is reviewed. Chapter 3 discusses relevant parts of the compliance and enforcement literature within fisheries and Chapter 4 presents the main result of our paper. The main conclusions are summed up in Chapter 5.

2 Previous Fisheries Economics Results on Prices vs. Quantities

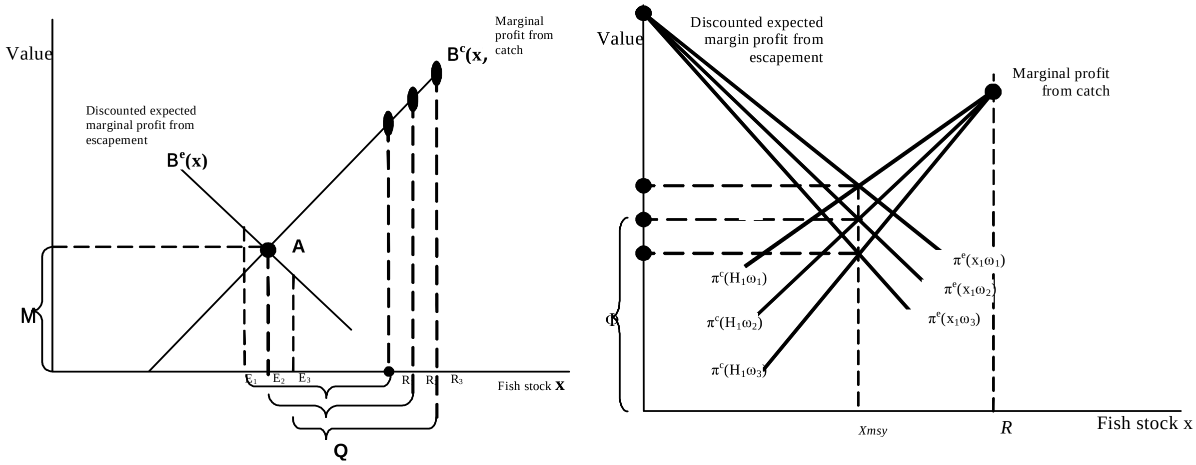
Fisheries are an example of a renewable resource use where economic overexploitation may result if harvest is not regulated. Without regulation the individual fisherman does not have an incentive to take account of the resource constraint and so finds it profitable to increase harvest above the optimal level. When a fisherman disregards the effect that his harvest has on the harvest of other fishermen through the resource constraint a stock externality arises that in general will have both current and future consequences (see Anderson 1986). To mitigate this externality regulatory authorities have in a number cases applied some form of individual quota system.[8] However, as noted in the introduction, two recent papers have reconsidered taxes as an alternative to individual quotas – a line of research that we extend in this paper.

Weitzman (2002) revived interest in the investigation of the use of taxes in fisheries management by considering ecological uncertainty in a stock-recruitment model where marginal harvest costs only depend on stock size. The regulator must fix the value of the regulatory instrument (i.e. a landing fee or a total quota) under what Weitzman calls ecological uncertainty. That is, when the landing fee or total quota is set the regulator knows the distribution of a stochastic fish stock variable for the coming period, but not its actual value. Fishermen, on the other hand, are assumed to observe the realised fish stock variable before deciding how much to harvest. It is this asymmetry in ecological information that drives the result in Weitzman (2002)[9]. The regulator's problem is to induce fishermen to harvest an optimal portion of the realised fish stock (or, as Weitzman puts it, to leave an optimal portion for the next period(s)). Intuitively, if the realised stock is lower than the expected fish stock it would be optimal to reduce the total quota below its expected optimal value. Under ITQs this is not possible since the total quota is set prior to observing the realised fish stock. With the tax instrument, on the other hand, this is possible by decentralising the harvest decision to fishermen who observe the realised fish stock value.

Weitzman's model and result are illustrated in figure 2.1a where we have fish stock on the x-axis and marginal value on the y-axis. The $\pi^e(x)$ curve indicates discounted expected marginal profit from escapement (the part of stock that is not caught, but left to parent future fish generations). Escapement is measured from the origin and we have that expected future marginal profit falls as escapement increases. The $\pi^c(x)$ curve indicates marginal profit from current harvest, where harvest is measured from the current period's recruitment (i.e. if the realisation of the stochastic recruitment variable for the current period is R_1 this is the total stock of fish available at the beginning of the fishing periods. Marginal profit of the first fish caught then is the indicated value for this fish stock and the relevant harvest measure is H_1). As more fish are caught the remaining fish stock falls (moving towards the origin) and marginal profit falls (since fish become increasingly scarce and, therefore, harder to find). At the intersection of the two curves (point A) marginal profit of harvest just equals the expected marginal profit forgone from reducing escapement. Therefore, point A indicates the optimal escapement level (measured from the origin) and the optimal harvest (measured from the realised recruitment for the current period, e.g. R_1). The key assumption made by Weitzman is that the marginal profit function only depends on current stock so variations in realised recruitment do not shift the marginal profit curve. This means that irrespective of the realisation of the stochastic recruitment variable (in figure 2.1a three such realisations are indicated by R_1, R_2 and R_3) the marginal harvest profit function is described by the same $\pi^c(x)$ curve (the only difference being the initial fish stock/starting point for harvest/profit measurement). Since the $\pi^c(x)$ curve is not affected by variation in recruitment the optimal level of escapement (the intersection of the two curves at point A) is always the same so that it is optimal to let all variation in recruitment be absorbed by harvest. If such a fishery is regulated through a landing fee, with optimal rate, Φ, independent of realised recruitment, it becomes unprofitable for fishermen to harvest fish below this stock level irrespective of the realised recruitment, and fishermen realize this because they are assumed to observe actual stocks in real time, so desired escapement is ensured. If the regulator imposes a total quota, Q, instead of a tax , then it is harvest that is held constant (equal to Q) and deviations in recruitment are absorbed in escapement (as indicated in the figure's escapement points E_1 and E_3 that correspond to realisations R_1 and R_3 of the recruitment variable). This is not optimal, illustrating the pro-tax result in Weitzman (2002) under ecological uncertainty for a fishery where the single marginal cost function depends only on recruitment (current stock). Furthermore, Weitzman (2002) suggests that ecological uncertainty may often be the more important information asymmetry and speculates that even when economic uncertainty is more significant a result favouring quotas would only be found when marginal costs are unresponsive to changes in fish stocks.

Figure 2.1

Figure 2.1a *Figure 2.1b*



This theme is taken up by Jensen and Vestergaard (2003) who compare taxes with ITQs under economic uncertainty in a simpler steady-state model where the seminal Weitzman (1974) prices versus quantities results are applied. For a schooling fishery where marginal costs only depend on the harvest level (and so are completely unresponsive to changes in the fish stock), it is clear that quota regulation is the preferred instrument in accordance with Weitzman's prediction[10]. Though the static model used here is different from Weitzman's (2002) dynamic stock recruitment model we may think of this result as applying to a profit function of the form $\pi^c(H)$ in a model similar to Weitzman's (2002) where there is uncertainty about the current profit function rather than about recruitment.

The pro quota result for such a model is illustrated in figure 2.1b where we again have fish stock on the x-axis and marginal value on the y-axis. The $\pi^c(H,\omega)$ curves indicate marginal profit from harvest, where harvest is again measured from the current period's recruitment (now a known point *R* since there is no uncertainty about recruitment). Note that marginal profit falls as harvest increases and so marginal profit like in figure 2.1a also falls with the fish stock (though of course the functional mechanism is different). The alternative current profit functions illustrate uncertainty about the cost function parameter ω[11]. The $\pi^e(x,\omega)$ curves indicate discounted expected marginal profit from escapement (measured from the origin). In figure 2.1b we have drawn the curves corresponding to a situation with no discounting where it then becomes optimal always to achieve maximum sustainable yield (MSY). Intuitively, sustaining MSY is optimal since, on the one hand, increasing fish stock over the MSY level does not reduce harvest costs and so there is no gain from reducing sustainable yield in this way. On the other hand, reducing fish stock below the MSY level, in effect swapping smaller future for larger current harvest, is not optimal either since there is no discounting. In effect, uncertainty about $\pi^c(H,\omega)$ implies uncertainty about $\pi^e(x,\omega)$ that is correlated so that optimal escapement always equals the MSY stock level. In this case the quota instrument can ensure optimal escapement despite the regulator's uncertainty about the cost function because the same optimal escapement (the MSY level) applies for all values of the ω-parameter. On the other hand, since the price instrument works by adjusting marginal fishing incentives the regulator's cost function uncertainty generates uncertainty about the resulting catch and escapement. Since the price instrument is less precise in this case the quota instrument is preferred.

Assuming the same type of cost information asymmetry, Jensen and Vestergaard (2003) also consider the more general search fishery type where the shape of the marginal cost function may depend on both stock size and e.g. capacity utilisation. For this type of fishery they find that it is not clear which regulatory scheme is preferred. It is also fairly straightforward to show that the specific pro tax proof used by Weitzman (2002) does *not* apply to this more general search fishery type (see appendix II) though we can not rule out the possibility that Weitzman's result might generalize using some other proof strategy[12]. As it stands now, irrespective of whether there is information asymmetry regarding recruitment or costs, the literature contains no clear guidelines telling us which policy instrument should be preferred for a general search fishery where the marginal cost function may depend on both stock size and capacity utilisation.

Further, and perhaps more important, it is not clear how important these information asymmetries are in practice. When considering the recruitment asymmetry it is clear that typically there is substantial uncertainty about the underlying ecological relationships. However, it is less clear that this uncertainty is substantially greater for the regulator than for the fishermen, when the decisions are made by each party, which is the key assumption. Fishermen must base decisions about on how much to harvest (whether to start a fishing trip or whether to continue it) on expected returns, but they are of course able to update their estimates of expected returns during the fishing period. For this reason fishermen may be better informed than the regulator was when instrument values were picked. However, updates of estimates of expected returns must be based on realisations of a highly stochastic variable (see e.g. Clark 1985) observed by individual fishermen during the period. Though this probably does give fishermen some informational advantage it is not clear how important this advantage is compared to the information advantage that regulatory authorities presumably have over fishermen in collecting and processing data and predicting recruitment. That is, though fishermen may have an advantage in being able to update expectations during the fishing period the regulator may have the advantage of a less uncertain initial estimate of recruitment.

It is also not clear that cost information asymmetry applies generally to search fisheries. On the one hand, each individual fisherman presumably has better information about how his own costs relate to his own catch than the regulator can collect. Thus, fishermen probably have a general informational advantage in this respect, even though, the regulator's estimate of the aggregate (or average) relationship between marginal cost (or profit) and catch may be reasonably precise for many large fisheries[13]. On the other hand, it is not clear that fishermen have an informational advantage when estimating how the fish stock affects costs. Here the regulators may have a superior ability to make stock estimates and to estimate the complex relationships between cost, catch and stock (and other variables of importance). Thus it is not clear how widely the cost information asymmetry applies to search fisheries characterised by important affects of stock on costs.

In conclusion, the existing literature suggests that taxes may be the preferred instrument for some of the many search fisheries that today are regulated with quotas while quotas may be preferred for others. On the other hand, neither ecological nor economic information asymmetry gives rise to a generally applicable argument for using either taxes or ITQs in the regulation of the more common search type fishery where the marginal cost function may depend on both stock size and e.g. capacity utilisation. It is also not clear if one generally should expect search fisheries to be characterised by important ecological and/or cost information asymmetries.

3 The Compliance Problem in Fisheries Regulation

Though non-compliance has been shown to have complex implications for instrument choice in the pollution control literature (e.g. Harford 1978; Schmutzler and Goulder 1994; Schmutzler 1996; Sandmo 2002)[14] the potential effects of compliance and enforcement problems have not been studied in the existing prices versus quantities literature. Both the original Weitzman paper on the implications of cost uncertainty for the choice of regulatory instruments and his more recent fisheries paper assume perfect compliance with whatever instrument is chosen by the regulator. Nevertheless, it seems that non-compliance is a widespread problem within fisheries management. Anecdotal evidence is plentiful and studies that have tried to estimate illegal landings seem to confirm this conclusion. Table 3.1 lists estimates of illegal landings from a number of studies we have surveyed covering a variety of countries, species and types of regulation. Except for the Australian Gulf of Carpentaria banana and tiger prawn fishery, illegal landing shares are estimated to be close to or in excess of 20% of total landings. Thus, including non-compliance problems in a model of fisheries regulation would seem relevant in its own right. In addition, (and, in our context, of primary importance) the reported estimates are not very precise, with confidence bounds typically spanning between 15 and 20 percentage points. Thus, in addition to illegal landings being an important problem in many fisheries, the studies also indicate that illegal landings may constitute an important source of information asymmetry between the regulator and the fishermen. Let us, therefore, give this suggestion a more formal structure through an explicit model of non-compliance behaviour.

On the basis of the general literature on the economics of crime (see Becker 1968; Stigler 1971) the incentives and motives underlying non-compliance behaviour with fisheries regulation have been modelled by a number of researchers (see e.g. Andersen and Sutinen 1983; Sutinen and Andersen 1985; Copes 1986; Milliman 1986; Anderson and Lee 1986; Anderson 1987 and 1989; Neher 1990a; Charles 1993; Charles et al. 1999; Hatcher 2005). Based on the theory of choice under uncertainty this literature models criminal activities (non-compliance) by the individual fisherman as the result of an evaluation of the gains from non-compliance against its expected cost (essentially the perceived probability of detection times the designated punishment when non-compliance is detected). The profit maximising level of non-compliance perceived by the fisherman will be where the marginal gain equals the expected marginal cost.

Table 3.1 Estimates of illegal landings

Year	**Country**	**Area and species**	**Type of regulation**	**Reference**	**Estimated share of illegal landings**[1]	**Bounds for share estimate**[1]
1992	U.S.A. and Canada	Cod line fishery in the Bering Sea	Individual non-tradable quotas	Triumble et al. (1993)	0.22	0.15-0.30
1992	U.S.A.	Aleutian Island rockfish hook fishery	Licence	Sullivan et al. (1993)	0.21	0.18-0.26
1994	Australia	Gulf of Carpentaria banana and tiger prawns	Individual tradable quotas	Alverson et al. (1994)	0.11	0.05-0.20
1997	Denmark, UK, Germany, the Netherlands	North Sea plaice fishery	Effort regulation[2], ITQs, Licence[3], Rations[4]	Svelle et al. (1997)	0.22	0.10-0.30
1997	Denmark, UK, Germany, the Netherlands	North Sea cod fishery	Effort regulation[2], ITQs, Licence[3], Rations[4]	Banks et al. (2000)	0.18	0.10-0.30

Source: Banks et al. (2000).
1) Estimated illegal landings do not include discard (legal or illegal).
2) Effort regulation is a limit on the number of days at sea and is used in Germany for plaice and cod harvested in the North Sea.
3) Licences, used by the UK for regulating fisheries in the North Sea, essentially correspond to monthly (for cod) and quarterly (for plaice) individual non-tradable quotas.
4) Rations, used by Denmark for regulating cod and plaice in the North Sea, also correspond to (normally monthly) individual non-tradable quotas. While entry control is practiced under the UK licence system this is not done under the Danish ration system.

In this paper we compare two types of instruments, landing fees and ITQs. For the fee, non-compliance consists in avoiding payment for some part of the catch, for the quota it involves catching over the limit.[15] Let H_{It} denote illegal landings undertaken by a representative fisherman in period t and let P_t denote the value (in monetary units) of the expected penalty perceived by the representative fisherman (that is the penalty perceived if illegal landing is detected times the perceived detection probability). We assume that the expected penalty is a function of the amount of illegal landings and a parameter, θ_t, characterising the fisherman's perception of enforcement efficiency in period t i.e.:

$$P_t = P(H_{It}, \theta_t) \tag{1}$$

This functional relation is obviously conditional on the current enforcement effort and the fines and other punishments currently stipulated in statutes and regulations. However, in the following analysis we will assume these to be unaffected by the change in regulatory instrument[16]. Furthermore, since the empirical studies we have surveyed indicate that the estimates of illegal landings are typically highly uncertain, this must also be the case for the penalty functions that can be deduced by a regulator from these estimates. Thus, while (1) describes the expected penalty function perceived by the representative fisherman, the estimate thereof available to the regulator is uncertain. In the following we capture this by assuming that the regulator does not know the value of the parameter θ_t characterising the fisherman's perception of enforcement efficiency. The regulator only knows a probability distribution for possible θ_t values described by the density function $g(\theta_t)$. This is the key information asymmetry that will be analysed in the following.

4 The Model and Main Result

In the following we insert the possibility of illegal landings into a general stock-recruitment model[17] of a search fishery where marginal costs are allowed to depend on both current fish stock and harvest[18]. This type of model is attractive since it encompasses the fundamentally dynamic nature of the fisheries management problem and allows the introduction of uncertainty in a natural way. In our case it has the additional attraction of facilitating a comparison with the Weitzman (2002) paper[19].

Using the notation in Weitzman (2002) recruitment (R_t) is the stock of fish available at the beginning of fishing period t. Let ε_t denote stochastic effects on the ecosystem (here particularly the fish stocks) from variations in, for example, water temperature and weather, and let S_{t-1} denote the stock available at the end of period $t-1$. The biological core of the model is a stochastic stock-recruitment equation:

$$R_t = F(S_{t-1}, \varepsilon_t) \tag{2}$$

where the stock of fish available at the beginning of period t is a function of the stock available at the end of the previous period and stochastic effects reflecting natural growth. Harvest, denoted H_t, reduces fish stock during the period so that:

$$S_t = R_t - H_t \tag{3}$$

Here we use a general search fisheries model of profit for the representative fisherman:

$$\Pi(H_t, R_t) = pH_t - C(H_t, R_t) \qquad (4)$$

where total profit from harvest is revenue (pH_t) less fishing costs ($C(H_t, R_t)$) which are rising in harvest and falling in the recruitment[20]. In the following we use expected profit and costs extensively and for ease of exposition define an expected profit function $\Pi^E(H_t, R_t) = E_{\varepsilon_t}[\Pi(H_t, R_t)]$ and the expected cost function $C^E(H_t, R_t) = E_{\varepsilon_t}[C(H_t, R_t)]$ where expectations are taken over ε_t (the stochastic component to R_t).

The regulator's problem is to maximise the sum of discounted expected future profit, i.e.:

$$\sum_{t=1}^{\infty} a^{t-1} \Pi^E(H_t, R_t) \qquad (5)$$

subject to (2) and (3), where a is the discount factor.

Following Weitzman (2002) the regulator's dynamic programming problem for period t corresponding to (5) is conditional on recruitment at the beginning of the period (R_t). If the regulator were all powerful and could set harvest (H_t) directly this problem becomes:

$$V^*(R_t) = \underset{H_t}{Max}\left(\Pi^E(H_t, R_t) + aE_{\varepsilon_t}\left[V^*(F(R_t - H_t, \varepsilon_{t+1}))\right]\right) \qquad (6)$$

where $V^*(R_t)$ is the expected sum (taken over $\varepsilon_t, \varepsilon_{t+1} \ldots$) of discounted future profit under the optimal policy, conditional on the distribution of R_t, $V^*(F(R_t - H_t, \varepsilon_{t+1}))$ is the corresponding expectation (taken over $\varepsilon_{t+1}, \varepsilon_{t+2} \ldots$), conditional on the realisation of R_t and the distribution of R_{t+1}; and $E[.]$ is the expectation taken over ε_t (the stochastic component of R_t). Under standard convexity assumptions this problem has a unique solution, which we denote H_t^*. This is the first-best policy reference point that we use in the following to evaluate the policy instruments actually available to the regulator[21]. To facilitate this evaluation we define the function:

$$V(H_t, R_t) = \Pi^E(H_t, R_t) + aE_{\varepsilon_t}\left[V^*(F(R_t - H_t, \varepsilon_{t+1})\right] \qquad (7)$$

It follows that:

$$V(H_t^*, R_t) = V^*(R_t)$$
$$\text{and} \tag{8}$$
$$V(H_t^*, R_t) > V(H_t, R_t) \quad \text{for} \quad H_t \neq H_t^*$$

Though the regulator has the information needed to calculate H_t^* the optimal harvest cannot be implemented directly. Instead the regulator must choose between two indirect regulatory instruments of implementation, landing fees or ITQs. Both are subject to non-compliance in the form of illegal landings for which either the landing fee is evaded or the total quota is exceeded. Under a landing fee the regulator's problem is to determine the optimal landing fee, given that there is non-compliance. With ITQs we assume a competitive ITQ market so that quotas are allocated efficiently between fishermen. Thus, the regulator's problem under this system is to determine the optimal total quota given that there is non-compliance. The chosen instrument is applied in combination with a given enforcement system (and a given level of enforcement effort) that generates expected penalties for illegal landings as described in equation (1) in the previous section[22]. Given this, the representative fisherman chooses how much to harvest legally (H_{Lt}) and how much to harvest illegally (H_{It}). Therefore, the total harvest in period *t* becomes: $H_t = H_{It} + H_{Lt}$.

ITQ Regulation

With ITQs combined with the enforcement incentives described in equation (1), the representative fisherman's profit maximisation problem becomes:

$$\underset{H_{Lt}, H_{It}}{Max} \left(\Pi_Q^E(H_{Lt}, H_{It}, R_t) = p(H_{Lt} + H_{It}) - C^E(H_{Lt} + H_{It}, R_t) - P(H_{It}, \theta_t) \right)$$
$$s.t. \tag{9}$$
$$H_{Lt} \leq Q_t$$

The fisherman receives a price *p* for both legally and illegally landed fish, fishing costs are a function of total harvest and recruitment while the expected penalty is a function of illegal harvest only. The total quota for period *t*, Q_t, is a constraint indicating the maximum value of legal harvest[23].

Assuming that the quota is binding, first-order conditions for profit maximisation are:

$$\begin{aligned} &H_{Lt} = Q_t \\ &p - C_H^E(H_{It} + H_{Lt}, R_t) - P_{H_{It}}(H_{It}, \theta_t) = 0 \end{aligned} \tag{10}$$

where $C_H^E(.)$ and $P_{H_{It}}(.)$ indicate first order derivatives of $C^E(.)$ and $P(.)$ respectively. Thus, legal harvest is given by the total quota, and the profit maximising H_{It} is implicitly given as an expectation over R_t depending on Q_t and θ_t. Letting $H_I^Q(Q_t, R_t, \theta_t)$ denote this expectation we have that profit maximising total landings also becomes an expectation depending on Q_t, θ_t and the distribution of R_t i.e.:

$$H^Q(Q_t, R_t, \theta_t) = H_I^Q(Q_t, R_t, \theta_t) + Q_t \tag{11}$$

We now return to the regulator's implementation problem. If the regulator knows the value of θ_t, it would be possible to calculate the value of the regulatory instrument, Q_t that implements H_t^* from (11)[24]. However, if the regulator only knows a probability distribution for θ_t, as we assume, this is not possible. Instead, the regulator must solve the following dynamic programming problem for period *t* corresponding to (6):

$$V^Q(R_t) = \underset{Q_t}{Max} \int \left(\Pi^E(H_t^Q(Q, R_t, \theta_t), R_t) + aE_{\varepsilon_t}\left[V^Q(F(R_t - H_t^Q(Q, R_t, \theta_t), \varepsilon_{t+1})) \right] \right) dg(\theta_t) \tag{12}$$

Let $\hat{Q}_t$ denote the solution to this problem, and let $\hat{H}_t^Q = H_t^Q(\hat{Q}_t, R_t, \theta_t)$. The important point here is that the regulator cannot expect to implement H_t^* with certainty. The regulator's perceived distribution, $g(\theta_t)$, over possible θ_t values implies a corresponding density function over implemented harvest that we denote $f(\hat{H}_t^Q)$. Clearly if θ_t is known (i.e. all probability mass is concentrated at one θ_t value) the corresponding $f(\hat{H}_t^Q)$ distribution concentrates all mass at H_t^*. If, on the other hand, the regulator is uncertain of θ_t the $f(\hat{H}_t^Q)$ distribution will not be degenerate.

We now prove the following proposition:

Proposition I: $V^Q(R_t) < V^*(R_t)$ *for all non-degenerate distributions g(*θ_t*) over possible* θ_t *values.*

Proof: *By definition* $V^Q(R_t) \leq V^*(R_t)$ *implying that*

$$V^Q(F(R_t - \hat{H}_t^Q, \varepsilon_{t+1})) \leq V^*(F(R_t - \hat{H}_t^Q, \varepsilon_{t+1})) \text{ for all } R_t \text{ so that:}$$

$$E_{\varepsilon_t}\left[V^Q(F(R_t - \hat{H}_t^Q, \varepsilon_{t+1}))\right] \leq E_{\varepsilon_t}\left[V^*(F(R_t - \hat{H}_t^Q, \varepsilon_{t+1}))\right]$$

$$\Rightarrow$$

$$\Pi^E(\hat{H}_t^Q, R_t) + E_{\varepsilon_t}\left[V^Q(F(R_t - \hat{H}_t^Q, \varepsilon_{t+1}))\right] \leq \Pi^E(\hat{H}_t^Q, R_t) + E_{\varepsilon_t}\left[V^*(F(R_t - \hat{H}_t^Q, \varepsilon_{t+1}))\right]$$

for all $\hat{H}_t^Q$ *so that*

$$V^Q(R_t) \leq \int V(\hat{H}_t^Q, R_t) df(\hat{H}_t^Q) \qquad (13)$$

where we have inserted definitions (7) and (12). By (8) we know that

$$V(\hat{H}_t^Q, R_t) < V^*(R_t) \quad \forall \hat{H}_t^Q \neq H_t^*$$

so that for all non-degenerate distribution $f(\hat{H}_t^Q)$ *(i.e. distributions that do not concentrate all mass at* $\hat{H}_t^Q = H_t^*$*) we have that*

$\int V(\hat{H}_t^Q, R_t) df(\hat{H}_t^Q) < V^*(R_t)$ *and so by (13) we have:*

$$V^Q(R_t) < V^*(R_t)$$

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Thus, unless the regulator has perfect knowledge of the penalty function, management with ITQs will be sub-optimal.

Tax Regulation

With a landing fee combined with the enforcement incentives described in equation (1) the representative fisherman's profit maximisation problem becomes:

$$\underset{H_{Lt}, H_{It}}{Max}\left(\Pi_\Phi^E(H_{Lt}, H_{It}, R_t) = p(H_{Lt} + H_{It}) - C^E(H_{Lt} + H_{It}, R_t) - \Phi_t H_{Lt} - P(H_{It}, \theta_t)\right) \quad (14)$$

As under ITQs the fisherman receives a price, *p*, for both legally and illegally landed fish, fishing costs are a function of total harvest and recruitment, while the expected penalty is a function of illegal harvest only. The difference is that instead of a quota constraint the fisherman now pays a landing fee (Φ_t) per unit of legally landed fish.

The first order conditions for profit maximisation are:

$$\begin{aligned} &p - C_H^E(H_{It} + H_{Lt}, R_t) - \Phi_t = 0 \\ &p - C_H^E(H_{It} + H_{Lt}, R_t) - P_{H_{It}}(H_{It}, \theta_t) = 0 \end{aligned} \tag{15}$$

From the top condition profit maximising total harvest ($H_t = H_{It} + H_{Lt}$) is implicitly given as an expectation over R_t depending on Φ_t (but *not* on θ_t). Let $H^{\Phi}(\Phi_t, R_t)$ denote this expectation. According to the second condition, profit maximising illegal harvest is implicitly given as an expectation depending on Φ_t, θ_t and the distribution of R_t. This expectation is denoted $H_I^{\Phi}(\Phi_t, R_t, \theta_t)$. Although both the optimal amount of illegal harvest and the optimal amount of legal harvest depend on the parameter θ_t, their sum does not (see figure 4.1b for the intuition of this result). Optimal total harvest $H^{\Phi}(\Phi_t, R_t)$ only depends on the R_t distribution and so the fee value that ensures optimal harvest can be found by setting:

$$H^{\Phi}(\Phi, R_t) = H_t^* \tag{16}$$

Equation (16) can be solved for Φ_t even though the regulator does not know the parameter θ. Thus using a landing fee the regulator can implement optimal harvest with certainty even if he does not have perfect knowledge of the penalty function. Therefore, when the regulator solves the dynamic programming problem corresponding to (6):

$$V^{\Phi}(R_t) = \underset{\Phi_t}{Max} \int \left(\Pi^E(H_t^{\Phi}(\Phi, R_t), R_t) + aE_{\varepsilon_t}\left[V^Q(F(R_t - H_t^{\Phi}(\Phi, R_t), \varepsilon_{t+1})) \right] \right) dg(\theta_t) \tag{17}$$

he can set Φ_t so that $H^{\Phi}(\Phi, R_t) = H_t^*$ in all periods which makes it possible to ensure that $V^{\Phi}(R_t) = V^*(R_t)$. Using this and proposition I we have that:

$$V^Q(R_t) < V^{\Phi}(R_t) \tag{18}$$

Result and Intuition

As the main result of this paper we conclude that if compliance uncertainty is the dominant type of information asymmetry then tax regulation is always more efficient than ITQ regulation. We stress that this result applies to the general search type fishery where marginal fishing costs are allowed to depend on both stock and harvest and so would seem to be a generally applicable result. On the other hand, we utilize two simplifying assumptions that may be important for our result: that the expected penalty function perceived by fishermen does not differ between quota and landing fee systems; and that fishermen's efforts to avoid discovery when they are not complying with the regulatory system can be ignored.

Dropping time indices the intuition of this result is illustrated graphically in figure 4.1a and 4.1b using essentially the same set up as in figure 2.1a and 2.1b. We have fish stock on the x-axis and value on the y-axis. The $\pi^e(x)$ curve indicates discounted expected marginal profit from escapement (measured from the origin), while the $\pi^c(x,R)$ curve indicates marginal profit from harvest (measured from recruitment R). The intersection of the two curves indicates the optimal escapement/harvest level.

Figure
4.1

Figure 4.1a

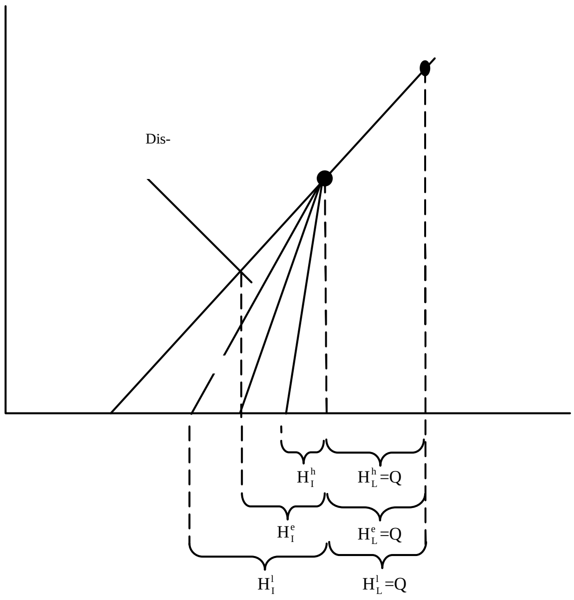
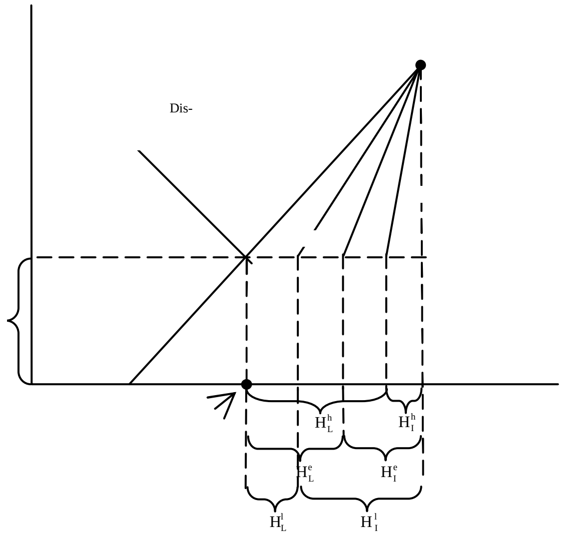


Figure 4.1b



Here there is no information asymmetry regarding recruitment or costs so both $\pi^e(.)$, $\pi^c(.)$ and R are known[25]. Instead, there is information asymmetry regarding the expected penalty function generated by the enforcement and control system. In both figures the marginal penalty function parameter expected by the regulator is denoted θ_e while θ_l and θ_h denote low and high parameter estimates held by the regulator.

Figure 4.1a illustrates the situation for the representative fisherman under quota regulation. Since legal fishing within the allocated quota does not impose extra costs on the fisherman, illegal landings are only considered after the entire quota Q has been used. When the quota has been landed legally he will continue fishing illegally until marginal expected penalty on the next fish reduces marginal profit to zero. We have assumed that the regulator sets Q so that optimal total harvest is reached when the expected marginal penalty function applies. Clearly, if the actual marginal penalty function deviates from the regulator's expectation so will illegal harvest. Since legal harvest is given by the quota these deviations carry over into the total harvest causing it to deviate from optimal harvest (as the results for the θ_l and θ_h penalty function parameters illustrate). Thus, unless the regulator knows the marginal penalty function expected by the fisherman with certainty he expects to incur a welfare loss under quota regulation.

Now, consider regulation by landing fee illustrated in Figure 4.1b. Since legal fishing now has a cost equal to the landing fee, the fisherman first considers illegal landings. He will continue fishing illegally until the expected marginal penalty equals the landing fee. From this point on expected profit from legal harvest exceeds expected profit from illegal harvest and so the fisherman continues to harvest legally until marginal profit equals the landing fee. We see that this cut-off point is not affected by variation in the marginal penalty function since it is given by the landing fee rate, Φ. Deviations from the expected penalty function affect the distribution of total harvest between legal and illegal harvest – but total harvest remains constant at the optimal level given by the landing fee rate. The flavour of this result is like that of the result in Weitzman (2002), but the mechanism driving it is different.

5 Conclusion

The current literature on instrument choice (landing fees vs. quotas) for fisheries regulation has considered special cases and arrives at mixed results. Depending on the type of information asymmetry (ecological or economic) assumed and whether marginal profit is specified as a function of current fish stock or current harvest level either landing fees or quotas are preferred. In this paper we have argued that for the more common search fishery (where marginal profit is a function of both current fish stock and current harvest level) neither the ecological nor the economic information asymmetry assumptions driving these results may, in fact, not be especially important, since neither the regulator nor fishermen seem to have sharply better information about stocks and how they affect profits in the current period. On the other hand, based on a number of empirical studies, we argue that regulator uncertainty about fishermen's noncompliance with regulations (fees or quotas) may be an important information asymmetry in many fisheries. When this is the case we show that price regulation can perform better than quantity regulation and that this result does apply under the more general search fishery specification of the marginal profit function (i.e. when marginal profit is a function of both current levels of fish stocks and the current harvest level).

Along the way to the proof, we have made two simplifying assumptions that seem potentially problematic: (1) that the expected penalty function perceived by fishermen does not differ between quota and landing fee systems; and (2) that fishermen's efforts to avoid discovery when they are not complying with the regulatory system can be ignored. These assumptions seem to be worth further exploration, both as to their empirical validity and their importance to the results presented here.

Appendix I

The starting point here is the steady-state formulation of the regulator's problem presented by Jensen and Vestergaard (2003) equation (6) and (7) adjusted to a schooling fishery[26]:

$$\begin{aligned} &\underset{x,q}{Max}\, E\left[B(q,\mu) - C(q,\omega)\right] \\ &s.t. \\ &F(x) = q \end{aligned} \qquad \text{(AI.1)}$$

where $B(q,\mu)$ and $C(q,\omega)$ are benefits (income) and cost of catch, *q*. These are also functions respectively of the parameters μ and ω, for which the regulator holds only distributions, which are assumed to be independent. $F(x)$ is the (concave/single maximum) natural growth function of fish stock *x*, and the constraint implies that in steady-state catch must equal natural growth. Note that costs are independent of the fish stock and so the only link between catch and fish stock for this fishery is through the resource constraint. With no discounting it is obvious that expected welfare is maximised by settling on the fish stock that allows the maximum sustainable yield (q_{msy}) as long as marginal benefits are greater than marginal costs at this catch level[27].

The regulator may choose between setting a quota $\hat{q}$ or a price $\tilde{p}$. When a quota is set fishermen are assumed simply to catch the quota (we assume it is binding), and so the resulting catch is known with certainty despite the regulator's uncertainty about the benefit and cost function parameters μ and ω. When a price is set fishermen solve their maximisation problem, $\underset{q}{Max}\,\tilde{p}q - C(q,\omega)$, and the resulting catch is a function $q(\tilde{p},\omega)$. After setting the price the regulator does not know the resulting catch with certainty, since his uncertainty about the ω plays into the resulting catch. Let $\tilde{q}(\omega)$ denote the distribution describing possible resulting catches implied by the distribution of ω after having set the price instrument. Since there is no regulator uncertainty about the maximum sustainable yield (q_{msy}) this can be implemented using the quota instrument (i.e. setting $\hat{q} = q_{msy}$ in steady-state) and so using the quota instrument in this way will maximise welfare for all combinations of realized values of μ and ω. On the other hand, this is not generally possible with the price instrument, since q_{msy} cannot be implemented with certainty. By definition all other sustainable yields are smaller than q_{msy} and so $\tilde{q}(\omega) \leq q_{msy}$ for all ω implying that $B(\tilde{q}(\omega),\mu) - C(\tilde{q}(\omega),\omega) \leq B(q_{msy},\mu) - C(q_{msy},\omega)$ for all combinations of realised values of μ and ω. Thus except for a degenerate ω distribution $E\left[B(\tilde{q}(\omega),\mu) - C(\tilde{q}(\omega),\omega)\right] < E\left[B(q_{msy},\mu) - C(q_{msy},\omega)\right]$ implying that the quota instrument is always preferred.

To see specifically where Jensen and Vestergaard (2003) go wrong consider their equation (15) for relative advantage of price over quantity regulation (denoted $\vartriangle$):

$$\vartriangle = E\left[B(\tilde{q}(\omega),\mu) - C(\tilde{q}(\omega),\omega) - B(\hat{q},\mu) + C(\hat{q},\omega)\right] \quad \text{(AI.2)}$$

and their second order Taylor series approximations (their (16) and (17)):

$$C(q,\omega) \approx a(\omega) + (C' + \alpha(\omega))(q - \hat{q}) + \frac{C''}{2}(q - \hat{q})^2 \quad \text{(AI.3)}$$

$$B(q,\mu) \approx b(\mu) + (B' + \beta(\mu))(q - \hat{q}) + \frac{B''}{2}(q - \hat{q})^2 \quad \text{(AI.4)}$$

where $E[\alpha(\omega)] = E[\beta(\omega)] = 0$. This then gives rise to the following marginal cost and benefit functions:

$$C_q(q,\omega) \approx C' + \alpha(\omega) + C''(q - \hat{q}) \quad \text{(AI.5)}$$

$$B_q(q,\mu) \approx B' + \beta(\mu) + B''(q - \hat{q}) \quad \text{(AI.6)}$$

Inserting AI.3 and AI.4 into AI.2 gives:

$$\begin{aligned}\triangle &= E[(B'+\beta(\mu))(q(\omega)-\hat{q})+\frac{B"}{2}(q(\omega)-\hat{q})^2 \\ &-(C'+\alpha(\omega))(q(\omega)-\hat{q})-\frac{C"}{2}(q(\omega)-\hat{q})^2]\end{aligned} \quad \text{(AI.7)}$$

$$\Leftrightarrow$$

$$\begin{aligned}\triangle &= B'(E[q(\omega)]-\hat{q})+\frac{B"}{2}E[(q(\omega)-\hat{q})^2] \\ &-C'(E[q(\omega)]-\hat{q})-E[\alpha(\omega)q(\omega)]-\frac{C"}{2}E[(q(\omega)-\hat{q})^2]\end{aligned} \quad \text{(AI.8)}$$

Jensen and Vestergaard now make the following assumption $E[\tilde{q}(\omega)]=\hat{q}$ which then implies that $\tilde{q}(\theta)=\hat{q}-\frac{\alpha(\omega)}{C"}$. After inserting into (AI.6) they derive the Weitzman equation:

$$\triangle=\frac{B"+C"}{2(C")^2}E[(\alpha(\omega))^2] \quad \text{(AI.9)}$$

leading them to conclude that for a linear benefit function where $B"=0$ we have $\triangle>0$ since $C">0$ and so the price instrument is preferred. The problem here is the $E[\tilde{q}(\omega)]=\hat{q}$ assumption. Since $\tilde{q}(\omega)\le q_{msy}=\hat{q}$ for all ω then for all non-degenerate distributions of ω we must have that $E[\tilde{q}(\omega)]<\hat{q}$. Bearing this in mind we can now retrace the derivations from (AI .7) which reshuffles to:

$$\triangle=E\left[\left(2(B'+\beta(\mu))+B"(q(\omega)-\hat{q})-2(C'+\alpha(\omega))-C"(q(\omega)-\hat{q})\right)\frac{(q(\omega)-\hat{q})}{2}\right]$$

$$\Leftrightarrow$$

$$\triangle=E\left[\left([(B'+\beta(\mu))-(C'+\alpha(\omega))]+[(B'+\beta(\mu))+B"(q(\omega)-\hat{q})-(C'+\alpha(\omega))-C"(q(\omega)-\hat{q})]\right)\frac{(q(\omega)-\hat{q})}{2}\right]$$

By assumption marginal benefits are greater than marginal costs for all ω values at $q_{msy}=\hat{q}$ and so $B_q(\hat{q},\omega)>C_q(\hat{q},\omega)$ which using AI.4 and AI.5 implies that $[(B'+\beta(\omega))-(C'+\alpha(\omega))]>0$ for all ω and since $\tilde{q}(\omega)\le\hat{q}$ also that $[(B'+\beta(\mu)+B"(q(\omega)-\hat{q}))-(C'+\alpha(\omega)+C"(q(\omega)-\hat{q}))]>0$ for all ω.

Since $(q(\omega)-\hat{q}) \leq 0$ for all ω the expectation $\vartriangle \leq 0$ and strictly less than 0 for all non-degenerate distributions implying that quotas are always preferred.

Appendix II

The starting point here is the Weitzman (2002) formulation of the regulator's optimisation problem under quotas when the regulator knows the realisation of a stochastic variable for the coming period *t*, ε_t, but not the realisation of the stochastic variable for the following periods, ε_{t+1} (equation (24) in Weitzman (2002))[28]. We assume that the total quota is binding and so that we have:

$$V^*(S_t,\varepsilon_t) = \underset{Q_t}{Max} \int_{F(S_t|\varepsilon_t)-Q_t}^{F(S_t|\varepsilon_t)} \pi(x)dx + aE_{\varepsilon_{t+1}}\left[V^*(F(S_t|\varepsilon_t)-Q_t,\varepsilon_{t+1})\right] \qquad \text{(AII.1)}$$

where variables have the same interpretations as in Weitzman (2002) and the present paper.

The corresponding marginal condition for optimal escapement (the part of recruitment that is not harvested), S_t^*, is obtained directly as:

$$\pi(S_t^*) = aE_{\varepsilon_{t+1}}\left[v^*(S_t^*,\varepsilon_{t+1})\right] \qquad \text{(AII.2)}$$

where $v^*(S_t^*,\varepsilon_{t+1}) = \partial V^*(S_t^*,\varepsilon_{t+1})/\partial S_t^*$. We note that optimal escapement, S_t^*, is independent of ε_t. The solution to (AII.1) is the quota, Q_t^*, that ensures optimal escapement which implies that:

$$Q_t^* = F(S_t|\varepsilon_t) - S_t^* \qquad \text{(AII.3)}$$

The corresponding optimal tax, Φ_t^*, ensuring zero marginal profit at optimal escapement implied by (AII.2) is:

$$\Phi_t^* = \pi(S_t^*) \qquad \text{(AII.4)}$$

The core of the result in Weitzman (2000) is that Q_t^* depends on the realisation of ε_t as seen from (AII.3) so that, when the regulator does not know ε_t, expected welfare resulting from any value of Q_t is strictly lower than the welfare level associated with Q^*_t. On the other hand, Φ_t^* is independent of ε_t as seen in (AII.4) and maximum expected welfare can, therefore, be induced with a tax even if the regulator does not know the realisation of ε_t.

Now let us generalise the model by allowing marginal profit to depend on harvest volume ($\pi(x,H)$). Introducing this into (AII.1) and remembering that optimal harvest $H_t^* = F(S_t|\varepsilon_t) - S_t^*$ implies that the marginal condition corresponding to (AII.2) becomes:

$$\pi(S_t^*, F(S_t|\varepsilon_t) - S_t^*) = aE_{\varepsilon_{t+1}}\left[v^*(S_t^*, \varepsilon_{t+1})\right] \qquad \text{(AII.5)}$$

We note that optimal escapement S_t^* now depends on ε_t. Thus, the optimal tax equation corresponding to (AII.4) becomes:

$$\Phi_t^* = \pi(S_t^*, F(S_t|\varepsilon_t) - S_t^*) \qquad \text{(AII.6)}$$

implying that optimum no longer can be induced with certainty if the regulator does not know the realisation of ε_t. This again implies that expected welfare under tax regulation no longer can be shown always to be greater than expected welfare under quota regulation using the proof strategy chosen by Weitzman (2002).

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Sammenfatning

Priser kontra mængde – regulering af fiskeri, når der er håndhævelses- og overholdelsesproblemer

Januar 2006

Lars Gårn Hansen, Frank Jensen og Clifford Russell

I flere nyere bidrag til den fiskeriøkonomiske litteratur sammenlignes efficiens af fiskeriregulering baseret på fangstafgifter med fiskeriregulering baseret på omsættelige fangstkvoter. Dette sker under usikkerhed om fiskebestandens vækstforhold, og når der er usikkerhed om fiskeflådens indkomst- og udgiftsforhold. De hidtidige resultater peger ikke entydigt på et af de to instrumenter som det bedste. Her introducerer vi overtrædelses- og håndhævelsesproblemet som en potentielt mere vigtig årsag til usikkerhed og navnlig informationsasymmetri og viser, at denne type af usikkerhed altid fører til, at regulering med fangstafgifter er mere efficient end regulering med omsættelige kvoter.

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Notes

1. For fisheries with a small number of participants the incentives generated by lump-sum revenue recycling may be significant, requiring these to be taken into account explicitly through a budget-balancing tax mechanism (see for example Govinsdasamy et al., 1994). However, for large fishing industries the incentive effect of recycling is small and can reasonably be ignored so that revenue can be recycled simply through lump-sum transfers.

2. If, for example, ITQs are grandfathered to fishermen using the same criteria as for lump-sum tax revenue recycling it is easy to show that the income effects generated in the two regulatory schemes are the same.

3. Weitzman calls uncertainty about biological functions “ecological uncertainty” and uncertainty about profit/cost functions “economic uncertainty”.

4. This means that marginal costs rise as the fish stock is reduced by catch, but no other causes of rising marginal costs are allowed. E.g. the extra costs that might arise as capacity utilisation levels increase are assumed to be negligible in Weitzman’s model and so marginal costs do not depend on the volume of harvest other than through the effect of harvest on fish stock.

5. So, in this fishery marginal costs do not depend on the current fish stock as such, but they may rise with the catch level, e.g. because of rising costs associated with increasing capacity utilisation.

6. Neher (1990b) argues that in most cases fishing costs do depend importantly on both harvest and stock size. Similar arguments are presented in Anderson (1986).

7. In section 3 we present empirical evidence to this effect.

8. Fisheries regulators do not often use the language of economics in discussing their problems and solutions. It is rather more common for them to stress the ecological situation being addressed, such as a population crash, and the strategy recommended to deal with it, such as a reduction of catch levels over some period.

9. Note that other papers have considered effects of “ecological” uncertainty on growth of fish stocks (see e.g. Roughgarden and Smith 1996; Sethi et al. 2005), but these do not consider the implications of information asymmetry for instrument choice.

10. Jensen and Vestergaard (2003) actually state that tax regulation is preferred over ITQs in this case – but this statement is based on a misinterpretation of their analytical results. In appendix I we show formally that a pro quota result applies in this case and indicate where Jensen and Vestergaard (2003) go wrong in their original analysis.

11. While boat type and gear may be observed by the regulator, asymmetric information between the regulator and fishermen could, for example, involve the fishermen's skill levels.

12. It is not clear whether Weitzman's result also holds with more general profit function specifications that allow for e.g. costs associated with increasing capacity utilisation (i.e. the specification $\pi^e(x,H)$). In appendix II we show that the proof used in Weitzman (2002) breaks down with a more general profit function specification. On the other hand, we have not off hand found clear cut examples contradicting a pro tax result so it may be possible to show this using another proof strategy.

13. Note that what is of importance here is the information asymmetry about the average cost function (i.e. when comparing the average cost function estimated by the regulator with the average of the individual cost functions estimated by fishermen).

14. Other authors (e.g. Yates 2002; Spubler 1988; Segerson 1988) consider optimal regulation of pollution with asymmetric information.

15. Other choices of regulatory instruments imply other meanings for non-compliance. Thus, gear restrictions are violated when forbidden gear is used. Limits on fishing time are violated when the time limits are exceeded.

16. Note that an important insight from the cited literature is that the optimal level of enforcement should be found as part of the optimal dynamic control problem where the optimal total catch is found. Thus, a change in regulatory instrument may affect the optimal enforcement effort. In this paper we focus on the problem of choosing between taxes and ITQs, and for reasons of parsimony we hold enforcement constant. This is strictly speaking not optimal. However, including the resulting adjustment of optimal enforcement effort in the dynamic control problem of the regulator (though easily done) complicates derivations without, we believe, affecting the results in any substantial way. We also assume that avoidance costs (costs incurred by fishermen so as to avoid/reduce the probability of detection) can be ignored. These assumptions and simplifications, especially the last one about avoidance costs, may be important for our results and raise interesting issues for further research.

17. See e.g. Reed (1979) for an original presentation of this model.

18. So in addition to allowing marginal costs to depend on the current fish stock (reflecting the effect of catch on fish stocks), marginal costs may also be affected by the catch level for other reasons, such as costs associated with increasing capacity utilisation.

19. There are essentially two modelling approaches within fisheries economics differing as to whether the (dynamic) adjustment to steady-state equilibrium is modelled explicitly or not (see Conrad and Clark (1991) for a classic presentation). The so-called Shaefer approach (Schaefer 1954) focuses on changes in long-run equilibrium stock found as

the stock size where natural growth equals harvest. This approach has the advantage of simplicity, giving rise to compact and intuitive models that in many situations capture the effects of primary importance. The second approach is the so-called Berverton-Holt model where the dynamic adjustment to steady-state is modelled explicitly through the stock-recruitment relation (hence this approach is often simply called the stock-recruitment model). Using this modelling approach a number of papers have introduced stochastic recruitment as a way of generating uncertainty about the natural growth function (a modelling tradition called stochastic bioeconomics). Both Weitzman (2002) and our paper fall within this tradition.

20. This is a generalisation of the constant marginal cost assumption (C_{HH} =0) in Weitzman (2002) since we allow C_{HH} >0.

21. Weitzman (2002) focuses on biological uncertainty (i.e. information asymmetry regarding recruitment) and so assumes that fishermen observe ε_t prior to determining harvest while the regulator does not observe ε_t prior to setting the value of the regulatory instrument. Here the focus is on the information asymmetry implied by the penalty function and we assume that neither the regulator nor the representative fisherman observes ε_t a priori so that our first-best policy is not conditional on ε_t. Alternatively, we could eliminate the biological information asymmetry by assuming that both regulator and fisherman observe ε_t a priori, which would not affect the results derived in the following.

22. Note that we have assumed enforcement effort to be exogenous to our decision problem so that it need not enter into the regulator's social welfare function. We also assume that the penalties imposed on fishermen for illegal landings take the form of monetary transfers without real cost to society and so they can also be excluded from the social welfare function (i.e. issues of tax distortion and double dividend are ignored here).

23. With an ITQ-market the representative fisherman sees a quota price and so does not perceive a quantity constraint as such. However, since the quota market price adjusts so that the quantity constraint is always satisfied the representative fisherman behaves as if he were quantity constrained. Following Weitzman (2002) we use this formulation.

24. This has a unique solution with standard convexity assumptions.

25. Strictly speaking only the expected value of *R* is known by the regulator as well as by fishermen, so *R* is this expectation, and $\pi^c(x,R)$ is expected current profit.

26. The notation used in this appendix corresponds to the notation developed in Jensen and Vestergard (2003), to which the reader is referred for precise definitions of variables and functions.

27. This is a standard result in the literature (see e.g. Neher 1990b). The only exception being if marginal benefits become smaller than marginal costs at a catch level lower than q_{msy} in which case regulation is unnecessary – so we disregard this possibility.

28. The notation used in this appendix corresponds to the notation developed in Weitzman (2002) and in the body of the present paper, to which the reader is referred for definitions of variables and functions.