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Fisheries Management under Uncertainty using Non-linear Fees

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Abstract

This paper considers non-linear taxation to regulate fisheries. It compares that instrument with quantity control and linear taxation. Traditionally the question of how to regulate fisheries has been posed as a choice between price and quantity control. A numerical example, concerned with demersal fisheries, indicates that non-linear taxation is superior to quantity control. When cost uncertainty is involved, it can also prove more efficient than the price instrument.

JEL classification: D82, H21, Q22

Keywords: Fisheries management; Uncertainty; Non-linear taxation; Dynamic optimization

1 Introduction

Fisheries management struggles, in practice and theory, with how to secure efficiency. Decisive for the biological and economic outcome is the choice of control instruments. While direct quantity regulation is most common,

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economists, in contrast, often prefer indirect control, using prices. Of current interest in that debate is a recent paper of Weitzman (2002). He proves the superiority of landing fees over quantity control when decisions must be made with inaccurate stock estimates. A major point of Weitzman is that greater *ecological* uncertainty seems to enhance the relative performance of the price instrument.

This paper adds to Weitzman's study by incorporating *economic* uncertainty as well. When Jensen and Vestergaard (2003) undertook a similar investigation, they aimed at generalizing Weitzman's (1974) proportions about "Prices vs. Quantities" to dynamic fisheries. His result, that price dominates quantity control if marginal costs are more sharply curved than marginal benefits, was found applicable for schooling fisheries. For demersal instances, however, where harvesting costs are stock dependent, they found an analytical approach intractable.

Since demersal species are economically most important, this motivates me to investigate how instruments compare for such fisheries. Numerical methods must be used anyway. Therefore, apart from considering price and quantity control, I will consider the non-linear tax alternative for fisheries management. This is motivated by the fact that nonlinear instruments have already been central in studies of static models (e.g. Weitzman, 1978; Kaplow and Shavell, 2002) and by the Berglann (2005) paper which shows that such fees can be shared between parties in a way that relieves them from strategic considerations.

As vehicle for comparison I use dynamic programming to compute, for each instrument, the optimal expected present value over an infinite time horizon. Out of concerns with safety I also investigate each scheme's ability to prevent resource extinction. Of particular interest is comparison of proportional taxation with the non-linear tax proposed here. Quantity control serves as a benchmark. The dynamic model is based on Reed (1979). Like Clark and Kirkwood (1986) and Weitzman (2002) I assume that the stock size is known only up to probability for the manager when he specifies the considered instrument.

The paper is organized as follows: Section 2 specifies the diverse regulation schemes. Section 3 describes the dynamic model and the information flow. Dynamic programming serves to optimize the instruments as described in Section 4. Section 5 compares optimal yields of the fixed quota-, the linear tax, and the non-linear fee systems when stock estimates are uncertain; and with and without cost uncertainty. Also included are results for a deterministic case. Section 6 investigates how the instruments fare in terms of the probability for extinction. Section 7 concludes.

2 Regulatory Instrument Specifications

Consider a fishing industry comprising a large fixed number of identical vessels. These exploit one species. Time is discrete and all parameters and variables are non-negative. Total harvest in an arbitrary period is denoted h, and x denotes the stock size in the beginning of that period. The first-hand price p for landed fish is constant. Costs $C(\tilde{x})$ per unit harvest depends on current stock $\tilde{x}$ as $C(\tilde{x}) := c/\tilde{x}$ where c is a constant common to all parties. All skippers are profit maximizers with a time perspective restricted to the current period, and they have perfect knowledge of c and current stock size $\tilde{x}$.

Absent regulation and capacity constraints, the fishing industry solves the problem

$$\max_h \left\{ ph - c \int_{x-h}^{x} \frac{1}{\tilde{x}} d\tilde{x} \right\} = \max_h \left\{ ph - c \ln\left(\frac{x}{x-h} \right) \right\}. \tag{1}$$

The necessary (and sufficient) condition for an interior solution of problem (1) is expressed by the function H^{OA} (Open Access) defined by

$$H^{OA}(x, c) := h = x - \frac{c}{p}. \tag{2}$$

It is well known that this outcome (2) might cause overfishing, the chief reason being absence of intertemporal concerns. Some central agent is bestowed with the authority to avoid the "tragedy of commons" by regulating the fishery. In doing so the agent must cope with blurred information on the cost parameter c and the stock size x at the beginning of the period. I consider three control instruments in the hands of the said authority:

- *quantity limitation*, denoted a **Fixed Quota (FQ)**;
- *price control*, denoted a **Linear Tax (LT)**;
- *non-linear taxation*, denoted an **Expected Quota (EQ)**.

We now define how fishermen comply with these schemes:

2.1 The Fixed Quota (FQ) Instrument

The regulator specifies a non-negative total quota q (TAC) for the period. The fishing industry solves the same problem as in the case with no regulation (1) except that the quantity restriction is binding when $q \leq H^{OA}(x, c)$. Thus fishermen, regulated by the FQ instrument, select a harvest h^{FQ} equal to

$$h^{FQ} = H^{FQ}(x, c, q) := \max\left(0, \min\left(H^{OA}(x, c), q\right)\right). \tag{3}$$

2.2 The Linear Tax (LT) Instrument

In this scenario the regulator specifies a linear tax b on catches in the period. The industry solve the problem

$$\max_h \left\{ (p-b)\, h - c \ln\left(\frac{x}{x-h}\right) \right\} \tag{4}$$

subject to the condition $0 \leq h \leq x$. This yields a harvest h^{LT} equal to

$$h^{LT} = H^{LT}(x, c, b) := \max\left(0, \min\left(x, x - \frac{c}{p-b}\right)\right). \tag{5}$$

2.3 The Expected Quota (EQ) Instrument

A second order approximation of a generic strictly convex tax (without a lump sum part) levied on the industry's total harvest in the period is given by[1]

$$t := \beta h + \frac{\gamma}{2} (h)^2 \tag{6}$$

where $\beta \geq 0$ and $\gamma > 0$ are parameters that the regulator can choose for the period. The problem for the industry is

$$\max_h \left\{ ph - t - c \ln \left(\frac{x}{x-h} \right) \right\} \tag{7}$$

subject to $0 \leq h < x$. Using the root that always gives $h < x$ of the necessary (and sufficient) condition

$$p - \beta - \gamma h - \frac{c}{x-h} = 0 \tag{8}$$

for an interior solution of (7) yields a harvest h^{EQ} equal to

$$\begin{aligned} h^{EQ} &= H^{EQ}(x, c, \beta, \gamma) \qquad (9) \\ : &= \max \left(0, \frac{1}{2\gamma} \left(p - \beta + \gamma x - \sqrt{(\beta - p + \gamma x)^2 + 4\gamma c} \right) \right). \end{aligned}$$

I have now determined how fishermen comply under the various regulating regimes. Let the integer k index a particular fishing period. To compact notation I hereby symbolize control parameter(s) in period k under regime

[1] Berglann (2005) shows that this non-linear tax, just like a total quota, can be distributed to individual fishermen in a way that overcomes strategic interaction amongst them.

$\mathfrak{R} \in (FQ, LT, EQ)$ as

$$\mathfrak{u}_k^{\mathfrak{R}} := \begin{cases} q_k & \text{in case } \mathfrak{R} = FQ \\ b_k & \text{in case } \mathfrak{R} = LT \\ \beta_k, \gamma_k & \text{in case } \mathfrak{R} = EQ \end{cases}$$

such that harvest in period k is expressed by $h_k^{\mathfrak{R}} = H_k^{\mathfrak{R}}\left(x_k, c, \mathfrak{u}_k^{\mathfrak{R}}\right)$. The task of the regulator could be the assignation of a "best value" of $\mathfrak{u}_k^{\mathfrak{R}}$ under an infinite time horizon perspective. To consider this, I must first specify the dynamic model and how information is updated.

3 The Model and the Information Flow

The information flow is illustrated in Figure 1. It comprises two stages and is described as follows: The exact escapement level s_{k-1}, the stock remaining at the end of stage $k-1$ after harvesting, is common knowledge. From the end of stage $k-1$ to the beginning of stage k, breeding takes place. Breeding is represented with the discrete resource model proposed by Reed (1979) given by

$$x_k = z_{k-1} G\left(s_{k-1}\right) \tag{10}$$

where the commonly known average stock-recruitment relationship $G(\cdot)$ is multiplied by the random factor z_{k-1}. At the beginning of stage k, stock size x_k emerges (10), but with uncertainty for the regulator since z_{k-1} has not yet been disclosed for him.

The random variables z_{k-1} for all k are assumed to be independent and identically distributed with probability density function $f(z_k) = f(z)$ with mean $\overline{z} = 1$. For the regulator, the cost parameter c is uncertain, but has a known probability density function $\theta(c)$ with mean $\overline{c}$. Based on this statistical information for x_k and c, the manager must decide for a "best" value of the parameter(s) $\mathfrak{u}_k^{\mathfrak{R}}$ of his control instrument $\mathfrak{R}$.

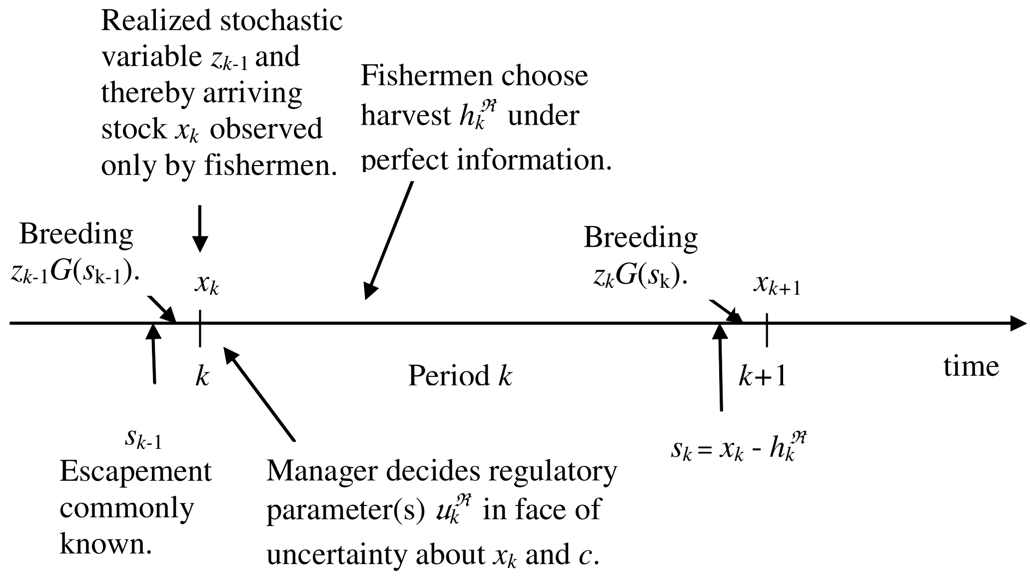

Figure 1. Informational sequence

The fishermen are better informed. They respond to a regulatory setting $\mathrm{u}_k^{\mathfrak{R}}$ during period k based on certain knowledge. In effect, they know the realization of z_{k-1} and thereby the arriving stock x_k when they determine the fishing effort that yields harvest $h_k^{\mathfrak{R}} = H_k^{\mathfrak{R}}\left(x_k, c, \mathrm{u}_k^{\mathfrak{R}}\right)$ for that year. At the end of the period k escapement is

$$s_k = x_k - h_k^{\mathfrak{R}}, \tag{11}$$

which now also is revealed for the regulator such that s_k becomes common knowledge. Then next period follows.

4 Optimal Management over Time

Due to the stationarity of the stochastic variables z and c, the dynamic problem that must be solved by the manager using regime $\mathfrak{R}$ is the same for every period k. So without loss of generality, I can in the following consider regulator's problem at the beginning of period $k = 1$ when s_0 is known. Stationarity of the environment also implies that the problem is expressed by the Bellman equation

$$V^{\mathcal{R}}(s_0) = \max_{\mathfrak{u}_1^{\mathcal{R}}} E\left\{\Pi_1\left(x_1, c, h_1^{\mathcal{R}}\right) + \rho V^{\mathcal{R}}\left(x_1 - h_1^{\mathcal{R}}\right) | s_0\right\} \tag{12}$$

where $V^{\mathfrak{R}}(\cdot)$ is the optimal expected present value function, $\rho \in (0, 1)$ denotes the discount factor and harvest is $h_1^{\mathfrak{R}} = H_1^{\mathfrak{R}}\left(x_1, c, \mathfrak{u}_1^{\mathfrak{R}}\right)$. The function $\Pi_1(\cdot)$ is the current social economic value of the fishery for year 1, given by[2]

$$\Pi_1\left(x_1, c, h_1^{\mathfrak{R}}\right) := ph_1^{\mathfrak{R}} - c\ln\left(\frac{x_1}{x_1 - h_1^{\mathfrak{R}}}\right). \tag{13}$$

The expectation operator $E\{\cdot\}$ in this paper pertains to the expected value of all uncertain variable(s) within the brackets. Here (12) the operator pertains to x_1 given s_0 that has the probability density function

$$g(x_1) := \frac{1}{G(s_0)} f\left(\frac{x_1}{G(s_0)}\right) \tag{14}$$

and to the cost parameter c with probability density function $\theta(c)$.

As customary the functional equation (12) is solvable through successive approximation and the result $V^{\mathfrak{R}}(\cdot)$ is unique[3].

5 Numerical Example

In my numerical example is the price for fish $p = 1$; the discount factor is $\rho = 0.9$. The stock-recruitment model that Clark and Kirkwood (1993) used in their numerical example is given by $(1 - \exp(-2s))$. Since extinction probabilities are of great interest (next section), however, I want to extend that example to include depreciation. Hence, I specify the model as

[2] This expression is equivalent to fishermen's profit function under open access (1).

[3] For s_0 high enough is $\Pi_1\left(x_1, c, h_1^{\mathfrak{R}}\right)$ concave. Under these circumstances the solution is unique (Weitzman, 2002).

$$G(s) = (1 - \exp(-2s))(1 - \exp(-10s)). \tag{15}$$

This model has a stable natural equilibrium at $x = 0.796$, but also an unstable equilibrium point at $x = 0.0776$. Thus, the population is doomed to extinction if the stock ever falls below the critical level given by the unstable equilibrium point.

The stochastic variables z and c are both assumed to be lognormally distributed. While the probability density distribution $f(z)$ has standard deviation $\sigma_z = 0.4$, and as already stated, a mean $\overline{z} = 1$, the corresponding parameters for the c distribution $\theta(c)$ are $\sigma_c = 0.1$ and $\overline{c} = 0.1$, respectively. The following diagrams are parametric plots with s_0 as the varying parameter. They use expected recruitment $E\{x_1\}$ as the abscissa function, given by

$$E\{x_1\} = E\{x_1 | s_0\} = E\{z_0 G(s_0)\} = \overline{z} G(s_0) = G(s_0). \tag{16}$$

Figures 2, 3 and 4 displays solutions of the functional equation (12) given in last section. The legends of these figures (and the figures that follow as well) indicate to which system the various curves belong, ranked after the ordinate value at the end of the abscissa axis. Figure 2 shows the optimal expected present value function $V^{\mathfrak{R}}(s_0)$ of the fishery for all systems $\mathfrak{R}$ and under the statistical parameter values I have picked out. Known costs for the EQ and LT system, stands for that costs are given by its mean value $\overline{c}$. The deterministic system is equivalent to an FQ system where the value of z_0 is known and given by its mean value $\overline{z} = 1$. The according optimal policies appear in Figure 3. These policies are displayed in the form of targets for the optimal expected escapement levels denoted $E\left\{s_1^{\mathfrak{R}*} | s_0\right\}$ for regime $\mathfrak{R}$ and calculated by

$$E\left\{s_1^{\mathfrak{R}*} | s_0\right\} = E\left\{\max\left(0, x_1 - H_1^{\mathfrak{R}}\left(x_1, c, \mathfrak{u}_1^{\mathfrak{R}*}(s_0)\right)\right) | s_0\right\} \tag{17}$$

where $\mathfrak{u}_1^{\mathfrak{R}*}(s_0)$ is the obtained optimal arguments functions defined as

$$\mathfrak{u}_1^{\mathfrak{R}*}(s_0) := \begin{cases} q_1^*(s_0) & \text{in case } \mathfrak{R} = FQ \\ b_1^*(s_0) & \text{in case } \mathfrak{R} = LT \\ \beta_1^*(s_0), \gamma_1^*(s_0) & \text{in case } \mathfrak{R} = EQ \end{cases}.$$

Figure 4 shows optimal arguments $b_1 = b_1^*(s_0)$ for the LT-system and $\beta_1 = \beta_1^*(s_0)$ and $\gamma_1 = \gamma_1^*(s_0)$ for the EQ-system. In addition I list in Table 1 and 2 the expected recruitment level $G\left(E\left\{s_\infty^{\mathfrak{R}*}\right\}\right)$ and the optimal expected present value $V^{\mathfrak{R}}\left(E\left\{s_\infty^{\mathfrak{R}*}\right\}\right)$ at the stationary optimal expected escapement level (defined implicitly as $E\left\{s_\infty^{\mathfrak{R}*}\right\} := E\left\{s_\infty^{\mathfrak{R}*} \middle| E\left\{s_\infty^{\mathfrak{R}*}\right\}\right\}$) for all of my choices.

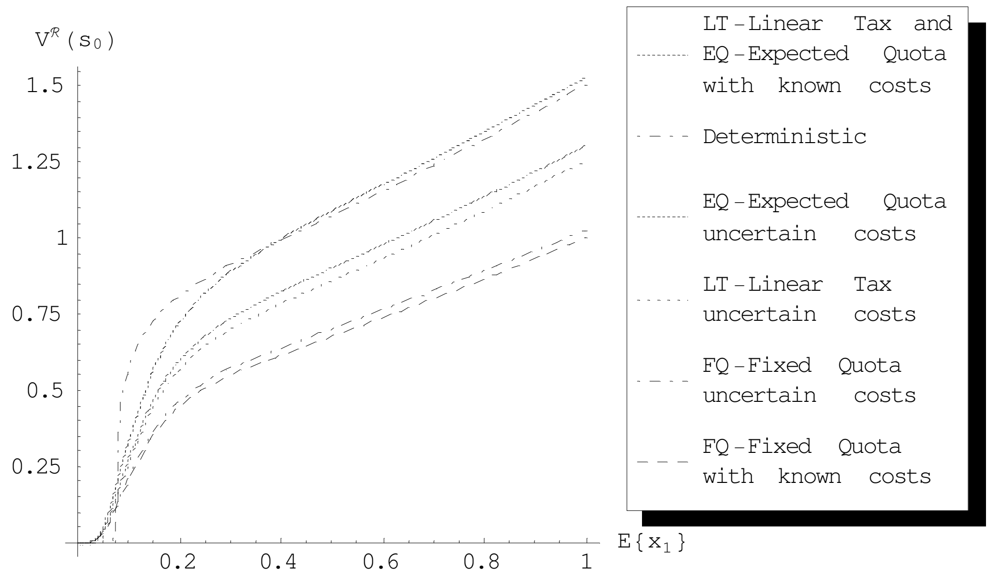

Figure 2. Expected value vs expected recruitment.

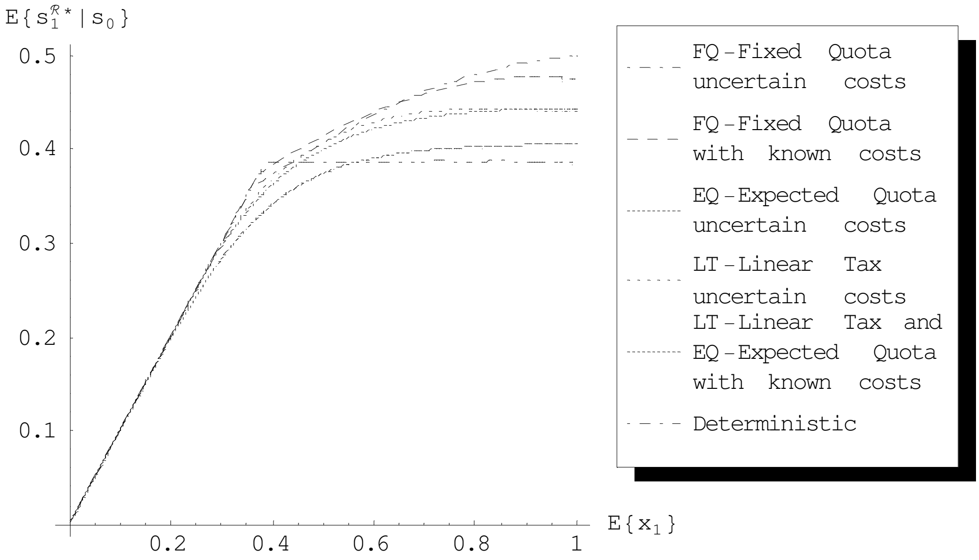

Figure 3. Expected escapement vs expected recruitment.

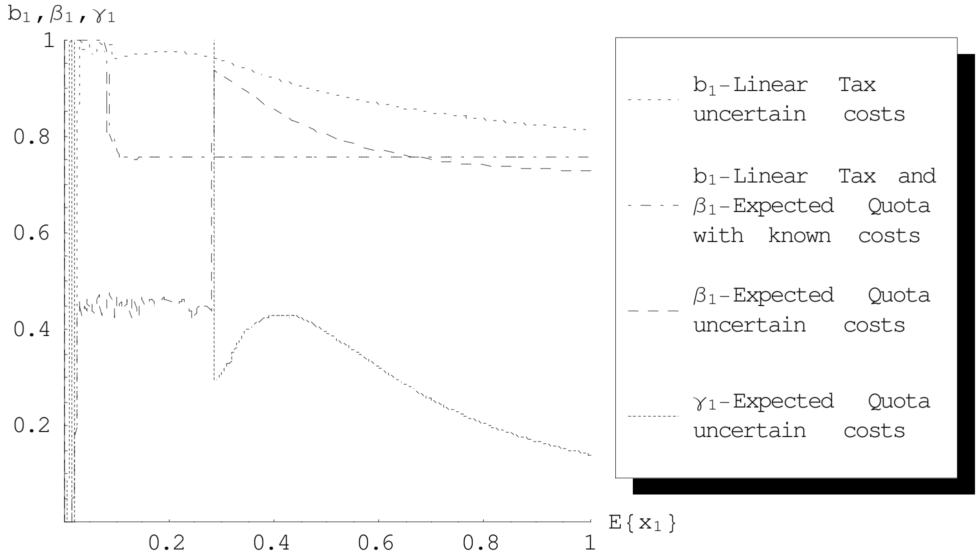

Figure 4. Instrument parameter values vs expected recruitment.

Table 1: Expected recruitment at the stationary expected escapement level, $G\left(E\left\{s_{\infty}^{\mathfrak{R}*}\right\}\right)$.

Deter- ministic	FQ σ_c=0.	FQ σ_c=0.1	LT / EQ σ_c=0.	LT σ_c=0.1	EQ σ_c=0.1
0.5273	0.5719	0.5668	0.5186	0.5620	0.5533

Table 2: Expected present value at the stationary expected escapement level, $V^{\mathfrak{R}}\left(E\left\{s_{\infty}^{\mathfrak{R}*}\right\}\right)$.

Deter- ministic	FQ σ_c=0.	FQ σ_c=0.1	LT / EQ σ_c=0.	LT σ_c=0.1	EQ σ_c=0.1
1.096	0.7197	0.7438	1.105	0.9051	0.9430

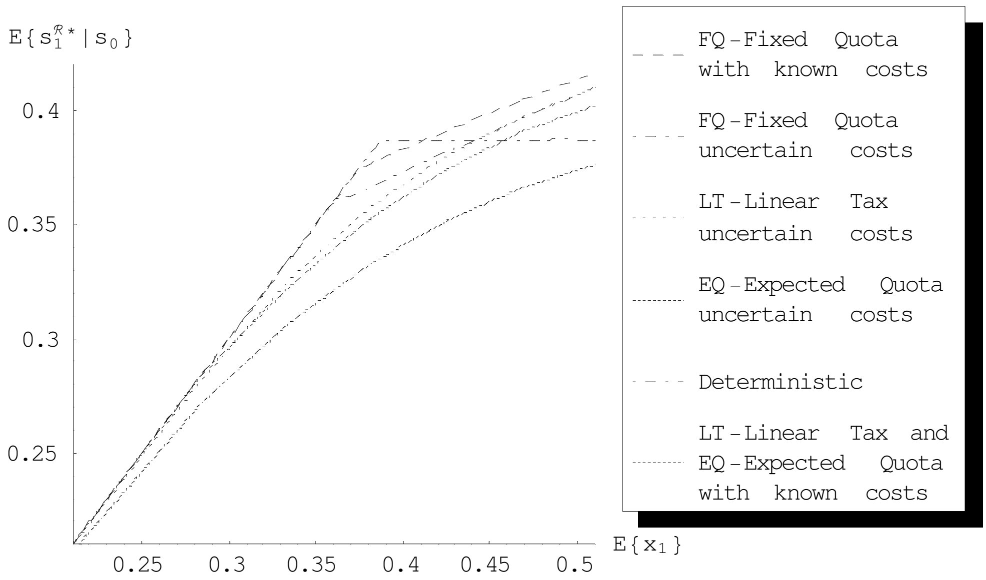

Figure 5. Expected escapement vs expected recruitment. Close-up of Figure 3.

Notice in Figure 3 how the constant escapement policy emerges for the deterministic case. No harvest takes place when $x_1\,(= E\{x_1\})$ is lower than a specific value; when $x_1\,(= E\{x_1\})$ is above this point, optimality dictates that all stock in excess of the specified escapement level should be harvested.

For the two FQ cases (with uncertain x_1; with and without cost uncertainty), the optimal escapement diagrammed in Figure 3 are non-constant feedback solutions, which yields quota settings $q_1 = q_1^*(s_0)$ dependent on the result of stock surveys. Not shown in any of my figures is that these quota settings are slightly higher than the harvest being expected by the manager, a gap that increases with the value of $E\{x_1\}$ and becomes more dominant in the cost uncertainty case. The gap is caused by that the quota q_1 will not always be binding because the open access solution in some cases can take over as the catch boundary. This limitation is favorable because it happens in instances when the stock happens to be low and can then save the stock from extinction. A high cost by itself means a low value of the fishery. Even though, under cost uncertainty is a cost level above mean costs $\overline{c}$ more honored because the mentioned harvest limitation is more likely to be active than if costs are correspondingly below $\overline{c}$. As seen in Figure 3 and Table 2, this asymmetry in cost appreciation (from the manager's side) is the reason why the FQ case with cost uncertainty has a higher expected present value than in the known cost case.

In Figure 5, a close-up of Figure 3, we see better the result remarked by Clark and Kirkwood (1986): the FQ (known costs) optimal policy is not uniformly cautious. The threshold for $E\{x_1\}$, when the FQ curve leaves the line where the optimal harvest is *zero*, is lower with stock uncertainty than with exact knowledge. Clark and Kirkwood found this effect to increase with the stock uncertainty level. The reason is that the optimal harvest, on the boundary when the threshold is exceeded, will be low. The harvest is then safe in the sense that the effect on the value due to the danger of extinction is minimal. Since stock uncertainty means the possibility of the stock becoming larger than the optimal deterministic threshold, it is optimal with a lower threshold level than that found in the deterministic case. My result indicates that adding cost uncertainty has the same influence on the threshold level as increased stock uncertainty.

With linear landing fees and known costs, the similar threshold for when harvesting should be allowed is, as we see in Figure 3 and 5, very low. The low threshold is caused by the possibility to instill the price in such a manner that it will block harvesting when the stock happens to be slightly lower than the favored value. Then, as I demonstrate in the next section, harvesting can take place with a risk of resource collapse that approximates the chance at no harvest. With these features it is difficult to perform better. Not surprisingly, I therefore find EQ regulation to approximate LT control in this known costs case: $\beta_1 \approx b_1$ and $\gamma_1 \approx 0$ for all s_0.

Another observation is in Figure 4: the optimal landing fee is independent of $E\{x_1\}$[4]. Weitzman (2002) finds an analytical expression for such a constant landing tax by assuming that the regulator knows recruitment x_1. He can assume common information of x_1 because he predicts ahead that the tax is equal for all x_1 $(= E\{x_1\})$ and then regulator does not need any stock size estimate. I, however, must neglect that approach to make the outcome comparable to my other cases where the optimal tax might depend on $E\{x_1\}$. Then I find (numerically) that the tax should be higher than in the Weitzman case and furthermore, a higher expected present value.

The effect that "only knowing x_1 up to probability" makes the fishery more valuable is peculiar but comparable to what I found above for the FQ system where cost uncertainty made the fishery more prized. The explanation is asymmetry in the appreciation of the uncertainty; the chance of a high stock level is weighted more than the loss of value, due to the corresponding chance of a lower stock level. As we see in Figure 2 for high values of $E\{x_1\}$ and in Table 2, the uncertain costs case considered here even dominates the deterministic instance.

While it is the other way round for the FQ-regime the entrance of cost uncertainty when regulating with the LT and EQ systems decreases the expected present value of the fishery. As we see in figure 4, for the LT system, the optimal b_1 control is no longer constant with respect to s_0. It decreases with expected recruitment and it is higher (which reflects a more cautious policy) than its "known costs" counterpart. Furthermore, contrary to FQ regulation, the threshold for when the fishery should open increases with the cost uncertainty level.

For the EQ instrument under cost uncertainty, the extra degree of freedom of having one more parameter to adjust to reach an optimum is now put to use. Figure 4 shows clearly at which $E\{x_1\}$-value an initially closed fishery

[4]For $E\{x_1\}$ below the treshold level is *zero* harvest the optimal policy. This closed state of the fishery is achieved with any tax choice equal to or above the constant value.

should be opened up. A fishery in a closed state (which can be achieved by many β_1, γ_1 combinations) is indicated here by that the γ_1-value has jumped out of the diagram to a very high (or infinite) value while the β_1 parameter value is arbitrary. We see in Figure 5 that the $E\{x_1\}$ threshold value falls together with the threshold for the LT regime with identical cost uncertainty. Returning to Figure 4 we observe, for the fishery in the open state, that the β_1 parameter decreases with expected recruitment while the γ_1- parameter first increase, and then reach a maximum level before it decreases again. A main finding is that the EQ system is superior to the LT-system. This is for instance reflected in Figure 2 and by that the stationary expected present value (in Table 2) is higher for the EQ system. Both the LT and EQ regimes, however, significantly outperform the FQ-system.

So far I have compared the systems in the context of the optimal expected present value. Some of these optimal policies can be very risky with respect to keeping the fish stock alive. As Clark and Kirkwood (1986) say about their own findings for the FQ system: "The counterintuitive nature of these results may in part be a consequence of our assumption of risk neutrality, or more precisely, of the assumption that there is no intrinsic 'preservation value' associated with the resource stock."

Such a "preservation value" would have been given a higher weight in above calculations if the discount factor had been assumed to be closer to *one.* My investigation focus on how instruments fare in terms of extinction probabilities.

6 The Probability for Extinction

There is depreciation in the resource model (15): if, in the next period, stock x_2 is below the unstable equilibrium point, the population will eventually die out. Let $\psi(x_2)$ denote the probability density function for x_2 after harvesting. Then the probability for extinction is calculated as the cumulative distribution function $\Psi(\underline{x}_2)$ for the stock to be below $\underline{x}_2$:

$$\Pr\left(x_2 \leq \underline{x}_2\right) = \Psi\left(\underline{x}_2\right) := 1 - \int_{\underline{x}_2}^{\infty} \psi\left(x_2\right) dx_2 \tag{18}$$

where $\underline{x}_2 = 0.0776$ is the unstable equilibrium point of the model. Since the probability density function for x_2 obviously varies with initial escapement s_0 I suppress this argument in the following notation.

The probability distribution function for x_2 when c is fixed, is written as

$$\psi\left(x_2 \left| c\right.\right) = \int_0^{\infty} \psi\left(x_2 \left| x_1, c\right.\right) g\left(x_1\right) dx_1 \tag{19}$$

where $g\left(x_1\right)$ is the probability density function for x_1 for a given s_0, as defined in (14) and

$$\psi\left(x_2 \left| x_1, c\right.\right) := \frac{dz_1\left(x_1, x_2, c\right)}{dx_2} f\left(z_1\left(x_1, x_2, c\right)\right) \tag{20}$$

is the probability distribution for x_2 for given values of x_1 and c. The function $f\left(\cdot\right)$ is the probability distribution for z and the function $z_1\left(x_1, x_2, c\right)$ is given by

$$z_1\left(x_1, x_2, c\right) = \frac{x_2}{G\left(x_1 - H_1^{\mathfrak{R}}\left(x_1, c, \mathfrak{u}^{\mathfrak{R}}\right)\right)} \tag{21}$$

where $H_1^{\mathfrak{R}}\left(x_1, c, \mathfrak{u}^{\mathfrak{R}}\right)$ is the harvest under regulation system $\mathfrak{R} \in \left(FQ, LT, EQ\right)$. The wanted probability distribution function for x_2 when allowing the cost parameter c to be uncertain is now determined by

$$\psi\left(x_2\right) = \int_0^{\infty} \psi\left(x_2 \left| c\right.\right) \theta\left(c\right) dc \tag{22}$$

where $\theta\left(c\right)$ is the probability density function for c.

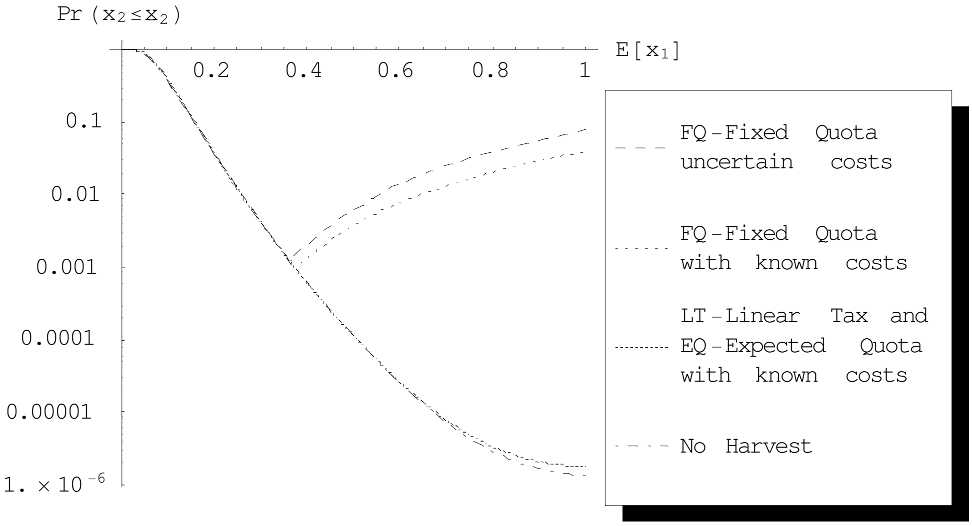

Figure 6. Probability for extinction after optimal harvesting for each system, respectively.

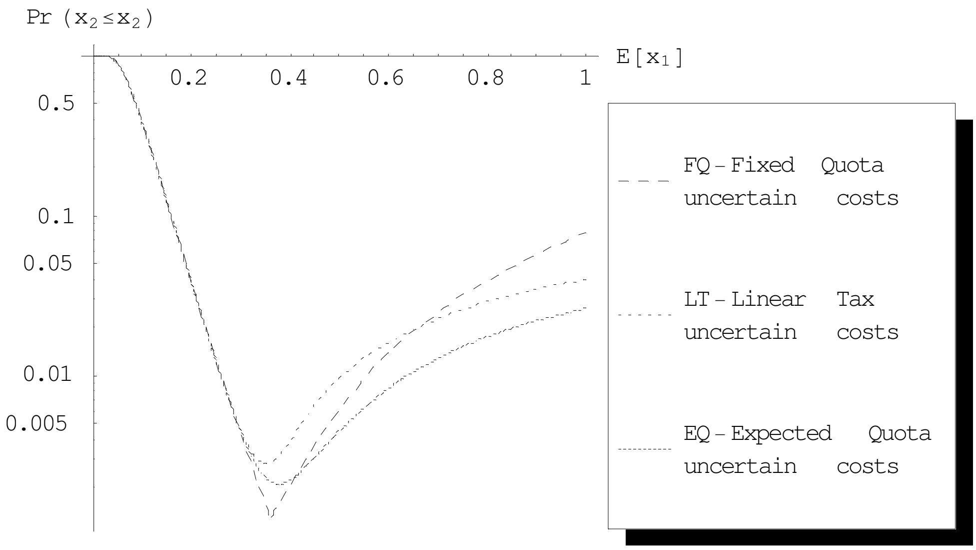

Figure 7. Probability for extinction after optimal harvesting for each system, respectively.

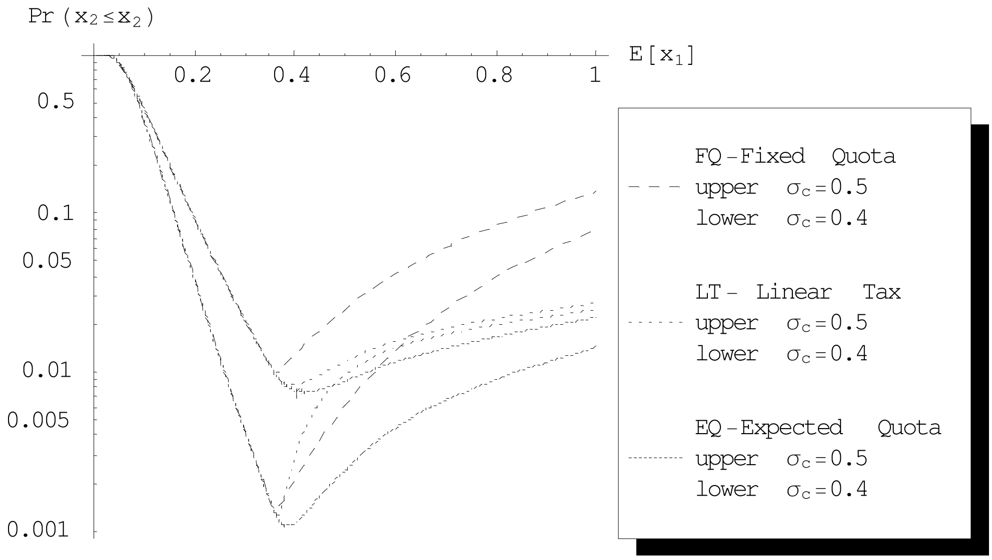

Figure 8. Probability for extinction after optimal harvesting for FQ with σ_c=0.4

Figures 6 and 7 show the probability of extinction on a logarithmic scale as a function of expected recruitment $E\{x_1\}$ when respective optimal policies are employed. Comparison between the two upper curves in Figure 6 reveals that the higher expected present value I found in last section for the fishery due to cost uncertainty in the FQ case presents itself at the expense of an increased extinction probability.

As mentioned can the LT (and the approximately equivalent EQ) regime with known costs be very effectively instilled. Optimal parameter settings will block the harvest if the stock size is slightly below the optimal level, and as we see in the lower part in Figure 6 the result is an extinction risk $\Pr(x_2 \leq \underline{x}_2)$ that is only meagerly higher than the risk associated with no harvesting at all. The distinctness is only recognizable in the figure for high values of $E\{x_1\}$. Still in Figure 6, we see that the FQ system expose the fish stock for a significantly higher extinction risk even though the harvest outcome of its optimal policy is considerably lower.

It is, however, under cost uncertainty that comparison with the FQ regime is upright; cost uncertainty is present in practice, and the FQ system is more resistant to its effects than the other regimes. In Figure 7, curves are displayed when the respective optimal policies in this case are employed. We see that the EQ system is superior to the FQ regime for most values of $E\{x_1\}$, while the LT system is inferior to all for the low and middle range of $E\{x_1\}$.

Regarding fair comparison between the various systems: A ceteris paribus condition for a comparison would emerge when the expected harvest outcomes are equal. For the EQ-regime there will in this case be many combinations of its two parameters that yield the same expected harvest. So for this system I determine which combination of β_1 and γ_1 that for a given expected harvest gives the minimum extinction probability. Today, regulation in fisheries is largely implemented by the FQ system. Then the intrinsic value of an eventual diminished extinction probability is a direct measure of the Pareto improvement (free lunch) when changing to an LT or an EQ regime.

Figure 8 shows curves for the systems under cost uncertainty when the expected harvest in all instances is the optimal harvest for the FQ system when $\sigma_z = 0.4$. The curve for this case is displayed in all the figures 6, 7 and 8. First, (in Figure 8) pay attention to the LT and EQ curves labeled $\sigma_z = 0.4$: The EQ regime gives the lowest extinction probability. Its superiority over the FQ system increases with $E\{x_1\}$ and the extinction probability is about 60% less for the highest abscissa values. Also the LT system is inferior to the EQ regime. For a small range of middle values of $E\{x_1\}$ the extinction probability for the LT regime is even higher than for the FQ system.

Now let us turn to all curves in Figure 8 labeled $\sigma_z = 0.5$. We know from Weitzman (2002) (although he did not include cost uncertainty) that the advantage of price compared to quantity control may increase along with ecological uncertainty. Thus, with cost uncertainty held fixed, and with a higher stock uncertainty, the LT-regime should perform better; at least compared to the FQ system. We see, as predicted by Weitzman, that the performance of the LT system is now markedly better than that of the FQ regime. The increased extinction probability associated with the increased stock uncertainty is minimal for the LT regime (on the logarithmic scale), and while the EQ system still dominates, its comparable advantage over LT regulation is much less.

7 Concluding Remarks

This paper compares various tools for managing fisheries using a numerical example. The two most important factors in the example are that unit harvesting costs depends on fish abundance (a demersal fishery), and, secondly, that specification of values for instrument parameters is based on statistical knowledge. For this I assume fish stock surveys to have a 40% standard deviation, and that uncertainty regarding fishermen's costs on unit effort has a 100% standard deviation of its mean.

I consider three instruments. Quantity control is most common: Wilen (2000) estimates that about 55 fisheries in the world are regulated with the ITQ regime, in which shares of TAC are distributed among fishermen by making the shares marketable. The purpose of privatizing the right to catch a Fixed Quota (FQ) is that the incentive to "race" for fish for strategic reasons may vanish. A Linear landing Tax (LT) is an alternative proposed by Weitzman (2002). In a general discrete model where the fish stock is a function of the last period escapement, Weitzman shows that such control, under pure ecological uncertainty, is unambiguously superior to quotas.

My alternative manager instrument is based on levying fishermen a strictly convex tax on catches. Berglann (2005) shows that it is possible to distribute total tax payments to individual fishermen in a way that prevents strategic moves between them concerning the sharing of payments. Then can for instance a market mechanism, like the one employed in an ITQ regime, be used to distribute shares of the total tax payment. The holding of a share certificate in such a regime will then correspond to the ITQ regime's privatized right to catch a certain amount of fish. I denote such a share of the expected industry harvest an Expected Quota (EQ).

The results with my example show that the EQ system significantly

Pareto dominates the practice of quota regulation. The domination is expressed both in terms of a higher optimal expected present value for the fishery and, under circumstances of an equivalent expected harvest outcome, in terms of a smaller stock extinction probability. When cost uncertainty is present, strictly convex taxation also dominates the linear landing fee approach but to a lesser extent when ecological variance increases.

Remonstrance may claim that strictly convex taxation may be too complicated for the fishing industry. Although this might be true, we should not underestimate the human capability to learn and to adapt to complicated situations. Hence, given that there might be political obstacles in imposing linear taxation for instance because the fishermen want to hold on to the resource rent, perhaps the non-linear alternative should be considered.

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