DEPARTMENT OF FOOD AND RESOURCE ECONOMICS
UNIVERSITY OF COPENHAGEN

IFRO Working Paper

Prices versus Quantities:
What is the discussion really about?

Lars Gårn Hansen
Frank Jensen

2013 / 15

IFRO Working Paper 2013 / 15

Prices versus Quantities: What is the discussion really about?

Authors: Lars Gårn Hansen, Frank Jensen

www.ifro.ku.dk/english/publications/foi_series/working_papers/

Department of Food and Resource Economics (IFRO)
University of Copenhagen
Rolighedsvej 25
DK 1958 Frederiksberg DENMARK
www.ifro.ku.dk

Prices versus Quantities

–

What is the discussion really about?

By Lars Gårn Hansen* and Frank Jensen**

Draft of August 2013

* Department of Food and Resource Economics- Denmark, Rolighedsvej 23, e-mail: lgh@foi.ku.dk

** Department of Food and Resource Economics- Denmark, Rolighedsvej 23, e-mail: fje@foi.ku.dk

Abstract: Weitzman (2002) studies the regulation of a fishery characterised by constant marginal harvest costs and shows that price regulation performs better than quantity regulation when the regulator is uncertain about the biological reproduction function (ecological uncertainty). Here, we initially illustrate that this result does not generalise to a search fishery, where marginal costs are allowed to depend on harvest. Hansen et al (2008) study a fishery where non-compliance with regulations is a problem. When the regulator is uncertain about non-compliance (compliance uncertainty), then landing fees are the preferred type of regulation, and Hansen et al (2008) find that this result does generalise to a search fishery where marginal costs depend on harvest. In this paper, we simulate a stochastic stock-recruitment model for the Danish cod fishery in the Kategat capturing both ecological and compliance uncertainty. We find that the gain from eliminating compliance uncertainty may be up to 5% of gross profit while the gain from eliminating ecological uncertainty is minimal. Under landing fee regulation, the entire gain from eliminating both types of uncertainty is captured, even if the regulator's stock measurement is uncertain. However, most of this gain can be captured within an ITQ system if the regulator is able to measure stocks accurately.

JEL-codes:Q2

Key words: Compliance uncertainty, fishery regulation, illegal landings, instrument choice.

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 also focused on quantity measures in their research, and recommendations for individual transferable fishing quotas (ITQs) are common (see Moloney and Pearse (1979)). 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 (the regulator) 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 bioeconomic setting, the 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)), the optimal tax regulation may aggravate income fluctuations for fishermen and thus impose extra risk.

These arguments for dismissing taxes may, however, be questioned. First, optimal taxes may well imply substantial information requirements, but so would an attempt to regulate in an optimal fashion with ITQs. 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 is unwanted, 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, the optimal tax rate may well vary over time, but 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, the serious consideration of taxes as an instrument for fisheries management was (re)introduced into the fisheries economics literature in an important paper by Weitzman (2002). In follow up papers, Jensen and Vestergaard (2003) and Hansen et al (2008) continue this line of research.

---

[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. 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.

All three papers consider a specific structure of the regulator's uncertainty about the cost, benefit and biological functions[3] characterising the fishing industry. The papers find that taxes in some cases perform better than ITQs, based on 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 and, therefore, are independent of harvest (i.e. are in effect characterised by constant marginal costs), Weitzman (2002) shows that tax regulation performs better than ITQs under ecological uncertainty (where the regulator is more uncertain than the fishermen about the stock-recruitment relation). For a search fishery where marginal fishing costs depend on both harvest and fish stock, Jensen and Vestergaard (2003) show that nothing definite can be said about the choice between price and quantity regulation under economic uncertainty (where the regulator is more uncertain about the cost and benefit functions than the fishermen).[4] Hansen et al (2008) study compliance and enforcement problems as a potential source of uncertainty. They argue that the uncertainty generated by compliance and enforcement problems constitute an important (perhaps the most important) source of information asymmetry between the regulator and the fishermen in fisheries regulation. Furthermore, they 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.

This paper is closely related to Hansen et al (2008). An issue that arises in connection with Hansen et al (2008) is how large the welfare gain from moving from quantity regulation to price regulation is. If this gain is small, the results in the price versus quantity regulation literature are mainly of theoretical interest. However, if the gain is large, the literature ought to have practical implications. We develop a stochastic stock-recruitment model for the Danish cod fishery in the Kategat and simulate the potential welfare gain from shifting to tax regulation from quantity regulation for this fishery. The simulations suggest that the gain from eliminating compliance uncertainty may be up to 5% of gross profit[5] and that most of this gain can be captured within an ITQ system if the regulator is able to measure stocks accurately. However, under landing fee regulation, the entire gain can be captured even if the regulator's stock measurement is uncertain.

In the next section, the recent literature on prices versus quantities is reviewed, while section 3 discusses relevant parts of the compliance and enforcement literature within fisheries.

---

[3] Uncertainty about biological functions is labelled ecological uncertainty by Weitzman (2002).

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

[5] Gross profit is profit before the deduction of capital costs.

Section 4 presents the main result in Hansen et al (2008), while simulations are described in section 5. Section 6 sums up the main conclusion.

2. Literature review

Fisheries are an example of a renewable resource use where economic overexploitation may result if the 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 (see Anderson (1986)). To mitigate this externality, regulatory authorities have, in a number cases, applied some form of individual quota system (see Wilen (2000)) and much of the fisheries economics literature considers ways of increasing the efficiency of such systems, e.g. by making quotas transferable (see Moloney and Pearse (1979)). However, as noted in the introduction, three recent papers have reconsidered taxes as an alternative to individual quotas – a line of research that we extend in this paper.

Weitzman (2002) revived the investigation of taxes used for fisheries management by considering ecological uncertainty in a stock-recruitment model, where marginal harvest costs are constant (depend on stock size, but are independent of harvest). The regulator must fix the value of the regulatory instrument (i.e. a landing fee or a total quota) with imprecise knowledge of the fish stock (i.e. ecological uncertainty). When a landing fee/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, observe the realised fish stock variable before deciding how much to harvest. It is this asymmetry with regards to ecological information that drives the result in Weitzman (2002). The regulator’s problem is to induce fishermen to harvest an optimal proportion of the realised fish stock. Intuitively, if the realised stock is lower than the expected fish stock, it will 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 tax regulation, on the other hand, this is possible by decentralising the harvest decision to fishermen who observe the realised fish stock value. Weitzman (2002) shows that when marginal fishing costs are independent of recruitment and the ecological uncertainty of the regulator, relative to that of fishermen, is the dominant type of information asymmetry, tax regulation is always more efficient than ITQs (the model result is illustrated below). Furthermore, Weitzman (2002) suggests that ecological uncertainty may often be the more significant information asymmetry and speculates that even when economic uncertainty is more significant, a result favouring quotas would only be found when costs are unresponsive to changes in fish stocks.

This theme is taken up by Jensen and Vestergaard (2003) who compare taxes with ITQs under economic uncertainty. Assuming cost information asymmetry, Jensen and Vestergaard (2003) consider a search fishery where marginal costs depend on both stock size and harvest (i.e. where marginal costs may rise with catch volume for fixed fish stock – so that marginal costs become dependent on recruitment). For this type of fishery they find that it is not clear which regulatory scheme is preferred. The optimal management approach will depend on the specific functional parameters. The reason for this is the complex cost relationship that arises for search fisheries when marginal costs are allowed to depend on harvest. This dependence implies cross partial derivative terms between stock size and harvest of undetermined sign and size that rule out a simple relative slope result in line with Weitzman (1974).

To sum up, the common search fishery type, where marginal costs depend on recruitment, has been investigated by Jensen and Vestergaard (2003), who show that there is no clear-cut case for preferring landing fee over ITQs when the regulator's economic uncertainty is the dominant type of information asymmetry. The implications of ecological uncertainty for the regulation of search fisheries have not been investigated, but:

1) if ecological uncertainty is often the more significant as Weitzman (2002) suggests, and
2) if the pro tax result in Weitzman (2002) for fisheries where costs are independent of harvest generalises to a search fishery where marginal costs depend on recruitment,

then there may be a strong case for generally preferring tax regulation over ITQs.

When addressing the first point. it is clear that 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, which is the key assumption. Fishermen must base decisions on how much to harvest (whether to start a fishing expedition or whether to continue it) on expected returns. Presumably, the regulator is at least as well informed about the state of the ecosystem as fishermen at any given time, but, as Weitzman (20002) argues, the value of regulatory instruments must be set prior to fishing so that the fishermen can 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 selected. 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 an informational advantage, it is not clear how important this advantage is or whether it is more important than other types of information asymmetry.

This brings us to the second point for which it is fairly straightforward to illustrate that the pro tax result in Weitzman (2002) does *not* generalise to a search fishery where marginal costs depend on recruitment. The basic intuition can be illustrated in Figures 1 and 2. Essentially, an argument analogous to Jensen and Vestergaard (2003) applies. When marginal costs depend on harvest as well as stock size, this gives rise to cross partial derivative terms between stock and harvest of undetermined sign and size.

Figure 1

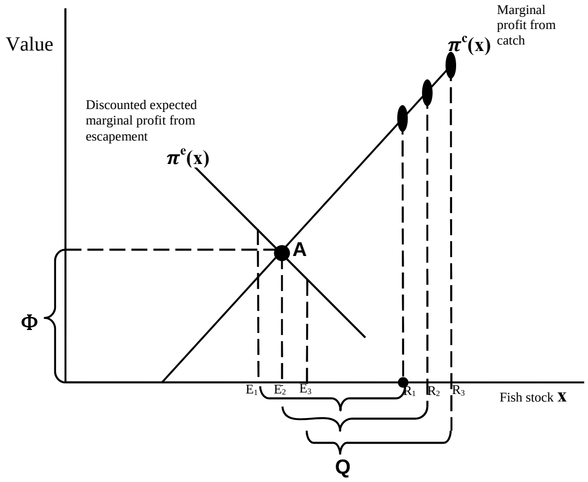
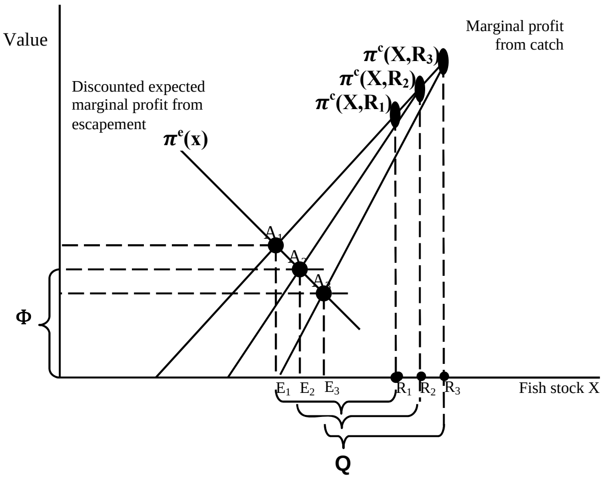


Figure 2



The original model and result in Weitzman (2002) are illustrated in Figure 1 where 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 (the part of stock that is not caught, but left to parent future fish generations). Escapement is measured from the origin and expected marginal profit falls as escapement increases. The $\pi^c(x)$ curve indicates marginal profit from 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, marginal profit of the first fish caught is the indicated value for this fish stock). As more fish are caught, the remaining fish stock falls (moving towards origin) and marginal profit falls (since fish become increasingly scarce and, therefore, harder to find). At the intersection of the two curves (point A), the 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 (2002) is that marginal profit for a given level of fish stock is *independent* of harvest volume and, thus, independent of realised recruitment[6]. This means that, irrespective of the realisation of the stochastic recruitment variable (in Figure 1 three such realisations are indicated by R_1, R_2 and R_3), the marginal harvest profit is described by the same $\pi^c(x)$ curve (the only difference being the initial fish stock/starting point for catch/profit measurement). Since the $\pi^c(x)$ curve as such 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 landing fees (whose optimal rate, Φ, is independent of realised recruitment), it becomes unprofitable for fishermen to harvest fish below this stock level irrespective of the realised recruitment, and so constant escapement is ensured. If the regulator instead of a tax imposes a total quota, *Q*, then the harvest 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 marginal costs are independent of recruitment.

In Figure 2, the same situation is illustrated, except we now let marginal profit depend on the harvest and, thereby, on the realised recruitment level, *R* (i.e. the marginal profit function is $\pi^c(x,R)$). With marginal costs rising as a function of total harvest we have that $\pi^c(x,R_1) > \pi^c(x,R_2) > \pi^c(x,R_3)$ when $R_1 < R_2 < R_3$ as illustrated in Figure 2. This implies that optimal escapement now depends on realised recruitment so that the optimal harvest tax is no longer independent of the realised recruitment (illustrated in Figure 2 by intersection points A_1, A_2 and A_3 with optimal escapements E_1, E_2 and E_3 corresponding to recruitments R_1, R_2 and R_3, respectively). Being set prior to this realisation, the tax can no longer ensure the optimum when recruitment deviates from the realisation for which Φ ensures optimum. A quota may, on the other

---

[6] The extra costs that might arise at high capacity utilisation levels are assumed to be negligible in Wietzman's model.

hand, be efficient. As illustrated in Figure 2, the shift in the $\pi^c(x, R)$ curve, induced by a change in R, might cause precisely the same shift in optimal escapement so that a total quota always ensures optimal escapement. This gives an intuitive illustration of why the pro-tax result in Weitzman (2002) under ecological uncertainty does not generalise to a search fishery, where marginal costs depend on recruitment (as already noted we show this formally in the appendix).

In conclusion, the existing literature suggests that taxes may be the preferred instrument for some of the many search fisheries that are today regulated by quotas. On the other hand, neither ecological nor economic uncertainty gives rise to a generally applicable argument for using either taxes or ITQs in the regulation of the more common search type of fisheries, where marginal costs depend on recruitment.

3. The Compliance Problem in Fisheries Regulation

The potential effects of compliance and enforcement problems have not been studied in the previous prices versus quantities literature. Nevertheless, non-compliance seems to be 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 1 lists estimates of illegal landings from a number of studies we have surveyed.

Table 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	Trumble *et al.* (1993)	0.22	0.15-0.30
1992	U.S.A.	Aleutian Island rockfish hook fishery	License[3]	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, 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, Netherlands	North Sea cod fishery	Effort regulation[2], ITQs, Licence[3], Rations[4]	Banks *et al.* (2000)	0.18	0.10-0.30

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 the case under the Danish ration system.

The surveyed estimates cover a variety of countries, species and types of regulation and, except for the Australian Gulf of Carpentaria banana and tiger prawns 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.

Furthermore, (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) and 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 (1990), Charles (1993), and Charles *et al.* (1999)). Based on the theory of choice under uncertainty, this literature models criminal activities (non-compliance) by the individual fisherman as being the result of an evaluation of the expected net benefits. The fisherman weighs the gains from non-compliance against the expected cost (essentially the perceived probability of detection times the designated punishment when non-compliance is detected). The optimal level of non-compliance perceived by the fisherman must then be where the marginal gain equals the expected marginal cost.

In this paper, we compare two types of regulation, landing fees and ITQs. In both cases, non-compliance is assumed to take the form of illegal landings for which the landing fee/quota is evaded. Let H_I denote illegal landings undertaken by a representative fisherman and let P denote the value (in monetary units) of the expected penalty perceived by the representative fisherman. Now we assume that the expected penalty is a function of illegal landings and a parameter, θ, characterising the fisherman's perception of enforcement efficiency, i.e.:

$$P = P(H_I, \theta) \tag{1}$$

This functional relation is obviously conditional on the current enforcement effort and the fines and other punishments currently stipulated in statutes and regulations. However, we will assume these to be unaffected by the change in regulatory instrument in the following analysis[7]. Furthermore, since the empirical studies we have surveyed indicate that the available 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 hereof 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 which characterises the fisherman's perception of enforcement efficiency. The regulator only knows a probability distribution for possible θ values described by the density function $g(\theta)$. This is the key information asymmetry that will be analysed in the following.

---

[7] 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. Hansen et al (2008) focus on the problem of choosing between taxes and ITQs, and for reasons of parsimony, we hold enforcement constant in the following presentation. 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 affecting the results in any substantial way. Hansen et al (2008) also assume that avoidance costs (costs incurred by fishermen so as to avoid/reduce the probability of detection) can be ignored.

4. The Model and Main Result

Hansen et al (2008) insert the possibility of illegal landings into a general stock-recruitment model of a search fishery where rising marginal costs are allowed. 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 addition, it has the additional attraction of facilitating a comparison with the Weitzman (2002) paper[8].

The main result in Hansen et al (2008) is that if compliance uncertainty is the dominating type of information asymmetry, then tax regulation is always more efficient than ITQ regulation. They stress that this result applies to the general search type fishery, where marginal fishing costs are allowed to depend on both stock and catch, and so would seem to be a generally applicable result.

Dropping time indices, the intuition of this result is illustrated graphically in Figure 3 and 4 using essentially the same set up as in Figure 1 and 2. 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 the catch (measured from recruitment R). The intersection of the two curves indicates the optimal escapement/catch level.

---

[8] There are essentially two modelling approaches within fisheries economics which differ 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 Hansen et al (2008) fall within this tradition.
.

Figure 3

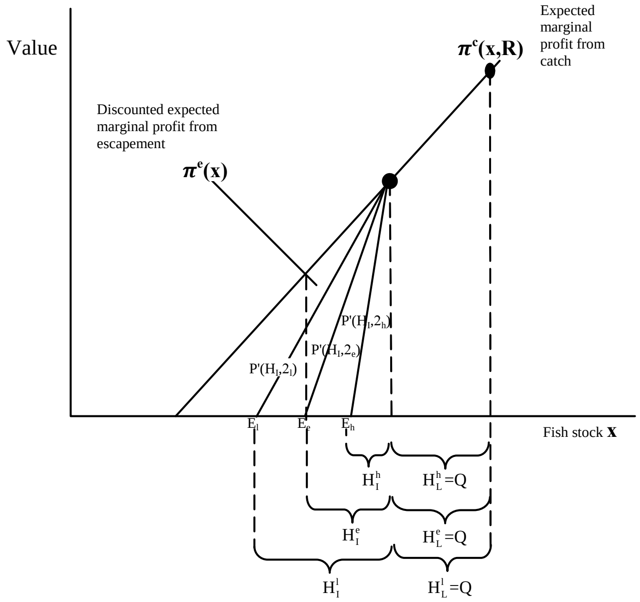
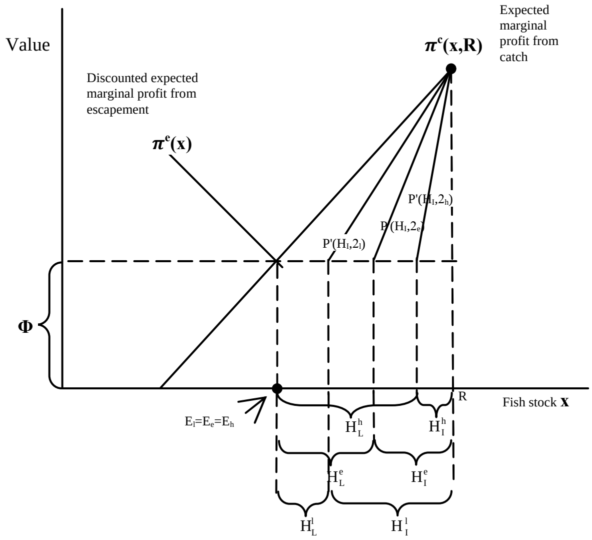


Figure 4



Here there is no information asymmetry regarding recruitment or costs so both $\pi^e(.)$, $\pi^c(.)$ and *R* are known[9] . 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 3 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, the fisherman will continue fishing illegally until marginal profit equals the expected marginal penalty. We have assumed that the regulator sets *Q* so that the optimal total catch 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 catch causing it to deviate from the optimal harvest (as the results for the θ_l and θ_h penalty function parameters

---

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

illustrate). Thus, unless the regulator knows the marginal penalty function with certainty, he expects to incur a welfare loss under quota regulation.

Now consider regulation by a landing fee illustrated in Figure 4. 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 the legal harvest exceeds expected profit from the 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.

This result is similar to that of Weitzman (2002), although the mechanism which drives it is different, so the result does not depend on the restrictive constant marginal cost assumption needed for the result in Weitzman (2002).

5. Simulations

In this section we present simulation results of the effects of moving from quantity to price regulation for the Danish cod fishery in the Kategat. Empirical studies indicate that there may be a substantial non-compliance problem, in which case we know from the previous section that a shift to tax regulation will increase aggregate profits. However, simulations are needed to obtain an indication of the magnitude of this gain.

The Danish cod fishery in the Kategat currently grosses about 6,800 tonnes/559 mill. DKK sales value per year with some 250 fishing vessels participating during a typical year (see Anon (1997) and Anon (2004)). The average gross profit per vessel (sales value less variable costs) is about 97,000 DKK. The fishery is currently regulated through a system of non-tradable quotas (see Arnason *et al.* (2000)), which are enforced by the Danish Fisheries Inspection through random harbour controls and crosschecking of logbooks and sales notes at first hand sales (see Banks *et al.* (2000)). Fishermen in violation are typically fined and profits from illegal landings confiscated. For the Danish cod fishery in the North Sea (that is subject to the same regulation and enforcement system), Banks *et al.* (2000) estimate that illegal landings constitute about 20% of total landings which suggests that there may be a comparable compliance problem for the Kategat cod fishery.

This fishery is a convenient choice for simulation in our case for three reasons. First, aggregate growth and cost functions corresponding to our theoretical model have recently been estimated by Jensen and Vestergaard (2002). Second, Jensen and Vestergaard (2002) also report a consistent estimate of the variance of the stochastic element of recruitment. Finally, Banks *et al.* (2000) not only estimate illegal landings to be 20% of total landings for the comparable cod fishery in the North Sea, but also indicate that the percentage may be as high as 30%, or as low as 10%. Svelle *et al.* (1997) find similar results for the Danish plaice fishery in the North Sea (see Table 1). These estimates suggest both a mean and a variance of the probability distribution over illegal landing percentages that a rational regulator might hold. We, therefore, have data that can be used to parameterise a simulation model incorporating illegal landings.

In the following, we specify a stochastic stock-recruitment model. With this model we simulate expected gross profit (income less variable cost) in the economically optimal steady state when this is ensured by ITQ and landing fee regulation, respectively – in both cases supported by the current enforcement system[10].

The basic simulation model equations

Jensen and Vestergaard (2002) compare various specifications of the commonly used logistic growth function and conclude that the following specification is preferred:

$$R_t = S_{t-1} + rS_{t-1}(1 - \frac{S_{t-1}}{K}) + e_t \tag{2}$$

where the intrinsic growth rate (r) is estimated to *0.79*, the carrying capacity (K) is estimated to *109,312* tonnes and e_t is normally distributed with a variance of *6,039* tonnes. Both parameters are significant (with t-values of *10.47* and *2.22*, respectively), no autocorrelation is detected and the explained proportion of data variation is substantial ($R^2 = 0.79$). The estimation seems statistically sound and the estimated intrinsic growth rate is consistent with other estimates in the literature (varying between *0.68* and *0.92* for cod (see Arnason *et al.* (2000)).

Jensen and Vestergaard (2002) assume the following commonly used profit function (see e.g. Arnason *et al.* (2000)):

---

[10] Note that we compare landing fees to ITQs. The current system of regulation by non-transferable quotas is presumably less efficient than ITQs, but the focus here is on the gain from shifting to tax regulation, and so we compare with the most efficient type of quota system.

$$\Pi_t = p_t H - \frac{c(H_t)^2}{R_t} \tag{3}$$

The marginal cost parameter (*c*) is calibrated for the representative fisherman to *8.77* (thousand *DKK/tonnes*) using accounting data for 1997 (see Anon (1997)) and ICES catch and recruitment data for 1997 (see Anon (2004)). In the following simulations, we assume that the average sales price (*p*) is *10.15* (thousand *DKK/tonnes*) corresponding to the average sales price in the calibration year.

Finally, we assume that the representative fisherman perceives the following quadratic penalty function:

$$P(H_{It}) = \frac{a}{2}(H_{It})^2 \tag{4}$$

We assume that the regulator holds a uniform distribution[11] over possible *a* values that generates a span of illegal landing proportions between 10.4% and 31.8% in the optimal steady-state under quota regulation, which results in an expected proportion of illegal landings of 20.2% (both corresponding closely to the values suggested by Banks *et al.* (2000) and Svelle *et al.* (1997)).

When evaluating the basic model equations, the estimated growth function used seems reasonably well-founded statistically, whereas parameters of both the cost and penalty function are only calibrated. In addition, the estimates we utilize may be subject to the more fundamental data problem caused by illegal landings (i.e. to the extent that data on recruitment and catch used by Jensen and Vestergaard (2002) are distorted by illegal landings, the estimated parameters may be biased). Thus, our results should be interpreted with caution. However, since our focus is on the relative performance of the two instruments – and not on absolute levels of welfare and profit –the results reported here presumably will be less sensitive to this type of parameter bias.

The simulation procedure

---

[11] The uniform distribution is chosen because neither Banks *et al.* (2000) nor Svelle *et al.* (1997) indicate the 20% estimate is more likely than other estimates within the indicated span.

We wish to calculate expected annual profit in the optimal steady-state[12] given that the regulator uses ITQs or landing fees. The basic model is run with interaction between periods defined by the stock recruitment function, (18), where a random variable is drawn independently for each period from a normal distribution with the specified variance (6,039 tonnes). We assume no discounting (i.e. $a=1$ in equation (5)) so that the profit aggregate to be maximised can be expressed as average profit per period. The mathematic simulation model can be found in the appendix.

Under quota regulation and landing fees, fishermen maximize expected profit. Under quota regulation, a restriction which states that legal landings are less than or equal to the quota is included. The regulator chooses the value of the regulatory instrument that maximizes expected profit in all time periods, given optimal values of the regulatory instruments in all time periods. The problem is a dynamic optimization problem solved by standard recursive methods.

Practical optimisation and results

We solve the optimisation problem, (see appendix), using SAS-NLP (the programme is available on request) for a 1000 period span and using 100 evaluations of the normal distribution when maximising the fisherman’s expected profit. Since the optimal path approaches optimal steady-state, we iterate the first period initial stock until it is equal to the mean stock for the following periods (ensuring that the simulation is initiated in the optimal steady-state). In addition, the objective function includes the final stock (minus first period initial stock) valued as the marginal profit of the first period’s initial stock. This ensures that the simulation is also terminated in the steady-state. Mean profits include this valuation of the stock change over the simulated span of periods[13]. Simulations were run for *G*-values of 1, 2 and 3 and the results are summarised in Table 2 below.

---

[12] We choose to compare steady state values in order to avoid the complications of comparing dynamic adjustment paths.

[13] Because of the stochastic recruitment element, the initial and final stock are not in general equal and the value of this change in fish stock should be credited profit of the simulated period.

Table 2. Simulation results for the Danish cod fishery in the Kategat

	Quota regulated steady state, annual means				Tax regulated steady state, annual means				% gross profit increase with tax regulation
	Profit (1000 DKK/ year)	Total catch (1000 tonnes)	% illegal catch	Ultimo stock (1000 tonnes)	Profit (1000 DKK/ year)	Total catch (1000 tonnes)	% illegal catch	Ultimo stock (1000 tonnes)	
G=1(uniform rate)	156.44	20.00	20.2%	70.0	164.34	20.72	16.8%	61.7	5.05%
G=2 (variable rate)	165.19	20.96	16.4%	61.31	165.35	20.97	16.5%	61.33	0.10%
G=3 (variable rate)	165.19	20.96	16.4%	61.31	165.35	20.97	16.5%	61.33	0.10%

Note: Annual values are averaged over the 1000 period simulation span.

For the Danish Kategat cod fishery, it seems that shifting from quantity regulation to tax regulation generates a noticeable gain of about 5% of gross profit when uniform rate instruments are applied ($G = 1$). Furthermore, and perhaps somewhat surprisingly, the gain from shifting to tax regulation almost disappears when more refined policy rules are applied (i.e. for $G > 1$ where tax rates/total quota are adjusted in response to the previous period's final stock size, which the regulator learns at the beginning of each period). Finally, it is clear that there is virtually no gain from further refinement of the first-order approximation (the linear quota/rate setting rule $G = 2$), and so increasing G over 2 does not noticeably increase regulatory efficiency.

When these results are considered more closely, they turn out to be quite illuminating. Seen from the regulator's point of view, the system is characterised by uncertainty about both recruitment and illegal landings. However, the regulator observes previous period stocks and so implicitly observes the sum of realised recruitment and illegal landings with a lag of one period. This implies perfect observation of recruitment (in the sense that there is no information asymmetry in relation to fishermen) and that illegal landings are observed imperfectly (i.e. with a one period lag relative to fishermen). Under uniform quota regulation (G=1), this observation is not utilised and, therefore, the mean profit is reduced by deviations from the regulator's expected values of both lagged recruitment and current illegal landings. The uniform rate tax policy (G=1) does not utilise this information either, but the generated incentives automatically ensure that profit is not reduced by deviations from the level of illegal landings expected by the regulator. Thus, the 5.05% gain when shifting from ITQs to taxes for G=1 is the result of eliminating the distortions caused by deviations in current illegal landings from the regulator's expectation. When the regulator utilises his knowledge of previous period stocks ($G > 1$), it becomes possible to set quotas that neutralise all of the distortion caused by stochastic recruitment and part of the distortion caused by illegal landings – since they are implicitly observed with a one period lag. Thus, the 5.59% gain when moving from a uniform quota (G=1) to a dynamic quota setting (G>1) reflects complete neutralisation of recruitment distortions and partial (one period lagged) neutralisation of illegal landing distortions. Moving from a uniform tax rate (G=1) to a dynamic tax setting ($G > 1$) results in the elimination of the recruitment distortion (resulting in a gain of 0.64%), since the illegal landings distortion has already been neutralised by the uniform rate tax. Finally, the difference between the distortions under quota and tax regulation for $G > 1$ is that taxes eliminate in the current period, while under quotas, the illegal landing distortion is taken into account one period later. With this in mind, it is perhaps not so surprising that the value of correcting for illegal landings immediately rather than with a one period lag is relatively small (a gain of only 0.10%).

The potential efficiency gains from correcting the different underlying information asymmetries are summarised in table 3.

Table 3.Profit gains from correcting information asymmetries for the Danish Kategat cod fishery*

Elimination of all compliance uncertainty	5.05%	
Elimination of all compliance uncertainty and all recruitment uncertainty	5.69%	0.64% (Marginal effect of eliminating recruitment uncertainty)
Elimination of compliance uncertainty with 1 period lag and all recruitment uncertainty	5.59%	0.10% (Marginal effect of going from lagged to complete elimination of compliance uncertainty)

* All gains in percentage of profit with uniform quota regulation.

Two observations are worth mentioning for the studied fishery. First, the profit loss associated with recruitment uncertainty is an order of magnitude smaller than the loss associated with compliance uncertainty. Second, when the last period's final stocks are observed perfectly by the regulator, a large part of the gain from eliminating compliance uncertainty can be captured within a quota system, if the regulator adopts a dynamic quota setting rule that in effect eliminates these uncertainties with a one year lag.

The first observation is interesting because it indicates that, once the profit loss from uncertainty about compliance has been eliminated, the gain from eliminating the effects of ecological uncertainty is relatively small[14]. Thus, for this fishery, basing instrument choice on an analysis of compliance uncertainty (and ignoring ecological uncertainty where quotas may be the preferred instrument) seems unproblematic. This may just be an artefact of the specific fishery studied here – but we suspect that this is not the case. Since the reviewed empirical studies (see section 3) suggest that illegal landings are generally of the magnitude assumed here, we suspect that uncertainty associated with non-compliance may dominate ecological uncertainty in many fisheries.

---

[14] The calculated 0.64% reflects the value of eliminating the effects of ecological uncertainty about lagged recruitment. An exact calculation using a version of the model where fishermen observe current recruitment (corresponding to the information asymmetry assumed by Weitzman (2002) results in a gain of 0.58% of gross profit when eliminating the effects of ecological uncertainty about current recruitment in the modelled fishery.

The second observation is perhaps even more interesting because it indicates that the tax advantage that is shown analytically in this paper (and in Weitzman (2002)) is relatively small in size. Thus, in the studied fishery, tax regulation only has a significant advantage over quotas when the regulator's stock measurements are uncertain[15]. For the reasons cited above, we suspect that this too may be more than just an artefact of the specific fishery studied here.

In summary, the gain from neutralising the distortions caused by illegal landings in the Danish cod fishery in the Kategat is about 5% of gross profit. When the last period's final stocks are observed perfectly by the regulator, a large part of this gain can be captured within a quota system if the regulator adopts a dynamic quota setting rule. For this particular fishery, the main advantage of tax regulation over quotas is that the regulator does not have to observe stocks and adjust quotas accordingly in order to neutralise the distortions caused by asymmetric information about illegal landings. This can instead be achieved automatically with a uniform rate tax system. Imperfect observation reduces the efficiency of correcting for illegal landings through quota adjustment – while the tax instrument's efficiency remains unaffected. Thus, depending on the precision with which the regulator is able to observe the previous period's final stock, we find the gain from shifting to tax regulation from ITQs to be between 0.1 and 5% of the gross profit for the Danish cod fishery in the Kategat.

6. Conclusion

When the regulator is more uncertain about the biological reproduction function than fishermen, Weitzman (2002) has shown that price regulation performs better than quantity regulation for a fishery where marginal harvest costs do not depend on recruitment.

In this paper, we illustrate that Weitzman's pro-tax result does not generalise to the more common search fishery where marginal costs may depend on recruitment. On the other hand, based on a number of empirical studies, we argue that regulator uncertainty about non-compliance

---

[15] The tax advantage generated by non-compliance uncertainty that is shown analytically in this paper only amounts to 0.10% of gross profit of the studied fishery. Using the version of the model where fishermen observe current recruitment, we have also calculated the gain from eliminating ecological uncertainty relative to the regulator observing recruitment with a one period lag (corresponding to the analytical set up used in Weitzman (2002)). For the modelled fishery, this results in a gain of 0.28% of gross profit. However, it is not generally possible for the regulator to capture all of this gain in a search fishery with increasing marginal costs, so this estimate is an upper bound on the gain from switching to landing fees. Further, as shown in section two, quotas may be the preferred instrument, in which case a switch to landing fees would in fact reduce gross profit. The point to be made here is that, irrespective of the type of uncertainty considered, the profit gain from switching to landing fees in the studied fishery is small, as long as the regulator can observe fish stocks accurately (and uses this information when setting annual total quotas).

with regulations may also be an important source of 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 applies in the general search fishery case.

In this paper, we develop a stochastic stock-recruitment simulation model for the Danish cod fishery in the Kategat corresponding to a theoretical model. For this fishery, rather uncertain empirical studies indicate that illegal landings probably constitute around 20% of total landings, though the percentage may be as low as 10% or as high as 30%. With the information asymmetry generated by this estimate of illegal landings, our simulations suggest that the gain from eliminating this asymmetry is about 5% of the gross profit, while the gain from eliminating recruitment uncertainty is an order of magnitude smaller. If fish stocks can be estimated accurately by the regulator, it is possible to capture most of the gain from eliminating compliance uncertainty within an ITQ system by implementing an optimal rule for adjusting the allowed total quota to new stock estimates. However, if the regulator’s fish stock estimates are highly uncertain, this gain can only be captured by shifting to price (landing fee) regulation. Since empirical studies suggest that illegal landings generally are of the magnitude assumed in our simulations, we suspect that results parallel to ours may apply in many other fisheries.

Literature

Alverson, D.J,.m Freeberg, S.A., Murawski, S.A. and Pope, J.G. (1994): A Global Assessment of Fisheries By-Catch and Discards, FOA Fisheries Technical Paper, No. 399

Andersen, P. and Sutinen, J.G. (1983): Fisheries Law Enforcement and International Trade in Seafood, in Melteff, B.R. (ed): Proceedings of the International Seafood Trade Conference, Alaska Sea Grant Report no. 83-2, University of Alaska, pp. 509-521.

Anderson, L.G. and Lee, D.R. (1986): Optimal Governing Instruments in Natural Resources, American Journal of Agricultural Economics, 68, pp. 679-690.

Anderson, L.G. (1987): A Management Perspective of the Economics of Fisheries Management, Marine Resource Economics, 4, pp.123-131

Anderson, L.G. (1989): Enforcement Issues in Selecting Fisheries Management Policy, Marine Resource Economics, 6, pp.261-277.

Anon (1997): Fiskeriregnskabsstatistik, SJFI.

Anon (2004): Report of the Working Group on the Assessment of Demersal Stocks in the North Sea and Skagerak, ICES

Arnason, R. (1990): Minimum Information Management in Fisheries, Canadian Journal of Economics, 9, pp.630-653.

Banks; R., James, C., Winnard, K., Buisman, E., Hoefnagel, E., Taal, R, Churchill, C. and Hedley, C. (2000); The Costs and Benefits of Compliance with Regulations in Northern EU Fisheries, London, Nautilus Consultants.

Becker, G.S. (1968); Crime and Punishment: An Economics Approach, Journal of Political Economy, 86, pp.169-212

Charles, A.T. (ed) (1993): fishery Enforcement: Economic Analysis and Operational Models, Halifax: Ocean Institute of Canada.

Charles, A.T., Mazany, R.L. and Cross, M.L. (1999): Economics of Illegal Fishing: A Behavioural Model, Marine Resopurce Economics, 14, pp.95-111

Clark, C.W. (1985): Towards a Predictive Model for the Economic Regulation of Commercial Fisheries, Canadian Journal of Fisheries and Aquatic Science, 37, pp. 1304-1312

Clark, C.W. (1990): Mathematical Bioeconomics. The Optimal Management of Renewable Resoueces. New York: John Wiley and Sons

Clark, C. and Munro, G. (1975): Economics of Fishing and Modern Capital Theory: A Simplified Approach, Journal of Environmental Economics and Management, 1, pp. 91-106.

Conrad, J.M. an d Clark, C.W. (1991): natural Resource Economics. Notes and Problems. New York, Johnn Wiley and Sons.

Copes; P. (1986): A Critical Review of Individual Quotas as a Device in Fisheries Management, Land Economics, 63, pp. 278-293

Hansen, L.G., Jensen, F. and Russell, C. (2008): The Choice of Regulatory Instruments when there is Uncertainty about Compliance with Fisheries Regulation, American Journal of Agricultural Economics, 90, pp. 1130-1142

Milliman, S.R. (1986): Optimal Fishery Management in the Presence of Illegal Activity, Journal of Environmental Economics and Management, 13, pp.363-383

Neher, P.A. (1990): Fishing with Costly Management, in Rodrigues, A.J.M.G.: Operations Research and Management in Fishing, Dordretch: Kluwer Academic Publishing, pp. 99-110.
Stigler, G.S. (1971): Theories of Economic Regulation, Bell Journal of Economics, 2, pp. 3-21

Sutrinen, J..G. and Andersen, P. (1985): The Economics of Fisheries Law Enforcement, Land Economics, 61, pp. 387-397

Svelle, M, Aarefjord; H., Heir, H.T. and Øverland, S. (1997): Assessment Report on Fisheries and Fisheries Related Species and Habitats Issues, Bergen, Ministry of the Environment.

Triumble, R.J., Neilson, J.D., Browning, W.R. and McCaughan, D.A. (1993); Atlantic Halibut and Pacific Halibut and their American Fisheries, Canadian Bulletin of Fisheries and Aquatic Science, 227, pp. 62-67

Weitzman, M.L. 81974): Prices vs Quantities, Review of Economic Studies, 41, pp. 477-492.

Weitzman, M. L (2002): Landing Fees vs. Harvest Quotas with Uncertain Fish Stocks, Journal of Environmental Economics and Management, 42, pp.325-338.

Wilen, J.E. (2000): Renewable Resource Economists and Policy: What Difference Have We Made, Journal of Environmental Economics and management, 39, pp. 306-327

Appendix

The representative fisherman maximises expected profit given the imposed regulation in each period and so under quota regulation solves the following problem:

$$\underset{H_{Lt},H_{It}}{Max}\left(p_t(H_{Lt}+H_{It})-\frac{c(H_{Lt}+H_{It})^2}{R_t}-\frac{a}{2}(H_{It})^2\right) \tag{A1}$$

s.t.

$$H_{It}\leq Q_t \tag{A2}$$

Under landing fee regulation, the representative fisherman solves:

$$\underset{H_{Lt},H_{It}}{Max}\left(p_t(H_{Lt}+H_{It})-\Phi H_{Lt}-\frac{c(H_{Lt}+H_{It})^2}{R_t}-\frac{a}{2}(H_{It})^2\right) \tag{A3}$$

First-order conditions for any given period *t* are easily derived, and since the fisherman ignores future periods, maximising expected values only involves integrating over the normally distributed e_t for the current period.

The regulator's maximisation problem for any given period, *t*, can be expressed as:

$$\underset{Z_t}{Max}\left(\Pi^E(H^Z(Z_t),R_t)+aE_{\varepsilon_t}\left[V^*(F(R_t-H^Z(Z_t),\varepsilon_{t+1}))\right]\right) \tag{A4}$$

where Z_t is the value of the stipulated regulatory instrument (Q_t or Φ_t) and $H^Z(Z_t)$ is the total catch implied by the solution to the fisherman's problem given by (A1) and (A2) or (A3) for the applied instrument value. Finally, $V^*(.)$ is the expected sum of future profit given optimal values of the regulatory instrument in all future periods.

The regulator's problem is a dynamic optimisation problem that can be solved numerically by standard recursive methods that yield a numerical approximation of the $V^*(.)$

function. Here we follow a slightly different approach that takes outset in the following equation (A5) found by reformulating (A4) after inserting $R_t = F(S_{t-1}, \varepsilon_{t+1})$.

$$V^*(S_{t-1}, \varepsilon_t) = \underset{Z_t}{Max}\left(\Pi^E(H^Z(Z_t), F(S_{t-1}, \varepsilon_t)) + aE_{\varepsilon_t}\left[V^*(F(F(S_{t-1}, \varepsilon_t) - H^Z(Z_t), \varepsilon_{t+1}))\right]\right) \tag{A5}$$

Equation (A5) implicitly defines the optimal instrument value, Z_t^*, as a function of S_{t-1} and we may therefore restate the regulator's problem as finding the function $Z^*(S_{t-1})$ that maximises average profit (π), i.e.:

$$\underset{Z^*(.)}{Max}\sum_{t=1}^{T}\Pi^E(H^Z(Z^*(S_{t-1})), R_t)/T \quad \text{for } T \to \infty \tag{A6}$$

s.t.

$$R_t = S_{t-1} + rS_{t-1}(1 - \frac{S_{t-1}}{K}) + e_t \tag{27}$$

Around any given S_{t-1} value (e.g. the mean optimal steady-state value) such a function may be approximated by a polynomial, i.e. $Z^*(S_{t-1}) \approx \sum_{g=0}^{G} a_g (S_{t-1})^g$. With this polynomial specification, the optimisation problem (A6) and (A7) is readily solvable (using standard optimisation routines) for given T and G with the approximation error falling as T and G increase (see, e.g. Sandal and Steinshamn (1997) for derivation of approximation results for fisheries models that with some modification also apply here).