Discussion paper
No. 2010–6

Fisheries Management under Uncertainty using a Hybrid Instrument

Helge Berglann

Norwegian Agricultural Economics Research Institute
P.O. Box 8024 Dep
No-0030 Oslo, Norway
E-mail to author: helge.berglann@nilf.no

This version: April 2012

Acknowledgements

A number of people has contributed with discussions and/or comments on previous drafts. Special thanks goes to Sjur Didrik Flåm, Rögnvaldur Hannesson, Snorre Kverndokk and Anders Skonhoft. The author also acknowledges funding support from the Research Council of Norway.

Oslo, April 2012

Helge Berglann

Abstract

This article considers the use of a hybrid instrument to regulate fisheries, comparing this instrument with quantity control and linear taxation in regards to economic yields and the risk of resource depletion. Hybrid instruments have shown to be central in studies with static models but have hardly ever been explored in the context of dynamic fisheries. A numerical example concerned with a single-species demersal fishery where the stock estimate is uncertain indicates that a combination of price and quantity control in the form of a strictly convex tax on landings is clearly 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; Asymmetric information; Uncertainty; Quotas; Taxes; Hybrid instruments; Dynamic optimization

1 Introduction

Due to the presence of uncertainty and asymmetric information, the managers of fisheries struggle, 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, economists often prefer to indirectly control quantities using prices (Jensen, 2008). The issue of comparing linear landing fees with quotas in fisheries management has been addressed in earlier studies (Koenig, 1984a, 1984b; Anderson, 1986; Androkovich and Stollery ,1991, 1994). Of current interest in this debate is a paper by Weitzman (2002) where he proves the superiority of landing fees over quantity controls when decisions must be made in the face of inaccurate stock estimates. One of Weitzman's major points is that greater *ecological* uncertainty seems to enhance the relative performance of the price instrument.

This paper adds to Weitzman's (2002) study by also incorporating *economic* uncertainty. When Jensen and Vestergaard (2003) undertook a similar investigation, they aimed to generalize Weitzman's (1974) propositions about "Prices vs. Quantities" to dynamic fisheries. They found Weitzman's analytical method to be applicable for schooling fisheries where the costs are additively separable in catches and stock size.[1] For demersal instances, however, where harvesting costs are stock dependent, Jensen and Vestergaard (2003) found an analytical approach intractable.[2] Consequently, when Hannesson and Kennedy (2005) investigated this case, they used simulations to generate results. They showed that either instrument can prove superior over the other depending on the parameter values of the fishery model.

I want to extend the study of how various instruments compare for demersal fisheries. Apart from considering price and quantity control, I will examine a third alternative for the management of dynamic fisheries: the hybrid of these two controls or, more precisely, a strictly convex tax on landed fish. My emphasis on investigating a hybrid instrument is motivated by the fact that such regulation tools have shown to be central in studies with static models (e.g., Roberts and Spence, 1976; Weitzman, 1978; Kaplow and Shavell, 2002; Pizer, 2002). More importantly, a recent paper by Berglann (2012) shows that a strictly convex tax on total quantity can be shared among parties in a way that relieves them from strategic considerations by incorporating a *share quota* parameter in the tax function. In a fishery context, and in the view of the planner, this share quota parameter is interpreted as the expected number of catches by a vessel divided by the total number of expected catches in the fishing industry. Because the total tax bill for each

[1] See also Hansen's (2008) comments on Jensen and Vestergaard's (2003) article.

[2] McGough et al. (2009) found analytical results for a dynamic stochastic fishery in this case by linearizing the model around the deterministic steady-state. Thus, the model can not for instance be used to determine corner solutions.

vessel becomes a strictly decreasing function of the individual share of the quota, these shares are wanted and tradable. Then, by employing a market with a fixed supply of shares, competitive behavior will ensure an *ex post* equilibrium where fishers acquire optimal share holdings. For a given tax function, the distribution of tax payments will therefore be optimal.[3]

An additional motivating factor for considering hybrid instruments is the appeal they have in the control of multispecies fisheries. Here, flexibility is often demanded because fishers targeting certain species frequently face the dilemma that they have insufficient quotas to cover other jointly caught species.[4] For instance, the "deemed value" system employed by the New Zealand authorities to manage (multispecies) fisheries is a hybrid quota-tax system that allows each vessel to land catches above its quota for a species if the owner pays a fee for each unit of catch in excess of his quota holding. For each species this per-unit charge increases in 20% increments for each 20% by which a skipper's catch exceeds his quota holding (Holland and Herrera, 2006; Sanchirico et al., 2006; Marchal et al., 2009a, 2009b). Embedding a strictly convex tax on landings with a quota parameter, as proposed by Berglann (2012), and doing this for each species constitutes a multispecies fishery control regime that can be viewed as a refinement of the "deemed value" system. By taxing the total quantity of catches landed by a fisherman (and not only catches in excess of his quota holdings), he may find it profitable to stop fishing before his quota is reached for one type of species, while for another species he may choose to exceed the quota holding. Another fisher may make the decision to stop with a totally different and opposite final catch composition. Thus, with an industry comprising of a large number of vessels, the aggregate of landings at the end of the year might be closer to the TAC (or the expected harvest in this tax context) for each species, at least in comparison to the biased outcome that may occur by employing the "deemed value" method.

[3] The given tax function, however, is second-best because the fishery authority has to *ex-ante* estimate the best tax function parameters under uncertainty.

[4] In the long run, dilemmas like these might jeopardize the legitimacy and effectiveness of a regulatory system as a whole (Spence, 2001). Among other things because of the economic incentive to discard unintended catches.

For simplicity, this article employs a single species model and ignores details about individual vessels by focusing on the expected aggregate catches of the fishing industry. As the vehicle for comparison I use dynamic programming to compute the optimal expected present value over an infinite time horizon, for each instrument. Out of concerns for safety (or ecological resilience), I also investigate each scheme's ability to prevent resource extinction (Roughgarden and Smith, 1996; Sethi et al., 2005; Kramer, 2009). Of particular interest is a comparison of proportional taxation with the hybrid scheme proposed here, with the quantity control serving as the benchmark. The dynamic model is based on the work of Reed (1979).

As in 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. I also assume that the manager faces economic uncertainty. Such uncertainty may have several sources, for instance regarding to the price fishermen get for landed catches, to the efficiency of various fishing gear and search tools, differences in fishermen skills and experience, and weather and local conditions at sea. To ease computation economic uncertainty should be limited to comprise of one stochastic variable. For this purpose I select that variable to be the cost per unit of fishing effort.

The present paper is organized as follows: Section 2 spells out the diverse regulation schemes. Section 3 describes the dynamic model and the information flow, while Section 4 shows how dynamic programming serves to optimize the instrument parameters. In Section 5, my numerical example is introduced and results are presented that compare optimal yields under the various regimes when stock estimates are uncertain and cost uncertainty may prevail. Also included are results for a deterministic case. Section 6 includes the investigation of how the instruments fare in terms of the probability of extinction and 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 the first-hand price p for landed fish is constant. Costs per unit harvest depends on current stock $\tilde{x}$ as follows: $C(\tilde{x}) := c/\tilde{x}$ where c is a constant common to all parties. All skippers are profit maximizers with a time perspective restricted to the current period. They have all perfect knowledge of c and current stock size $\tilde{x}$.

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

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

where x denotes the stock size in the beginning of the period. The necessary (and sufficient) condition for an interior solution of problem (1) is expressed by the function H^{OA} (Open Access) defined by

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

It is well known that outcome (2) might cause overfishing, the chief reason being absence of intertemporal concerns. Suppose 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)**;
- *strictly convex 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. With reference to (1) the industry, in this case, 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

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

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

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

The necessary (and sufficient) condition for an interior solution of (7) is

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

The solution of (8) with respect to h yields two roots. Using the root that ensures $h < x$ and the condition $h \geq 0$ yields a harvest h^{EQ} given by

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

I have now determined how fishermen comply under the various regulating regimes. Let henceforth the integer k refer to time. For the purpose of simple notation I hereby symbolize control parameter(s) in period k under regime $\mathcal{R} \in \{FQ, LT, EQ\}$ as

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

Correspondingly, the harvest in period k is expressed by $h_k^{\mathcal{R}} = H_k^{\mathcal{R}}\left(x_k, c, \mathfrak{u}_k^{\mathcal{R}}\right)$. Within each regime the task of the regulator amounts to find a "best value" of $\mathfrak{u}_k^{\mathcal{R}}$ under an infinite time horizon perspective. To elaborate on his problem, I must first specify the dynamic model and tell how information is updated.

3 The Model and the Information Flow

The information flow, which is illustrated in Figure 1, resembles that assumed by Weitzman (2002), and Clark and Kirkwood (1986). It comprises in every period two stages and is described as follows: The exact escapement level

s_{k-1} (being 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 accounted for by 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}. From (10) stock size x_k emerges at the beginning of stage k. The regulator cannot however, "see" x_k since z_{k-1} has not yet been disclosed for him.

The random variables z_{k-1} for all k are assumed 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 such statistical information for x_k and c, the manager must decide a "best" value of the parameter(s) $\mathrm{u}_k^{\mathcal{R}}$ of his control instrument $\mathcal{R}$.

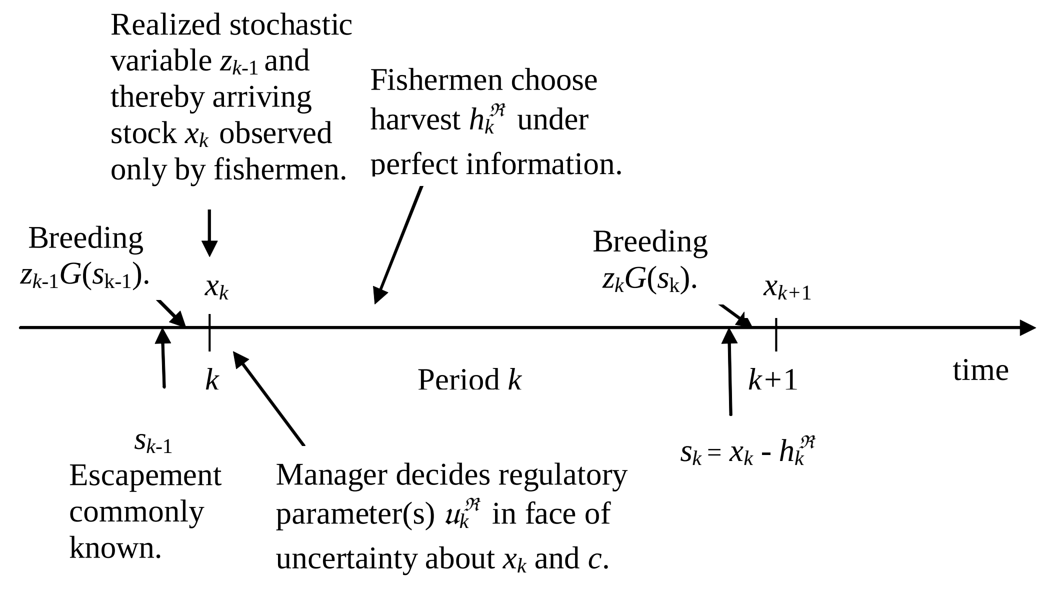

Figure 1. Informational sequence

There is an information asymmetry. The fishermen are better informed. They know the realization of z_{k-1} and thereby the arriving stock x_k. Being aware of costs and of current stock, they respond to the prevailing $\mathfrak{u}_k^{\mathcal{R}}$ during the year by choosing their most economical level of effort and thereby a flow of catches that at the end yields the profit maximizing harvest $h_k^{\mathcal{R}} = H_k^{\mathcal{R}}\left(x_k, c, \mathfrak{u}_k^{\mathcal{R}}\right)$ for that year. The escapement becomes

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

which eventually, at the end of the year k, for instance through reports on catch and effort data, 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 $\mathcal{R}$ is the same for every period k. So without loss of generality, I can in the following consider the regulator's problem at the beginning of period $k = 1$ when s_0 is known. Stationarity 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 $V^{\mathcal{R}}(\cdot)$ is the optimal expected present value function, $\rho \in (0,1)$ denotes the discount factor and harvest is $h_1^{\mathcal{R}} = H_1^{\mathcal{R}}\left(x_1, c, \mathfrak{u}_1^{\mathcal{R}}\right)$. The function $\Pi_1(\cdot)$ is the current social economic value of the fishery for year 1, given by[5]

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

The expectation operator $E\{\cdot\}$ in this paper stands for the expected value

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

of whatever is contained within the brackets. In the Bellman equation (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 approximations and the result $V^{\mathcal{R}}(\cdot)$ is unique[6].

5 Numerical Example

In my numerical example fish commands price $p = 1$, and the discount factor $\rho = 0.9$. The stock-recruitment model that Clark and Kirkwood (1986) used in their numerical example is given by $(1 - \exp(-2s))$. Since extinction probabilities are of great interest and concern (see next section), I want to extend that example to include the possibility of resource collapse. Hence, I specify the model as

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

The deterministic model thus has a stable natural equilibrium at $x = 0.796$, but also an unstable equilibrium point at $x = 0.0776$.[7] Thus, the population is doomed to extinction if the stock ever falls below the critical depensation level given by the unstable equilibrium point.

The stochastic variables z and c are both assumed 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

[6] 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).

[7] These natural equilibrium points are determined by setting $x = s$ (i.e. no harvesting), and the equation becomes $x = G(x)$.

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 5 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 $V^{\mathcal{R}}(s_0)$ of the fishery for all systems $\mathcal{R}$ 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 $E\left\{s_1^{\mathcal{R}*}\,|s_0\right\}$ for regime $\mathcal{R}$ and calculated by

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

where $\mathfrak{u}_1^{\mathcal{R}*}(s_0)$ is the obtained optimal argument functions that are depicted in Figure 5 and defined as

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

In addition, Table 1 and 2 list the optimal expected present value $V^{\mathcal{R}}\left(E\left\{s_\infty^{\mathcal{R}*}\right\}\right)$ and the expected recruitment level $G\left(E\left\{s_\infty^{\mathcal{R}*}\right\}\right)$ at the stationary optimal expected escapement level (defined implicitly as $E\left\{s_\infty^{\mathcal{R}*}\right\} := E\left\{s_\infty^{\mathcal{R}*}\left|E\left\{s_\infty^{\mathcal{R}*}\right\}\right.\right\}$) for all of my choices.

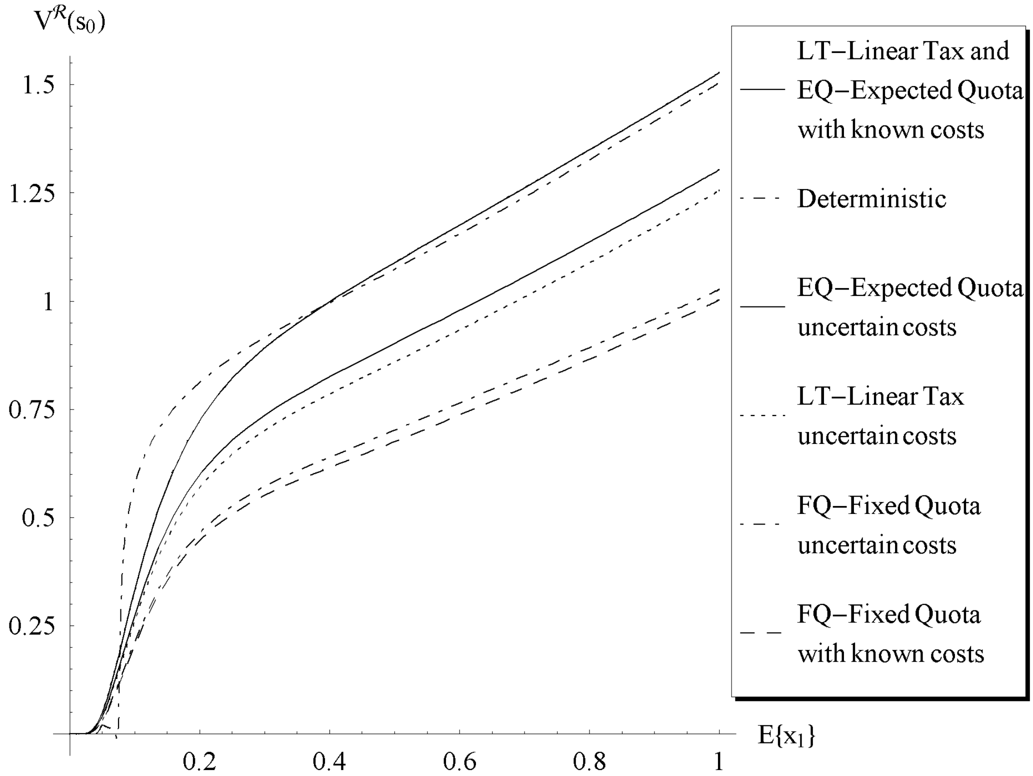

Figure 2. Expected value vs expected recruitment.

Table 1: Expected present value at the stationary expected escapement level, $V^{\mathcal{R}}\left(E\left\{s_{\infty}^{\mathcal{R}*}\right\}\right)$.

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

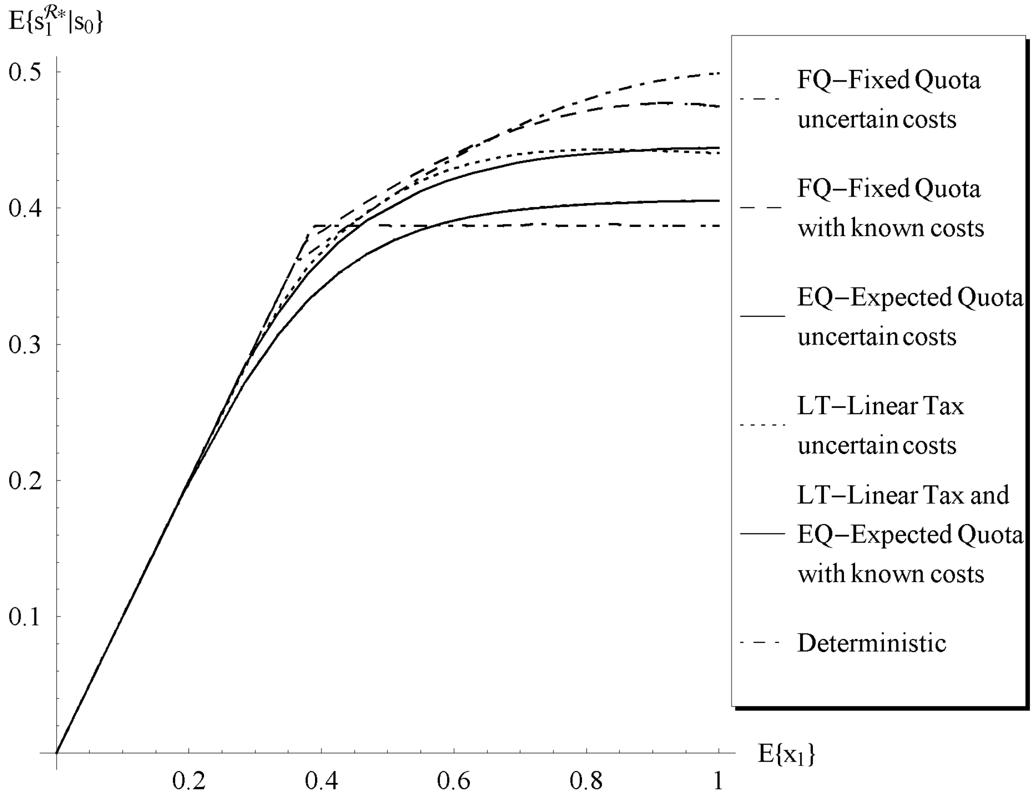

Figure 3. Expected escapement vs expected recruitment.

Table 2: Expected recruitment at the stationary expected escapement level, $G\left(E\left\{s_\infty^{\mathcal{R}*}\right\}\right)$.

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

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 $q_1 = q_1^*(s_0)$ (Figure 5) dependent on the result of stock surveys. Not shown in any of these 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 1, 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.

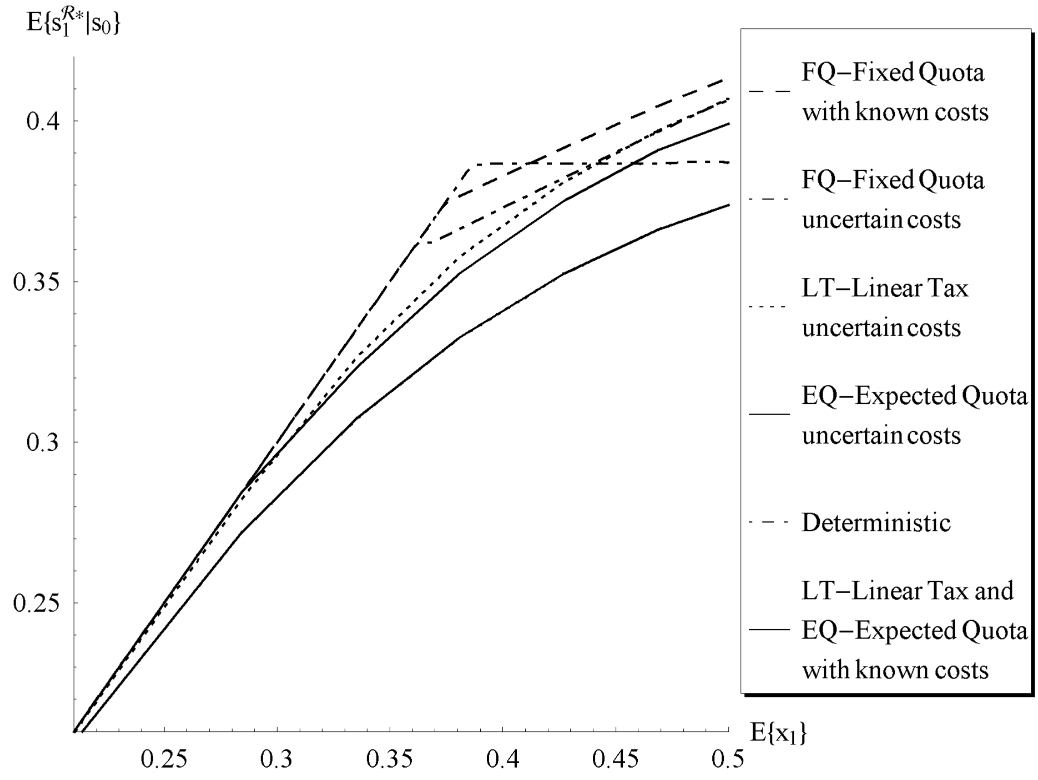

Figure 4. Expected escapement vs expected recruitment. Close-up of Figure 3.

In Figure 4, 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 4, 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.

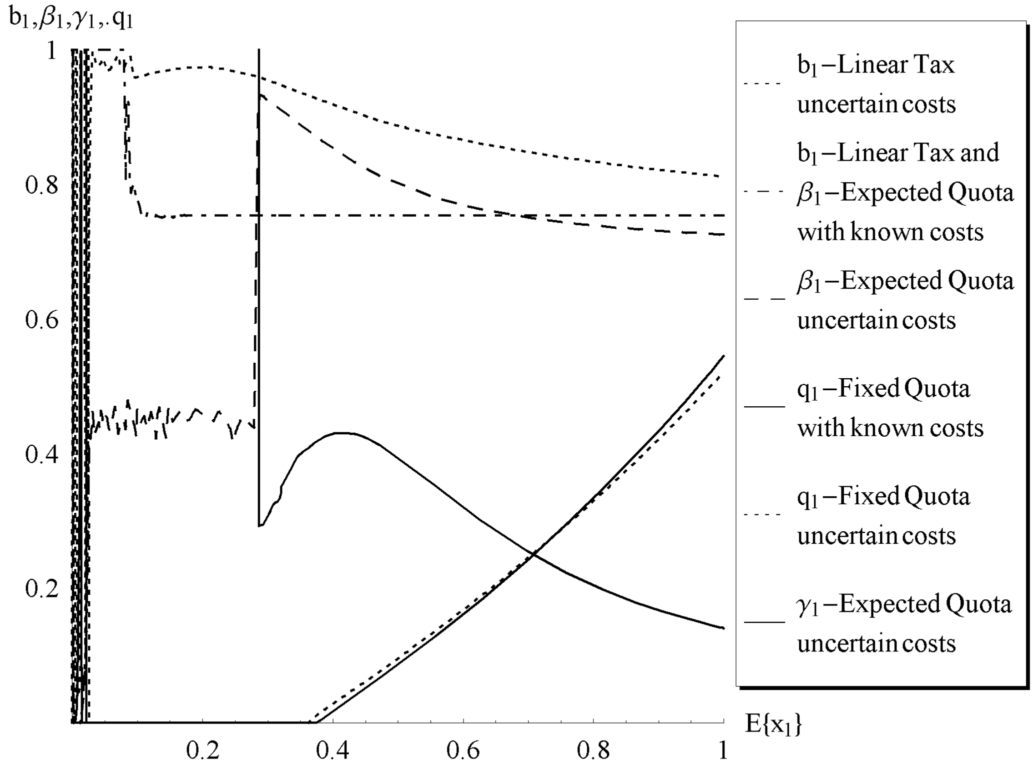

Figure 5. Optimal instrument parameter values vs expected recruitment.

Another observation is in Figure 5: the optimal landing fee is independent of $E\{x_1\}$[8]. Weitzman (2002) finds an analytical expression for such a

[8] For $E\{x_1\}$ below the treshold level is *zero* harvest the optimal policy. This closed

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 1, 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 5, 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 5 shows clearly at which $E\{x_1\}$-value an initially closed fishery 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 4 that the $E\{x_1\}$ threshold value falls together with the threshold for the LT regime with identical cost uncertainty. Returning to Figure 5 we observe, for the fishery in the open state, that the

state of the fishery is achieved with any tax choice equal to or above the constant value.

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 1) 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

The resource model (15) allows for the possibility of critical depensation. More precisely, if the next period stock x_2 falls 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 for each initial escapement level s_0, is calculated as the cumulative distribution function $\Psi(\underline{x}_2)$ for the stock to be below $\underline{x}_2$:

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

where $\underline{x}_2 = 0.0776$ is the unstable equilibrium point of the model.

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 $g(x_1)$ 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 $f(\cdot)$ is the probability distribution for z and the function $z_1(x_1, x_2, c)$ is given by

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

where $H_1^{\mathcal{R}}\left(x_1, c, \mathfrak{u}^{\mathcal{R}}\right)$ is the harvest under regulation system $\mathcal{R} \in \{FQ, LT, EQ\}$. 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 $\theta(c)$ is the probability density function for c.

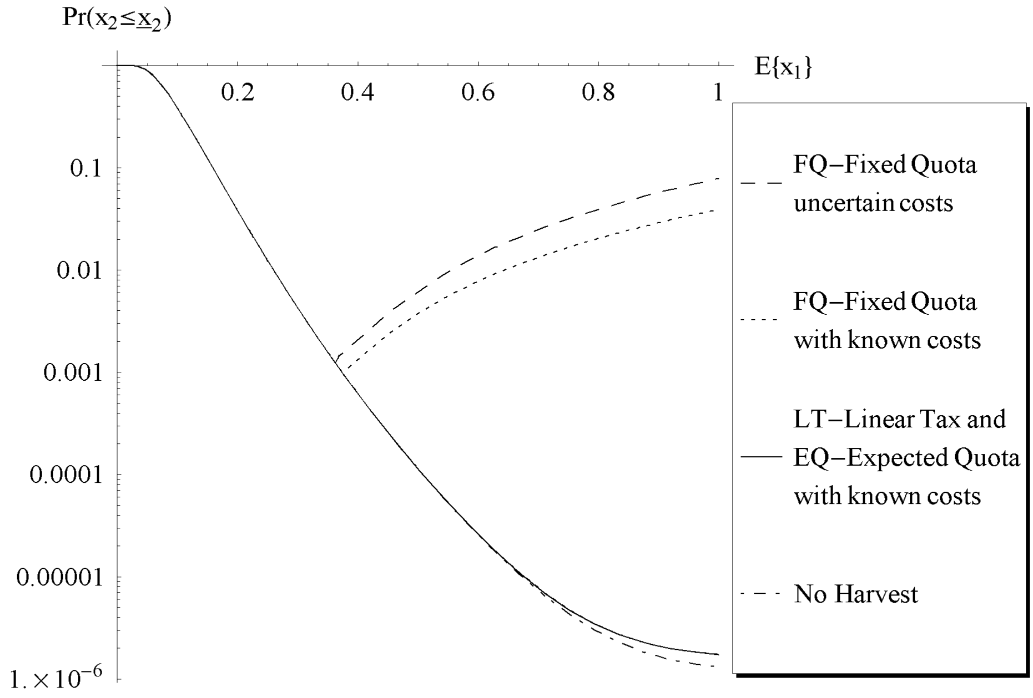

Figure 6. Probability for extinction after optimal harvesting for each system, respectively.

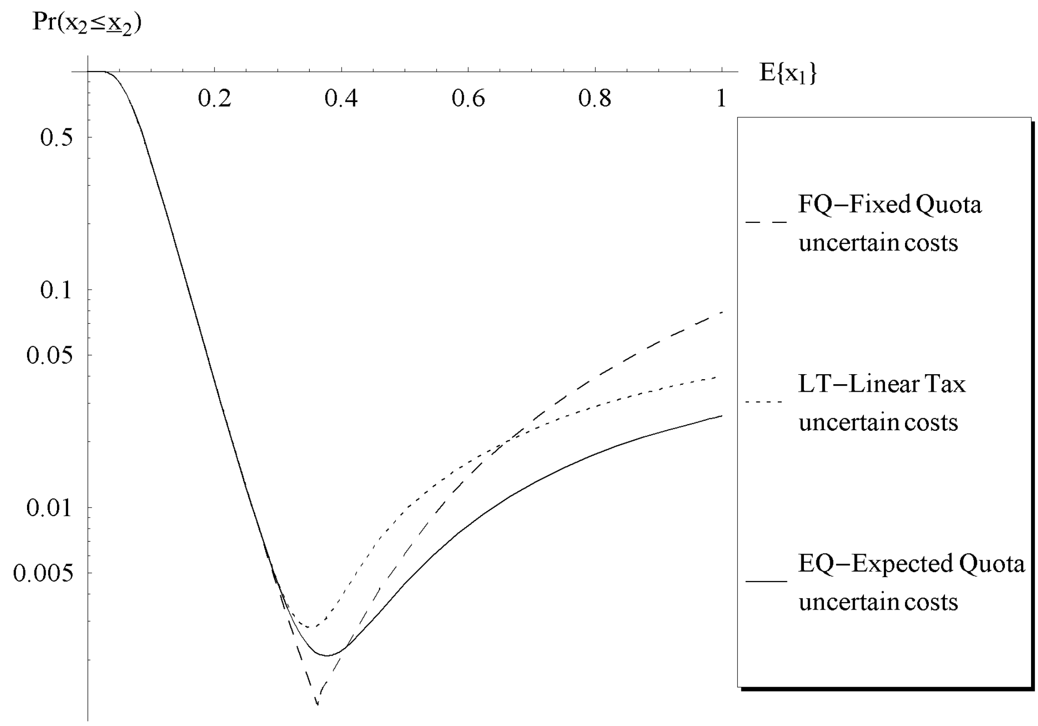

Figure 7. Probability for extinction after optimal harvesting for each system, respectively.

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.

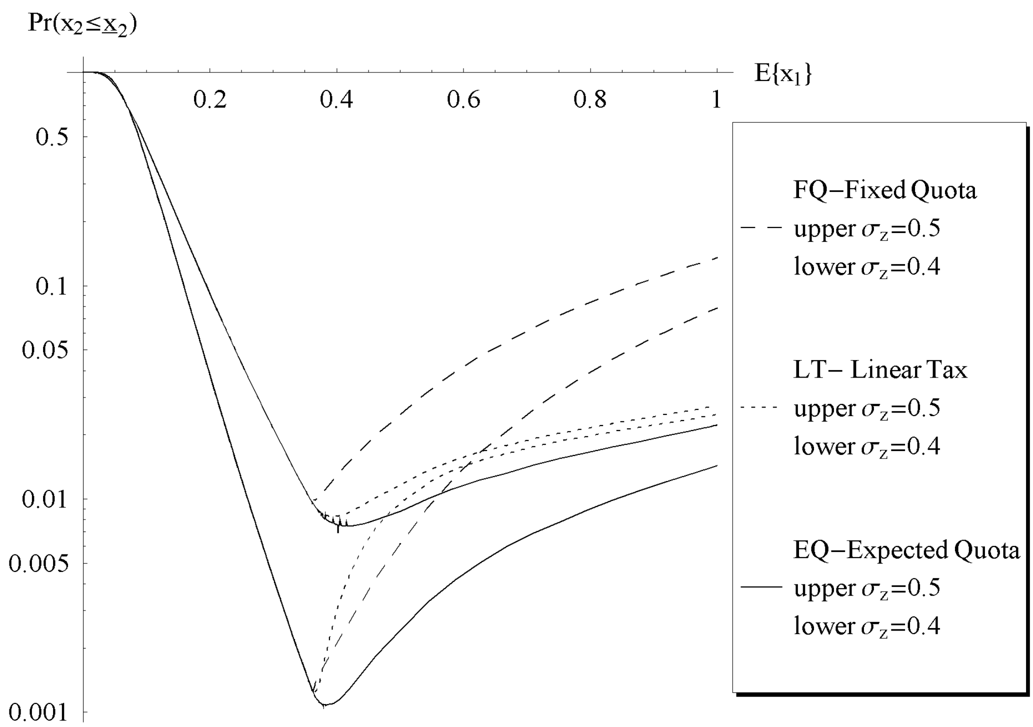

Figure 8. Probability for extinction after optimal harvesting for FQ with σ_z=0.4

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: (a) unit harvesting costs depend on fish abundance (as is typical in a demersal fishery), and (b) instrument parameters are assigned a "best value" based on statistical knowledge. I assume that the fish stock survey has a 40% standard deviation from its mean, and that uncertainty regarding fishermen's costs on unit fishing effort has a 100% standard deviation from its mean.

I consider three instruments: quantity control (FQ), linear taxes (LT), and expected quotas (EQ). The name of the latter instrument denotes the amount of catches expected by the planner when fishers are levied a strictly convex tax on catches. The most commonly used tool is quantity control. Chu (2009) estimated that several hundred stocks in eighteen countries around the world are regulated through the individual transferable quota (ITQ) regime, in which shares of TAC are efficiently distributed among fishermen by trades in a competitive share market. 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), among others. In a general discrete model where the fish stock is a function of the last period escapement, Weitzman shows that such a control is unambiguously superior to quotas under pure ecological uncertainty.

The alternative manager instrument (EQ) presented in this paper is based on levying fishermen a strictly convex tax on landing. The results in my example show that the EQ system significantly Pareto dominates the practice of quota regulation. This 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, as conjectured by Weitzman (2002), to a lesser extent when ecological variance increases.

As Berglann (2012) shows, the scheme may be as potentially easy to implement as an individual transferable quota (ITQ) regime. The individual quota in the ITQ regime will then correspond to an individual transferable expected quota (ITEQ) in the hybrid regime. The flexibility of that latter quota notion might, as mentioned in the introduction, be particularly valuable in managing a multispecies fishery. Total (expected) quotas, each indirectly specified by tax parameters, could be set for each regulated species. The tax amount saved by landing less than the quota for one species will be used to cover the extra tax amount levied for exceeding the expected quota of another species.

Vessel owners in an ITQ managed fishery that already possess quotas or are accustomed to getting them for free will of course oppose the transition to a regime where they suddenly are levied an extra tax. However, as Berglann

(2012) also demonstrates, the proposed system can easily be adjusted to redistribute the tax gained by the government by giving the individual skipper a rebate that ensures that his tax expenses is nullified if he happens reach the expected quantity exactly. In this way the transition from ITQ based management to the proposed scheme might be smoothly carried out.

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