INSTITUTE OF FOOD AND RESOURCE ECONOMICS
UNIVERSITY OF COPENHAGEN

FOI Working Paper

Instrument Choice when Regulators are Concerned about Resource Extinction

Lars Gårn Hansen
Frank Jensen
Clifford Russell

2011 / 6

FOI Working Paper 2011 / 6

Instrument Choice when Regulators are Concerned
about Ressource Extinction

Authors: Lars Gårn Hansen, Frank Jensen, Clifford Russell

Institute of Food and Resource Economics

University of Copenhagen

Rolighedsvej 25

DK 1958 Frederiksberg DENMARK

www.foi.life.ku.dk

Instrument Choice when Regulators are Concerned about Resource Extinction*

By Lars Gårn Hansen[a,*] , Frank Jensen[a] and , Clifford Russell[b,c]

February, 2011

revised July, 2011

[a] Institute of Food and Resource Economics, University of Copenhagen

[b] Bowdoin College, Brunswick, ME 04011, USA

[c] Vanderbilt University, Nashville, TN 37212, USA

[*] Corresponding author: lgh@foi.dk

Abstract: In this paper we undertake a systematic investigation of instrument choice when preventing a population collapse rather than maximizing industry profit is the overriding concern. Contrary to what seems to be the general consensus we find that landing fees do provide more effective insurance against extinction than quotas under more or less the same conditions as those implying that landing fees are better at maximising industry profit. Thus, the efficiency of the regulatory instrument mainly depends on the basic information asymmetries characterizing the fishery, and is not sensitive to whether the regulators total catch goals are set according to economic or precautionary principles.

* We are grateful to Dale Squires for helpful comments and suggestions on earlier versions of the paper. All remaining errors and omissions are our own.

1. Introduction

Threatened extinctions of fish stocks capture headlines periodically and not without reason. Collapses of locally important fishing stocks have been experienced in a number of cases, often with dramatic consequences for the affected fishermen and local communities. An example of such a collapse is the Atlanto-Scandic herring stock at the end of the 60s (see Primack (1998)) and a number of fisheries are currently threatened. [1] The practical reality for many fishery regulators is in fact dominated by the concern that fish stocks have been reduced to a level where the resource itself may be threatened and therefore possibly also the surrounding ecosystem, fishing industry and local communities[2]. For these regulators the industry profit objective that is the dominant welfare measure in the fisheries economics literature may seem too narrow. While there is a (mainly biological) literature that provides a foundation for setting goals when the regulator is concerned about the risk of a extinction there is little guidance to be found in the literature as to the choice of regulatory instrument in this situation. We will address this issue in the following.

The biological literature presents a picture of what a fish stock collapse is and how it may occur (see Soule (1987), Raup (1991), Quammen (1996),Primack (1998), Hutchings (2000), Hutchings and Reynolds (2004) and Pauly (2009)). At the core of this literature is the recognition that species viability is determined by stochastic processes, and that the key viability concept should be cast in terms of probability. Of primary relevance here is that low population levels become risky because of stochastic variation affecting the biological regeneration process characterising the fish stock. This literature has provided the operational concept of maximum

[1] Examples of threatened fisheries are numourous e.g. Tridacna gigas on many Pacific islands (Tegner et al,1996), Bolbometopol mullcatum on many Indo-Pacific shores (Roberts and Hawkins,1999), Stereolepis gigas on parts of the California cost (Jennings et al ,2001), Diptures tatis in the Irish Sea (Dulvy et al, 2000), Pterapogan kauderni in India (Tegner et al,1996), Cod in the North Sea (Banks et al,2000).

[2] For example within the EU the precautionary principle dominates(see Holden (1994)). This principle states that regulators must ensure that a fish stock do not collapse (see Anon (2008))

allowable catch (reflecting the largest acceptable probability of extinction during the following seasons) which in fact is the foundation for e.g. Anon (2008) recommendations and the EU common fisheries policy stock goals and harvest quotas set according to the precautionary principle. Though the focus of this literature is far from the choice between regulatory instruments, this choice is discussed occasionally in an informal way, and output quotas are almost exclusively recommended (see e.g. Primack (1998), Raup (1991) and Hutchings (2000)). The flavour of the underlying argument is that with an output quota the catch is certain while this is not the case when a landing fee is used, and so the quota instrument helps reduces uncertainty about the resulting post harvest stock levels.

In the fisheries economics literature a handful of authors have considered the potential collapse of fish stocks (see Clark (1990), Bulte and van Kooten (1999) , Bjørndal et al (2004), Standal (2006), Ekerhovd (2008) and Clark et al (2010). These studies all use a deterministic biological reproduction function that allows for a non-concave interval of negative growth at low stocks implying a minimum viable population level, under which the stock will collapse. The choice of regulatory instrument is once again not the main focus of this literature, but Bulte and van Kooten (1999), Bjørndal et al (2004) and Ekerhovd (2008) do recommend the use of quotas without any discussion. The underlying argument is the same as in the biological literature. A quota ensures that the regulators catch target is met with certainty while this does not hold for a fee.

A number of recent papers in the fisheries economics literature have investigated which regulatory instrument is best at maximising industry profit under various types of regulatory uncertainty (Weitzman (2002), Jensen and Vestergaard (2003), Hannesson and Kennedy (2005), Hansen (2008), Fisher and Laxminarayan (2010) and Hansen et al (2008)). Here Weitzman (2002) is the paper of primary interest since he shows that if uncertainty about the biological regeneration process dominates, then landing fees are preferred to quotas. This result contrasts with the quota recommendation coming out of the above mentioned literature. However, Weitzman (2002) studies a fish stock that is not threatened by extinction and where the regulators problem is to find the regulatory instrument that is best at fine tuning harvest to maximise industry profit. Thus this result seems of limited relevance when the regulators problem is to find the instrument that provides the most effective insurance against a threat of extinction.

This is our point of departure. In this paper we address the question of how best to insure against extinction by explicitly introducing regulatory concern about population collapse into a stochastic stock-recruitment model of a regulated search fishery. Contrary to what seems to be the general consensus, we find that landing fees do provide more effective extinction insurance than quotas under more or less the same conditions as those implying that landing fees are better at maximising industry profit. Specifically, we show that the pro fee result for a profit maximizing regulator under biological uncertainty from Weitzman (2002) extends to regulators that are concerned about extinction.

The paper is organised as follows. In section 2 we develop a general stock-recruitment model, while section 3 describes the problem of the regulator. Second 4 present the main results, while section 5 offers conclusions and qualifications.

2. The Model

We develop a dynamic stock-recruitment model in the Berverton-Holt tradition for a search fishery that allows for ecological uncertainty. This makes possible a detailed and explicit representation of the interactions between parameters about which there is uncertainty and regulatory constraints.

Let R_t, denote the stock of fish available at the beginning of fishing period t before fishing starts (which we will call recruitment) and let S_{t-1} denote the stock left at the end of period t-

1 after fishing has stopped. Finally let ε_t denote stochastic effects on the fish stocks of variations in, for example, water temperature and weather so that: [3]

$$R_t = R(S_{t-1} + \varepsilon_t) \tag{1}$$

Thus we assume that natural growth takes place between fishing seasons and what we call recruitment is stock at the end of the previous fishing season plus natural growth between the two seasons.[4]. Harvest during period *t* (denoted H_t) reduces fish stock during the period so that:

$$S_t = R_t - H_t \tag{2}$$

Clearly harvest is bounded above by recruitment and bellow by zero:

$$0 \le H_t \le R_t \tag{3}$$

We assume that ε_t are independently distributed with unbounded distribution functions $g_t(.)$ and that $E[\varepsilon_t] = 0$ [5]. 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 variations in ecosystem conditions. In the following we will assume that:[6]

[3] Note that the stochastic term is assumed to be additive. The reason for this will be clear in connection with (4) A multiplicative error term is common within fisheries (see e.g. Reed (1979)) but the results in the present paper generalize to non-additive error terms.

[4] This definition of recruitment is typical in the stochastic bioeconomics tradition(see e.g. Reed (1979) and Weitzman (2002)). Other studies define recruitment as the *addition* to the stock between close of one and the beginning of the next fishing season.(see Clark (1990)

[5] Results in the following easily generalize to non-additive correlated stochastic shocks, but these assumptions simplify the presentation.

[6] Now we see the reason for the additive term. The conditions in (4) make an additive term natural.

$$\begin{aligned} R(S_{t-1}+\varepsilon_t)=0 \quad \text{if} \quad S_{t-1}+\varepsilon_t < S^0 \\ R(S_{t-1}+\varepsilon_t)>0 \quad \text{if} \quad S_{t-1}+\varepsilon_t \geq S^0 \end{aligned} \tag{4}$$

so that the recruitment function is discontinuous at S^0 (if $S^0 > 0$) reflecting that there is a critical level of stock below which regeneration is not possible[7]. If the stock through a combination of fishing and natural shocks is reduced under this critical level (i.e. if $S_{t-1}+\varepsilon_t < S^0$) at the end of a fishing season then it is no longer able to recover because gross recruitment becomes smaller than mortality and the stock declines to zero. This may take several fishing seasons, but the process is irreversible once initiated and so assuming an immediate plunge to zero seems a parsimonious way of capturing the ever present risk of extinction.[8] Thus, if $S_{t-1}+\varepsilon_t < S^0$ at some point in time, then the stock disappears and is not available for fishing in any future periods. Provided S^0 is close to or equal to zero then the fish stock has substantial regenerative power and can recover from substantial overfishing and unfavourable natural shocks to its ecosystem. If, on the other hand, $S^0 >> 0$, then the stock is more vulnerable to overfishing and natural shocks. A useful way of expressing vulnerability is the risk of extinction associated with a known size of the 'end of period' stock S_{t-1}. Letting $P(S_{t-1})$ denote this risk, we have that:

$$P(S_{t-1}) = \int_{-\infty}^{S^0 - S_{t-1}} g_t(\varepsilon_t)d\varepsilon_t \tag{5}$$

[7] This is the substantive difference in the basic model compared to Weitzmann (2002), who assumes that the fish stock cannot become extinct (i.e. that $R_t > 0$ for all realizations of ε_t irrespective of the initial stock value S_{t-1}.

[8] At S^o the growth function is defined as subject to critical dispensation (see Clark (1990) and Ekerhovd (2008) for an introduction to the concept).

is the risk of extinction associated with this stock size which by definition is always positive[9].

We assume that fishermen have constant returns to scale, but that fishing costs depend on the size of the fish stock because of search costs (see e.g. Neher (1990)).[10] Following Hannesson and Kennedy (2005), let $\pi(x)$ be the marginal profit of harvest for the representative fisherman when x is the current stock of fish. At the beginning of the fishing season the fish stock equals recruitment ($x = R_t$). However, as harvest progresses stock is reduced (by one unit for every unit harvested) and so marginal profit is reduced as fishing progresses over the season. The total profit of harvesting H_t during the season ($\Pi(H_t, R_t)$) is found by integrating marginal profit from initial stock recruitment available at the beginning of the period (R_t) to the stock available at the end of the period (R_t-H_t):

$$\Pi(H_t, R_t) = \int_{R_t - H_t}^{R_t} \pi(x)dx \tag{6}$$

Fishermen observe current fish stock during the season as they fish (in the sense that they observe the realized relationship between effort and catch during the fishing season). Thus, the representative fisherman in effect observes recruitment with certainty. Without regulation the fisherman chooses the catch level that maximises his profit (given the realisation of ε_t) where the first order condition for maximising current profit (6) is:

$$\frac{d\Pi_t}{dH_t} = \pi(R_t - H_t) = 0 \tag{7}$$

[9] Note that the corresponding risk of extinction in the model studied by Weitzmann (2002) in contrast is zero for all possible initial stock values S_{t-1}.

[10] We include stock effects for generality. Note however that marginal stock effects are small for most species (see Clark et al (2010)).

Thus subject to the constraint (3) fishermen stop catching fish when the same end of season stock is reached ($\pi^{-1}(0)$ where π^{-1} is the inverse function implicitly defined in (7)) irrespective of the initial natural shock to recruitment. Letting H_t^0 denote the catch fishermen find optimal in the unregulated situation by (3) and (7) we have that[11]:

$$H_t^0 = Max(R_t - \pi^{-1}(0), 0) \tag{8}$$

Regulation and the distribution and timing of information

The basic regulatory set up and distribution of information follows Weitzman (2002). Initially the regulator chooses between two regulatory instruments, a landing fee, Φ_t, that representative fishermen must pay per unit harvest, or a maximum harvest quota, Q_t, that the representative fisherman must respect.[12] The regulator may adjust the value of the chosen instrument at the beginning of each period. At the beginning of the period when the regulator sets the value of the chosen regulatory instrument (Φ_t or Q_t), he observes the fish stock, S_{t-1}, but not recruitment R_t. Thus, while fishermen observe recruitment, the regulator only knows the probability distribution ($g_t(.)$) over possible states of nature ε_t that will apply at the end of the season when next period´s stock is recruited. Given the value of the regulatory instrument set by the regulator at the beginning

[11] We assume that marginal profit is zero before the entire stock is caught i.e. $\pi^{-1}(0) > 0$ so that the upper bound on catch ($H_t^0 \le R_t$) is always satisfied.

[12] We ignore issues of enforcement and compliance and assume that regulations are perfectly enforced. We also assume that quotas are tradable. When quotas are tradable all individual fishermen perceive the same shadow price of quotas and so (as for fee regulation), the representative fisherman subject to quota regulation represents a perfect aggregate of an ITQ regulated industry (see Hansen et al (2008))).This gives a parsimonious formulation of the problem of instrument choice.

of the period the fisherman chooses the catch level that maximises his profit (given the realisation of ε_t).

Under quota regulation the fisherman simply sets:

$$H_t^Q = Min(Q_t, H_t^0) \tag{9}$$

Thus, the effect of the chosen instrument value on harvest can *not* be predicted with certainty by the regulator (even though we assume perfect compliance). Though the regulator knows with certainty that $H_t^Q \leq Q_t$ there is generally a positive probability that $H_t^Q = H_t^0 < Q_t$ since H_t^0 depends on ε_t about which the regulator is uncertain. The resulting period *t* total profit is $\Pi(H_t^Q, R_t)$. The profit expected by the regulator at the beginning of period *t* is the expectation of this taken over ε_t ($\underset{\varepsilon_t}{E}\left[\Pi(H_t^Q, R_t)\right]$) where both H_t^Q and recruitment R_t depend on ε_t

Under landing fee regulation the fisherman chooses the catch that maximises current period profit[13] i.e.

$$\underset{H_t}{Max}\left(\int_{R_t-H_t}^{R_t} \pi(x)dx - \Phi_t H_t\right) \tag{10}$$

The first-order condition is:

[13] We make the standard assumption that fishermen are myopic in the sense that they disregard the effect that current catch has on future profit. This assumption is reasonable in situations where the number of fishermen extracting from the common fish stock is large.

$$\pi(R_t - H_t) - \Phi_t = 0 \tag{11}$$

so that $R_t - H_t = \pi^{-1}(\Phi_t)$.We can define the resulting optimal catch as the following function of recruitment, fee rate and profit function parameter. Inserting (4) this implies that:

$$H_t^{\Phi}(\Phi_t, R_t) = Max(R_t - \pi^{-1}(\Phi_t), 0) \tag{12}$$

Thus, both the resulting harvest and aggregate fishing season profit depends on ε_t about which the regulator is uncertain.

.

3. The Regulator

It is useful as a reference point to introduce the regulator's problem of maximising the sum of discounted expected future profit the policy choice criterion assumed in most of the fisheries economics literature (and in all of the above mentioned contributions on instrument choice). The expected sum of discounted future profits at the beginning of period *t* is:

$$V(S_{t-1}) = \sum_{\tau=0}^{\infty} a^{\tau} E\left[\Pi(H_{t+\tau}, R_{t+\tau})\right] \tag{13}$$

(13) is maximised subject to (1),(2) and (3), where *a* is the discount factor, and all probabilities and expectations are conditional on the information available to the regulator at the beginning of period *t*. Note specifically that this expression takes into account that there is a risk of the resource disappearing. The solution to the regulator's dynamic programming problem at the beginning of

period t where the value of the instrument has to be set is conditional on recruitment at the beginning of the period (R_t), the distributions held over ε_t and $\varepsilon_{t+1}, \varepsilon_{t+2} \ldots$, and also conditional on the harvest-instrument function of the chosen instrument. Let $H_t^I(I_t)$ denote the harvest-instrument function where I indicates the chosen instrument (i.e. under quota regulation the harvest-instrument function is given by (9) and under fee regulation by (12)). Corresponding to (13), the recursive formulation (the Bellman equation) of the dynamic optimisation problem (see e.g. Ljungqvist and Sargent (2000)) becomes:

$$V^{I*}(S_{t-1}) = \underset{I_t}{Max} \left(E\left[\Pi(H_t^I(I_t), R_t) \right] + aV^{I*}(R_t) - H_t^I(I_t) \right) \tag{14}$$

The value function, $V^{I*}(S_{t-1})$, is the expected sum (taken over $\varepsilon_t, \varepsilon_{t+1} \ldots$) of discounted future profit under the optimal policy, conditional on S_{t-1}, and $V^{I*}(R_t - H_t^I(I_t))$ is the corresponding expectation (taken over $\varepsilon_{t+1}, \varepsilon_{t+2} \ldots$). Let H_t^{I*} denote a solution to (14). As noted above the probability that the resource disappears at the end of period t conditional on end of period stock is $P(S_t)$ (by equation (5)). This implies a $P(S_t)$ probability of R_{t+1} being equal to zero and so a $P(S_t)$ probability of the (presumably zero) profit associated with the stock disappearing. This probability feeds into the next period´s expected profit and so on. Since this risk is influenced by the harvest during season t chosen by the regulator at the beginning of the season the effect that this has on the risk of extinction will be taken into account. The harvest levels the regulator implements are adjusted to ensure that the increase in risk of future profit loss due to extinction caused by a marginal harvest increase just balances the gain in current profits. Thus a regulator who only values industry profit does take the risk of extinction into account to the extent that it affects discounted future profits. However, the optimal response to the introduction of a risk of extinction may be to *reduce* fish stocks compared to a situation without this risk which *increases* the risk of extinction further (see e.g. Sutinen 1981). This is because expected profit from leaving fish stock for future harvest is reduced when the risk of extinction is introduced.

Regulator preferences for precaution

Now consider a regulator concerned with reducing the risk of extinction. Such a regulator dislikes scenarios where S_t comes close to or is reduced below S^0. As already noted, such a concern is to a specific extent implied by maximisation of industry profit as specified above, and if this is the only driver of 'precautionary' regulation then its practical implications cannot meaningfully be distinguished from profit maximising regulation. However, we have in the previous section argued that such a precautionary concern may also be driven by a general environmental valuation of the exploited ecosystem over and above its value as an economic resource for the fishing industry. In addition, precautionary regulation may be driven by concerns for the negative indirect effects that a fisheries extinction might have on local communities. If concern for external effects of this type is important for fisheries managers then 'precautionary' concerns distinct from those derived from profit maximisation may apply and there may be a real trade off between profit and the risk of extinction. For example the optimal reaction to the introduction of a risk of extinction might then be to *increase* fish stocks instead of *reducing* them as profit maximisation may imply. To reflect such additional concerns we assume that the regulator may also associate an additional disutility with the risk of extinction $P(S_t)$ i.e.:

$$u_t = u(P(S_t)) \quad \text{for all } t \text{ where } u < 0, \frac{du}{dS_t} > 0 \text{ and } \frac{d^2u}{d^2S_t} < 0 \text{ and } u'' < 0 \qquad (15)$$

where we assume that marginal utility, $u(.)$, is decreasing and concave in ultimo stock size (reflecting that the regulator derives disutility from increasing risk of extinction).

One reason for such an added precautionary utility element is if the regulator associates an existence value with the fish stock (as e.g. suggested by Van Kooten and Bulte (2000)). If the present value of this utility flow is *w* then the expected utility loss from extinction as a function of stock would be $u_t = wP(S_t)$. Equation (15) is therefore a general expression that can capture this and other welfare losses that the regulator associates with extinction of the fish stock.

The concavity assumption implies that the regulator is risk averse. That is, at the beginning of period *t*, he prefers implementation of any particular final stock level with certainty to implementation resulting in a distribution over possible ultimo stock levels with this mean value. This would seem to capture the type of added concern about increasing the risk of a resource extinction by depleting stocks that many regulators appear to have. Assuming that u_t is normalized to the monetary unit used to measure profit the regulators utility function becomes $U_t = u_t + \Pi_t$ and he seeks to maximize the sum of discounted future expected utility[14]:

$$W(S_{t-1}) = \sum_{\tau=0}^{\infty} a^{\tau} E\left[u(P(S_{t+\tau})) + \Pi(H_{t+\tau}, R_{t+\tau})\right] \tag{16}$$

4. Instrument choice under ecological uncertainty

[14] Note that this is a general regulator utility function that contains the traditional profit maximizing regulator at one extreme where the *u* is zero and the precautionary regulator at the other extreme where the scale of u goes to infinity.

In this section we study how well a regulator can do if he uses the quota instrument compared to using the fee instrument when he is uncertain about ε_t (the current state of nature). It is useful initially to define a first best benchmark case against which we can evaluate different regulatory instruments. Let this benchmark case be the catch that the regulator would want to set if he could perfectly predict the realisation ε_t before setting instrument values for season *t*. Under these assumptions the recursive formulation of the dynamic optimisation problem becomes:

$$W^*(S_{t-1},\varepsilon_t) = \underset{H_t}{Max}\begin{pmatrix} u(P(R(S_{t-1}+\varepsilon_t)-H_t)+\Pi(H_t,R(S_{t-1}+\varepsilon_t)) \\ +aE_{\varepsilon_{t+1}}[W^*(R(S_{t-1}+\varepsilon_t)-H_t),\varepsilon_{t+1}] \end{pmatrix} \tag{17}$$

The value function, $W^*(S_{t-1},\varepsilon_t)$, is the expected sum (taken over $\varepsilon_{t+1}, \varepsilon_{t+2}\ldots$, where ε_t is perfectly predicted) of discounted future profit under the optimal policy, conditional on S_{t-1}, and $W^*(R_t - H_t, \varepsilon_{t+1})$ is the corresponding expectation (taken over $\varepsilon_{t+2}, \varepsilon_{t+3}\ldots$, where ε_{t+1} is perfectly predicted). Note that ε_t enters into (17) only through its effect on recruitment R_t which is now made explicit for clarity. Let $H_t^*(\varepsilon_t)$ denote the unique solution to (17) where this solutions dependence on ε_t is also made explicit for clarity. Note that while this solution assumes that ε_t is perfectly predicted the regulator is uncertain about all future period realisations when setting catch at the beginning of period *t*. Specifically he only holds a distribution over possible ε_{t+1} values. This implies that at the beginning of season *t* when the regulator sets the harvest level for the season there is uncertainty about the natural shock to the stock at the end of the season. There is, therefore, a risk of $P(S_t) = P(R_t(S_{t-1}+\varepsilon_t)-H_t)$ that the fish stock will disappear at the end of fishing season *t* (i.e. the risk that $R_{t+1}=0$) the utility value of which is taken into account when solving (17).

The first order condition for (17) is:

$$-u'(P(R(S_{t-1}+\varepsilon_t)-H_t))+\frac{d\Pi(H_t,R(S_{t-1}+\varepsilon_t))}{dH_t}$$
$$+aE_{\varepsilon_{t+1}}\left[\frac{dW^*(R(S_{t-1}+\varepsilon_t)-H_t,\varepsilon_{t+1})}{dH_t}\right]=0 \tag{18}$$

Incerting the derivative of the second term given by (7) and the definition (2) assuming an interior solution to (8) this is equivalent to:

$$-u'(P(S_t)+\pi(S_t)+aE_{\varepsilon_{t+1}}\left[\frac{dW^*(S_t,\varepsilon_{t+1})}{dH_t}\right]=0 \tag{19}$$

Note that this equation does not depend on R_t . Thus when optimum is defined in terms of end of season stocks recruitment drops out of the equation and so the optimal solution does not depend on natural shocks to recruitment at the beginning of period *t,* ε_t . Let S_t^* denote the solution implied by (19) which is the end of season stock that results when optimal harvest ($H_t^*(\varepsilon_t)$) is implemented. The optimal harvest is given by (2) as a function of end of season stocks and recruitment and so it does depend on ε_t in a specific way. Since optimal stock at the end of the fishing season is independent of ε_t the optimal harvest during the period must be adjusted to exactly counteract the effect that natural shocks have on recruitment. This is an important property of the first best solution to (17) and it is critical for the results we show in the following.

We use the solution to (17) ($H_t^*(\varepsilon_t)$) as the first-best reference against which we evaluate the quota and fee policy instruments actually available to the regulator. To facilitate this evaluation we follow Hansen (2008) and define the function:

$$\begin{aligned}&W(H_t, S_{t-1}, \varepsilon_t) = u(P(R(S_{t-1} + \varepsilon_t) - H_t)) + \Pi(H_t, R(S_{t-1} + \varepsilon_t)) \\ &+ aE_{\varepsilon_{t+1}}\left[W^*(R(S_{t-1} + \varepsilon_t) - H_t, \varepsilon_{t+1})\right]\end{aligned} \tag{20}$$

This function gives the present value when harvesting H_t in period *t* and then harvesting optimally in all following periods (again conditional on perfectly predicting ε_t). It follows that:

$$\begin{aligned}&W(H_t^*, S_{t-1}, \varepsilon_t) = W^*(S_{t-1}, \varepsilon_t) \\ &\qquad \text{and} \\ &W(H_t^*, S_{t-1}, \varepsilon_t) > W(H_t, S_{t-1}, \varepsilon_t) \quad \text{for} \quad H_t \neq H_t^*\end{aligned} \tag{21}$$

The regulator is uncertain about ε_t but since (19) is independent of ε_t the regulator can calculate S_t^* precisely. From (2) he can derive the harvest that implements this stock conditional on ε_t which he does not observe:

$$H_t^*(\varepsilon_t) = R(S_{t-1} + \varepsilon_t) - S_t^* \tag{22}$$

Fee regulation

From (12) we know that a fee of Φ_t implements the following catch:

$$H_t^{\Phi}(\Phi_t, R_t) = R(S_{t-1} + \varepsilon_t) - \pi^{-1}(\Phi_t) \tag{23}$$

Clearly setting $\Phi_t^* = \pi(S_t^*)$ will implement optimal catch and end of season stock irrespective of the realisation of ε_t. Furthermore since this parameterisation does not depend on ε_t , which the regulator is uncertain about, the regulator can implement $H_t^*(\varepsilon_t)$ with certainty. So from (21) we have that

$$E_{\varepsilon_t}\left[W(H_t^{\Phi}(\Phi_t^*, R_t), S_{t-1})\right] = W(H_t^*, S_{t-1}, \varepsilon_t) = W^*(S_{t-1}, \varepsilon_t) \qquad (24)$$

Thus under ecological uncertainty the regulator can set the fee level so that the the first best benchmark is set to implement with certainty even though the regulator is uncertain about ε_t.

Quota regulation

Under quota regulation the regulator sets harvest according to (9) and the question we want to answer is whether he can implement H_t^* with certainty using this instrument. If he cannot then the fee instrument is preferred.

From (9) we know that a quota of Q_t implements the following catch:

$$H_t^Q(Q_t, R_t) = Min(Q_t, H_t^0(R(S_{t-1} + \varepsilon_t))) \qquad (25)$$

If fishermen are *not quota constrained* (i.e. $H_t^Q(Q_t, R_t) = H_t^0(R(S_{t-1} + \varepsilon_t) < Q_t))$ they behave as if they are not regulated. Comparing (8) with (23) when $\Phi_t = \Phi_t^*$ it is clear that $H_t^0 = H_t^*$ only when

$\Phi_t^* = 0$. This corresponds to the situation where no regulation is needed which is clearly not relevant here and so we disregard it in the following. When regulation is required (when $\Phi_t^* > 0$) we have that $H_t^* < H_t^0$ and then optimal catch can only be implemented if the fishermen are quota constrained. If fishermen *are quota constrained* (i.e. $H_t^Q(Q_t, R_t) = Q_t < H_t^0(R(S_{t-1} + \varepsilon_t))$) then catch is equal to the quota set by the regulator and it is clear that optimal catch is implemented only when $Q_t = H_t^*$. Thus the regulator can only be certain to implement optimal catch when he knows $H_t^*(\varepsilon_t)$ at the time when he sets the quota which generally requires him to know the realisation of ε_t. Since the regulator does not know the realisation of ε_t but only holds a distribution $g_t(.)$ over possible ε_t realisations he cannot in general implement H_t^* with certainty using this instrument when regulation of the fishery is required.

To show this formally, define the recursive formulation of the regulator's problem under quota regulation, incorporating that the regulator's uncertainty about ε_t when the quota for period *t* is set :

$$W^{Q*}(S_{t-1}) = \underset{Q_t}{Max}\, E\begin{bmatrix} u(P(R(S_{t-1}+\varepsilon_t) - H_t^Q(Q_t, R(S_{t-1}+\varepsilon_t))) \\ +\Pi(H_t^Q(Q_t, R(S_{t-1}+\varepsilon_t)), R(S_{t-1}+\varepsilon_t)) \\ +aW^{Q*}(R(S_{t-1}+\varepsilon_t) - H_t^Q(Q_t, R(S_{t-1}+\varepsilon_t))) \end{bmatrix} \tag{26}$$

and let Q_t^* denote the solution to this problem. We prove the following proposition:

Proposition I: $W^{Q*}(S_{t-1}) < W^*(S_{t-1}, \varepsilon_t)$ *for any non-degenerate distribution* $g(\varepsilon_t)$ *that assigns strictly positive probabilities to at least two* ε_t *values whose optimal catches* $H_t^*(\varepsilon_t)$ *differ*.

Proof: *By definition* $W^{Q*}(S_{t-1}) \le W^*(S_{t-1})$ *implying that*

$$u(P(R(S_{t-1}+\varepsilon_t)-Q_t^*))+\Pi(Q_t^*,R(S_{t-1}+\varepsilon_t))+aW^{Q*}(S_{t-1}) \le$$
$$u(P(R(S_{t-1}+\varepsilon_t)-Q_t^*))+\Pi(Q_t^*,R(S_{t-1}+\varepsilon_t))+aW^*(S_{t-1})$$
$$\Leftrightarrow$$
$$W^{Q*}(S_{t-1}) \le W(Q_t^*,S_{t-1})$$

For all possible values of ε_t *we have that:*

$$W(Q_t^*,S_{t-1}) \le W^*(S_{t-1})$$
and
$$W(Q_t^*,S_{t-1}) < W^*(S_{t-1}) \quad \text{if} \quad Q_t^* \ne H_t^*$$

so that $$E_{\varepsilon_t}\left[W(Q_t^*,S_{t-1})\right] < W^*(S_{t-1})$$

for any non-degenerate distribution $g(.)$ *implying that:*

$$W^Q(S_{t-1}) < W^*(S_{t-1})$$

□

Corollary to Proposition I: $W^{Q*}(S_{t-1}) = W^*(S_{t-1})$ *for any degenerate distribution g(*ε_t*) where all* ε_t *values that are assigned a positive probability have the same associated optimal catch* $H_t^*(\varepsilon_t)$. *By setting* $Q_t = H_t^*(\varepsilon_t)$ *the quota instrument implements this optimal catch with certainty.*

This implies that under ecological uncertainty (when the regulator is uncertain about natural shocks ε_t) quota regulation generally implements a lower expected regulator utility level than fee regulation. Thus the pro-fee result found by Weitzman (2002) for ecological uncertainty extends to a situation where the regulator is concerned about the risk of resource extinction.

Our result does, however, differ in two important respects from that of Weitzman (2002). *First* Weitzman shows that when the object function (which in his case is industry profit) is concave in the fish stock and linear in catch then the value function of the corresponding recursive formulation of the problem will be concave. This in turn implies that the fastest possible approach to the long run preferred escapement is optimal (a so called bang-bang solution to the dynamic optimisation problem). This not only implies that the fee instrument is preferred to the quota instrument but that the optimal solution is implemented by imposing a constant fee (i.e. setting the same landing fee in all periods according to the long run preferred escapement). However, because of recruitment falling to zero when initial stock falls below a certain cut off level, our object function will not be concave in all possible fish stock values. Thus, the value function for our problem is not necessarily concave in the fish stock and so we cannot be sure that the fastest possible approach to long run preferred escapement is optimal. What we show is that the fee instrument is preferred to the quota instrument and that the optimal path can be implemented with this instrument. However, it may be that this requires adjustment of fee levels over time (i.e. if the preferred adjustment to long run preferred escapement is not the 'bang-bang' solution).

The *second* difference is that some degenerate distributions (that allow the quota instrument to perform as well as the fee instrument) may in fact be meaningful approximations of the practical problem faced by regulators in our case. When stocks are close to extinction and the regulator has a substantial concern about this he may find himself in a situation where optimal catch in the coming period is zero or close to zero for most realisations of ε_t. Though it would still be optimal to use an optimally set fee this would only induce positive harvest levels in unlikely situations with extraordinarily large recruitment. The expected welfare loss of closing the fishery in period *t* (i.e. setting $Q_t = 0$) could be small in this situation (because $H_t^*(\varepsilon_t) = 0$ for most likely ε_t values). Thus the quota instrument could perform almost as well as the fee instrument when the fish stock is highly threatened. Clearly though as stocks are rebuilt the welfare cost of continuing to use quota regulation increase.

5. Discussion and conclusion

We have incorporated into a stock recruitment model the possibility of the fish stock becoming extinct as the result of stochastic natural processes and regulator concern about this. We consider instrument choice under biological uncertainty where the regulator is less certain about the state of nature when setting the value of the regulatory instrument than fishermen are when they produce. Because of the structure of this problem the regulator's concern about extinction affects his preferred escapement (how much of the fish stock is left for next period). This is the key because the main difference between the two instruments is in how escapement is affected by ecological uncertainty. The fee ensures that the escapement left by fishermen is independent of the current state of nature. On the other hand escapement left by fishermen subject to a fixed quota will vary with the state of nature.

Our result is that under biological uncertainty the fee instrument dominates the quota instrument irrespective of the regulator's preferences over profit and precaution. The basic intuition here is the regulator having no uncertainty about the fisherman's profit function can implement the preferred escapement using a fee because he is certain about how fishermen react to the fee incentive. In effect the fee allows the regulator to decentralize the decision about the size of the catch to fishermen who observe the state of nature since he can predict precisely what escapement this decentralisation will produce. Since the quota implies a fixed harvest, escapement will vary with the state of nature no matter the size of the quota set by the regulator.

This result depends on two assumptions. First, that there are no economies of scale in catch during the fishing season. Without such economies of scale the marginal profit of catch is independent of the season's catch and only depends on the current fish stock which at the end of the season is escapement. The second assumption we need is that the risk of extinction only depends on the stock at the end of the season. Weitzman (2002) uses the first assumption to show that fees are preferred under biological uncertainty when the regulator wants to maximize profit. We use the second assumption to extend this result to the situation where the regulator has an additional concerned about extinction.

However, the existing literature points to several other types of uncertainty that also may generate systematic differences in the relative efficiency of tax versus ITQ-regulation. Regulators may be uncertain about profit functions (economic uncertainty). Weitzman (2002) speculates that quota regulation will be preferred under economic uncertainty when the regulator is only concerned about profit though this has not to our knowledge been shown. It can be suggested that a systematic difference between regulator's monitoring and enforcement costs under price and quantity regulation may result if a fisherman who is cheating on ITQs is perceived as cheating other fishermen from whom the cheater would otherwise have to buy quotas, while cheating on a landing fee is seen as cheating the regulator. In addition, Hansen et al. (2008) suggest that compliance uncertainty (where the regulator is uncertain about the extent of non-compliance/illegal landings) may be an important source of information asymmetry.

Therefore even though our result both seems relevant for a regulator concerned with the risk of stock collapse and implies fairly robust policy recommendations, applying those recommendations to any particular fishery would require a complete evaluation of the relative efficiency of instruments taking all of the potentially important types of uncertainty into account. In any case, the main contributions of this paper is that we show, contrary to what seems to be the general consensus, that landing fees are able to provide more effective extinction insurance than quotas under the same conditions as those implying that landing fees are better at maximising industry profit. We also provide a blueprint for incorporating regulator concerns about extinction (that are not profit driven) into models suitable for studying instrument choice.

Literature

Anon (2008), Report of the Working Group on the Assessment of Demersal Stocks in the North Sea and Skagerak, Copenhagen: ICES

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

Bjørndal, T, Gordon, D., Kaitala, V. and Lindroos, M. (2004), International Management Strategies for a Straddling Fish Stock: A Bioeconomic Simulation Model of the Norwegian Spring-spawning Herring fishery, Environmental and Resource Economics, 29, pp. 435-457

Bulte, E.H. and van Kooten, G.C., Marginal Valuation of Charismatic Species: Implications for Conservation, Environmental and Resource Economics, 14, pp. 119-130

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

Clark, C.W., Munro, G.R. and Sumaila, U. R. (2010), Limits to Priivatization of Fishery Resources, 86, pp. 614-618.

Dulvy, N.K., Metcalfe, J.D., Glanville, J., Pawson, M.G. and Reynolds. J.D. (2000), Fishery Stability, Local Extinctions and Shifts in Community Structure in Skates, Conservation Biology, 14, pp. 1309-1315.

Ekerhovd, N.A. (2008), Climate Change and the Blue Whiting Agreement, SNF Working paper no. 35.

´

Fisher, C. And Laxminarayan, R. (2010), Managing Partially Protected Resources under Uncertainty, Journal of Environmental Economics and Management, 59, pp. 129-141.

Hanneson, R. and Kennedy, J.(2005): Landing fees versus Fish Quotas, Land Economics, 81 (4), pp. 518-529.

Hansen, L.G. (2008): ‘Prices versus Quantities in Fisheries Models: Comment’,
Land Economics 84 (4).

Hansen, L.G., F. Jensen and C. Russell (2008): ‘The choice of regulatory instrument – When there is Uncertainty about Compliance with Fisheries Regulations’, American Journal of Agricultural Economics 90(4) pp1130-1142.

Holden, M (1994), The Common Fisheries Policy, Oxford: Fishing News Books

Hutchings, J.A. (2000), Collapse and Recovery of Marine fishes, Nature, pp. 1016-1025

Hutchings, J.A. and Reynolds, J.P. (2004), Marine Fish Populations Collapse: Consequences for Recovery and Extinction Risks, BioScience, 54, pp. 297-309.

Jennings, S., Kaiser, M.J. and Reynolds, J.D. (2001): Marine Fisheries Ecology, Oxford: Blackwell Science.

Jensen, F. and Vestergaard, N. (2003), Prices versus Quantities in Fisheries Economics, Land Economics, 79, pp. 415-426.

Ljungqvist, L. and T.J. Sargent (2000): Recursive Macroeconomic Theory – second edition. Boston, MIT.

Neher, P.A.(1990): Natural Resource Ecomomics. Conservation and Exploitation. Cambridge: Cambridge University Press.

Pauly, D. (2009), Aquacalypse Now, Environment and Energy, September, pp. 288-305.

Primack, R.B. (1998), Essentials of Conservation Biology, Sunderland: Sinauer Associates

Quammen, D. (1996), The Song of the Dodo: Island Biography in an Gae of Extinction, London: Pimlico.

Raup, D.M. (1991), Extinction: Bad Genes or Bad Luck, New York: Norton.

Roberts, C.M. and Hawkins, J.P. (1999), Extinction Risk in the Sea, Trends in Ecology and Evolution, 14, pp. 241-246

Standal, D. (2006), The Rise and decline of the Blue Whiting Fisheries – Capacity Expansion and Future regulation, Marine Policy, 30, pp. 315-327.

Soule, M. (1987), Viable Populations for Conservation, Cambridge: Cambridge University Press.

Sutinen, J.G. (1981), Optimal Extraction of a Renewable Resource under Uncertainty: The Case of Stock Collapse in the Fishery, Department of Resource Economics, College of Resource Development, Staff Paper Series, University of Rhode Island, Kingston, Rhode Island.

Tegner, M.J., Basch, L.V. and Dayton, P.K.: Near Extinction of an Exploited Marine Resource,

Trends in Ecology and Evaluation, 11, pp. 278-280

Van Kooten, G.C. and Bulte, E,H. (2000), Economics of Nature: Managing Biological Assets, London: Wiley Blackwell.

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