Fisheries Management under Uncertainty using a Convex Tax

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Abstract

This article considers the use of convex taxation as an instrument to regulate fisheries, comparing it with linear taxation in regards to economic yields and the risk of resource depletion. Convex taxation is shown to be central in studies with static models but has hardly ever been explored in the context of dynamic fisheries. Literature shows that a linear tax regime is superior to quantity regulation when the stock estimate is uncertain in the terms of economic gains and of its ability to prevent resource extinction. When cost uncertainty is also involved, a strictly convex tax on landings can prove even more efficient. A numerical example with a single-species demersal fishery having both ecological an economic uncertainty demonstrates the gain in value of moving from a linear to a strictly convex tax.

JEL classification: D82, H21, Q22

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1 Introduction

Fishing practices are far more effective now than a few decades ago. More effective fishing vessels and gear that contribute to overcapacity necessitate the introduction of measures to control and restrict the harvesting activity to a sustainable level (Bjorndal & Munro, 2012). However, sustainability in the fishing fleet is a multi-dimensional concept. The total value of fisheries is regularly calculated based on market prices and operating characteristics (Utne, 2009). Nevertheless, non-market issues such as environmental and social effects, climate change and so on, i.e. ecosystem-based management (EBM), is increasingly included in the fishery evaluation criteria (Kvamsdal et al., 2020; Utne 2009). Although EBM has been adopted in many places, it has not yet been put into practice (Skern-Mauritsen et al., 2015). Moreover, despite development of models and methods to create judicious total allowable catch (TAC) advice, the success of implementing proposed management goals with efficiency has languished (Villasante et al., 2011).

While direct quantity regulation is most common, economists often prefer to indirectly control quantities using prices (Jensen, 2008). The issue of comparing uniform tax rates with quotas in fisheries management has been addressed in earlier studies (Koenig, 1984a, 1984b; Anderson, 1986; Androkovich & Stollery 1991, 1994). Of current interest in this debate is a paper by Weitzman (2002) where he proves the superiority of uniform fees over quantity controls when decisions must be made in the face of inaccurate stock estimates. One of Weitzman's major points are that taxes is always preferred over quotas under ecological uncertainty.and 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 generalise Weitzman's (1974) propositions about "Prices vs. Quantities" to dynamic fisheries. They found Weitzman's analytical method to be applicable for 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

[1]Weitzman (1974) in a "static" fishery context, says: Linear landing taxes are prefered to quotas if the marginal cost function is steeper than the benefit function. 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.

other depending on the parameter values of the fishery model. When costs are independent of stock size, which is often assumed for schooling fisheries, linear taxation is inferior to quota regulation (Hansen et.al., 2013).

In this study I will compare uniform fees with another alternative for the management of dynamic fisheries, namely a strictly convex[3] tax on landed fish. My emphasis on investigating a non-uniform tax instrument is motivated by the fact that such regulation tools have shown to be central in studies with static models (e.g., Roberts & Spence, 1976; Kaplow & Shavell, 2002; Pizer, 2002; Berglann, 2012). For simplicity, the article employs a single species model and focuses on aggregate catches.

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 ecological resilience, I also investigate each scheme's ability to prevent resource extinction (Roughgarden & Smith, 1996; Sethi et al., 2005; Kramer, 2009; Hansen et.al., 2013). Of particular interest is a comparison of proportional taxation with the strictly convex scheme proposed here, with quantity control in the deterministic case 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 manager only has statistical knowledge of the stock size when he specifies the considered instrument. I also assume the presence of asymmetric information where the regulator has uncertain information about the fleet's technology costs. Such uncertainty faced by the manager may have several sources,

[3] A function $f : X \to \mathbb{R}$ is called convex if the following condition hold, For all $0 \leq t \leq 1$and all $x_1, x_2 \in X$. $f(tx_1 + (1-t)x_2) \leq tf(x_1) + (1-t)f(x_2)$. (https://en.wikipedia.org/wiki/Convex_function)

for instance regarding to the price fishermen fetch for their catches, to the efficiency of various fishing gear and search tools, differences in fishermen skills and experience, and weather and other conditions at sea. To ease computation this economic uncertainty, faced at the time when instrument calibration must be carried out, will be limited to comprise one stochastic variable. For this purpose I select that variable to be the cost per unit of fishing effort. I also assume homogenious vessels because otherwise the result might be inefficient due to different marginal tax rates across firms. Since an optimal non-uniform tax instrument is hard to find, I will use a quadratic approximation to this tax.

The present paper is organised 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 that compare optimal yields under the linear and non-linear tax regimes where regulator make decisions when stock estimates are uncertain and cost uncertainty may prevail are presented. Results for a deterministic case are also presented. 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. Intermittent harvesting costs depends on current stock $\tilde{x}$ as follows: $C(\tilde{x}) := c/\tilde{x}$, where c is a constant and common to all parties. All vessel operators have perfect knowledge of c and current stock size $\tilde{x}$. Ignoring fixed costs, the accumulated or total costs over the year is the integral over current stock size at the beginning of the year to the end of the year.

Assuming that the whole fleet maximizes profit with a time perspective restricted to the current period, then, 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 at the beginning of the period and where $x - h$ is the stock size at the end of the year. The necessary (and sufficient) condition for an interior solution of problem (1) is expressed by the function H^{OA} (Open Access) defined by

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

It is well known that outcome (2) might cause overfishing. The reason is that individual fishers disregard the impact they have on other fishers catches which results in a stock externality. Fishing activity increases until average rather than marginal product equals opportunity costs. Economic waste occurs because harvesting uses more inputs than necessary.

Suppose a social planner is bestowed with the authority to avoid the "tragedy of commons" by regulating the fishery. In doing so the planner must cope with blurred information on the cost parameter c and the stock size x at the beginning of the period. I consider four control instruments, of which some can be a special case of others, in the hands of the said authority:

- *quantity limitation*, denoted a **Fixed Quota (FQ)**;
- *price control*, denoted a **Linear Tax (LT)**;
- *convex taxation*, denoted a **Convex Tax (CT);**
- *quadratic taxation*, denoted a **Quadratic Tax (QT);**

We now define how fishermen comply with these schemes:

2.1 The Fixed Quota (FQ) Instrument

One solution to the fundamental open access problem is to establish property rights (Bjorndal & Munro, 2012). The regulator specifies a non-negative total quota q (TAC) for the period and divides it equally between vessels. This instrument addresses the property right problem directly. Its rationale is that fishermen are now free to focus on profit for a given quota instead of racing for fish. The fishing industry solves the same problem as in the case with no regulation (1) except that the quantity restriction is binding when $q \leq H^{OA}(x, c, p)$. I.e. even when the population becomes extinct the quota is always taken except in the case when it exceeds actual stock size. Thus fishermen, regulated by the FQ instrument, select a harvest h^{FQ} equal to

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

2.2 The Linear Tax (LT) Instrument

An alternative regime is to impose a tax per kg of landed fish. Almost independent of the stock size of demersal species, a linear landing tax more or less directly controls the size of the breeding stock. Most fishery models predict that a relatively stable reproducing fish stock enhances efficiency. On closer scrutiny, this explains why price control might dominate quantity regulation in the fishery case.

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 $0 \leq h \leq x$ telling that the catch can not exceed the available stock and, naturally enough, can not be negative. This yields a harvest h^{LT} equal to

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

Uncertainty in the industry's costs of effort (Hannesson and Kennedy, 2005) will diminish the linear tax instrument's potential advantage as a linear tax will not secure accuracy of the wanted escapement target. The reason is that the expected escapement target in this case must be set, for the sake of precaution, at a higher level. In turn this gives lower expected outcome.

2.3 The Convex Tax (CT) Instrument

A generic convex tax T (without a lump sum part) is levied on the industry's total harvest h in the period. The desired conception of that tax function is to nest the LT instrument with tax rate b and the FQ instrument with quota q as special cases. That is achieved with assuming a tax with a design specified by three parameters $\{a, b, q\}$ and the variable h (harvest) as follows

$$\begin{aligned} & T\left(h, a, b, q\right) \geqq 0 \text{ for } h, b, q = [0, \infty) \text{ and } 0 \leq a \leq 1 \\ & T\left(0, a, b, q\right) = 0,\ \frac{\partial T}{\partial h} \geq 0,\ \frac{\partial^2 T}{\partial h^2} \geq 0 \end{aligned} \tag{6}$$

In this function[4] the parameter a is defined is a shape parameter. For $a = 0$ the function becomes a linear tax while when $a = 1$ the tax function corresponds to a fixed quota[5], i.e.

$$\begin{aligned} T\left(h, 0, b, .\right) &= bh \\ T\left(h, 1, ., q\right) &= \begin{cases} 0 & \text{in case } h \leq q \\ \infty & \text{in case } h > q \end{cases} \end{aligned} \tag{7}$$

[4] An example of such a tax function is

$$T\left(h, a, b, q\right) = bh \exp\left(\frac{a}{1-a}\left(h - q\right)\right).$$

The author is grateful to Øyvind Hoveid for suggesting this equation.

[5] An infinite tax would in reality mean an administrative response or a very high fine.

The industry problem is

$$\max_h \left\{ ph - T\left(h,a,b,q\right) - c\ln\left(\frac{x}{x-h}\right)\right\} \tag{8}$$

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

$$h^{CT} = \max\left(0, \min\left(x, H^{CT}\left(x,c,p,a,b,q\right)\right)\right) \tag{9}$$

where $0 \leq a \leq 1$, $b \geq 0$ and $q \geq 0$ are the definition of these parameters that the regulator can choose for the period. Note that when $a = 0$ or $a = 1$ only one parameter, respectively b or q, is applied for function adjustment, while when $0 < a < 1$ the form of the function is in its "strictly convex" state and is determined by both the b and q parameters.

2.4 The Quadratic Tax (QT) instrument

The optimal form of the convex tax $T\left(h,a,b,q\right)$ (6) is difficult to determine, so instead we choose to apply a second order approximation. That yields a quadratic tax (QT) regime with two parameters, given by

$$t := \beta h + \frac{\gamma}{2}\left(h\right)^2 \tag{10}$$

where $\beta \geq 0$ and $\gamma \geq 0$ are parameters that the regulator can choose for the period. With this simpler quadratic form the linear tax nesting is sustained while we loose the embodiment of the fixed quota we could define for the generic tax. More importantly, we are able to derive an analytical solution for the harvest chosen by the fishermen. With this tax t the problem for the industry is

$$\max_{h}\left\{ph - t - c\ln\left(\frac{x}{x-h}\right)\right\} \tag{11}$$

The necessary (and sufficient) condition for an interior solution of (11) is

$$p - \beta - \gamma h - \frac{c}{x-h} = 0. \tag{12}$$

The solution of (12) with respect to h yields two roots. Using the root that ensures $h < x$ and the condition $h \geq 0$ yields a harvest h^{QT} given by[6]

$$\begin{aligned} h^{QT} &= H^{QT}\left(x, c, p, \beta, \gamma\right) \\ &:= \max\left(0, \frac{1}{2\gamma}\left(p - \beta + \gamma x - \sqrt{\left(\beta - p + \gamma x\right)^2 + 4\gamma c}\right)\right). \end{aligned} \tag{13}$$

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} (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

[6]Note: The square root expression is simplified: $(-\beta + p + \gamma x)^2 + 4\gamma(c + \beta x - px) = (\beta - p + \gamma x)^2 + 4\gamma c$

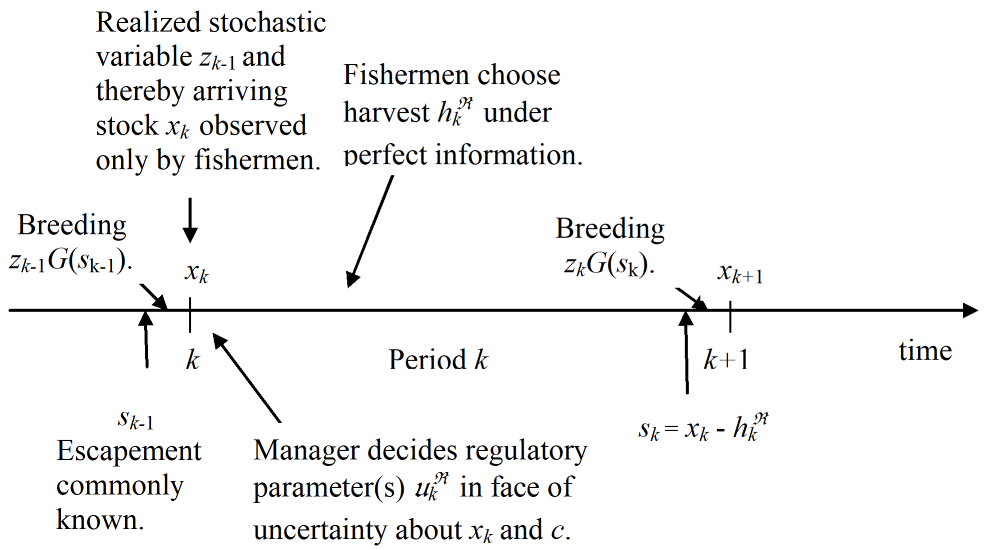

Figure 1: Informational sequence of the model starting at each stage with exact knowledge of escapement

model proposed by Reed (1979) given by

$$x_k = z_{k-1}G\left(s_{k-1}\right) \tag{14}$$

where the commonly known average stock-recruitment relationship $G(\cdot)$ is multiplied by the random factor z_{k-1}. From (14) 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 to 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 $\overline{c}$.[7] Based on such statistical

[7] We assume that the regulator cannot learn about c e.g. by observing ex post escapement. This is possible when we assume that c changes inter-annually, that the fishermen

information for x_k and c, the manager must decide a "best" value of the parameter(s) $\mathfrak{u}_k^{\mathcal{R}}$ of his control instrument$\mathcal{R} \in \{FQ, LT, CT, QT\}$.

There is an information asymmetry. The fishermen are better informed. They know c but also the realization of z_{k-1} and thereby the "incoming" stock x_k together with current stock size during the fishing seasom. The latter because they see the relationship between effort and harvest as they fish. Being aware of costs and of current stock, they respond to the prevailing $\mathfrak{u}_k^{\mathcal{R}}$ during the year by choosing a flow of catches that at the end yields the profit maximising harvest $h_k^{\mathcal{R}} = H_k^{\mathcal{R}}\left(x_k, c, p, \mathfrak{u}_k^{\mathcal{R}}\right)$ for that year. The escapement becomes

$$s_k = x_k - h_k^{\mathcal{R}}, \tag{15}$$

which eventually, at the end of the year k, for instance through reports on catch and effort data, is also revealed for the regulator such that s_k becomes common knowledge[8]. Then the 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 planner is the same in 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. The management

observe these variations in real-time but expect c to be constant in the future. The regulator has the same relation to $\theta(c)$ and has no other way of learning about costs.

[8]We assume that this update leads to exact information about the escapement level. Relaxing this assumption will increase the mathematical difficulty marketly (Clark & Kirkwood, 1986).

problem can be formulated with Bellman's functional equation

$$V^{\mathcal{R}}(s_0) = \max_{\mathfrak{u}_1^R} E\left\{\Pi_1\left(x_1, c, p, h_1^{\mathcal{R}}\right) + \rho V^{\mathcal{R}}\left(x_1 - h_1^{\mathcal{R}}\right) | s_0\right\} \tag{16}$$

where control instruments are $\mathcal{R} \in \{FQ, LT, CT, QT\}$, $V^{\mathcal{R}}(\cdot)$ is the optimal expected present value function (discounted future profit) of the current instrument and $\rho \in (0,1)$ denotes the discount factor. . The expectation operator $E\{\cdot\}$ stands for the expected value of what is contained in the brackets. Here the operator pertains to x_1 given s_0. The control variable $\mathfrak{u}_1^{\mathcal{R}}$,consisting of parameter(s) of instrument $\mathcal{R}$, is set to its optimal value $\mathfrak{u}_1^{\mathcal{R}*}$ by the regulartor who takes the resource restriction into account. The setting $\mathfrak{u}_1^{\mathcal{R}*}$ generates a harvest determined by the fishermen reaction function $h_1^{\mathcal{R}} = H_1^{\mathcal{R}}\left(x_1, c, p, \mathfrak{u}_1^{\mathcal{R}*}\right)$ determined by the first-order conditions specified in section 2. The function $\Pi_1(\cdot)$ is the current economic value of the fishery in year 1[9]

$$\Pi_1\left(x_1, c, p, h_1^{\mathcal{R}}\right) := p h_1^{\mathcal{R}} - c \ln\left(\frac{x_1}{x_1 - h_1^{\mathcal{R}}}\right). \tag{17}$$

The random variable z with density function $f(z)$ is transformed through (14) as $z_0(x_1) = x_1 / G(s_0)$ which gives the corresponding probability density function

$$g(x_1) := z_0^{'}(x_1) f(z_0(x_1)) = \frac{1}{G(s_0)} f\left(\frac{x_1}{G(s_0)}\right). \tag{18}$$

As customary the functional equation (16) is solvable through successive approximations and the result $V^{\mathcal{R}}(\cdot)$ is unique[10] and it is maximised when

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

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

the harvest function is optimal $h_1^{\mathcal{R}} = h_1^{\mathcal{R}*} = H_1^{\mathcal{R}*}\left(x_1, c, p, \mathfrak{u}_1^{\mathcal{R}*}\right)$.

Previous literature has focused on the performance of FQ versus LT. Weitzman (2002) shows that FQ is dominated by LT under pure ecological uncertainty. This happens because LT works through implicitly determining a stock level at which further fishing becomes unprofitable and thus very effectively instills the spawning stock to its optimal level more or less independent.of initial stock size. Hansen et. al (2013) extend that analysis and get the same result in the case when resource extinction is at stake due to "precautionary" concerns. Hanneson and Kennedy (2006) show numerical examples where FQ out-performs the LT regime. The latter might take place when economic uncertainty is present for the regulator and ecological uncertainty is low. In this case the LT method will not guarantee that the target escapement will be realized. The reason that is economic uncertainty makes it difficult for managers using fee control to reach their target escapement. Thus a precautonary higher LT are set in optimum, resulting in an outcome that might be lower than the outcome achieved with an appopriately set FQ.

These examples where FQ dominates LT, derived by Hanneson and Kennedy (2006) under economic uncertainty, might be further improved (as measured by optimal expected present value) by introducing some flexibility. Being in a stochastic cost context, it might be an improvement to have a higher or a lower realised catch than the one determined by the origional FQ. For instance, by using a quadratic tax, QT, such flexibility can be achieved while much of the control is maintained compared to LT. Such maintained control is achieved by limiting the variance around the expected optimal harvest level. More fishing than expected can, for example, lead to the extinction of fish stocks. Less fishing than expected is not so catastrophic, but the effect is not necessarily linear. The square tax (QT) may create the wanted curvature and as we will show in the next section QT is weakly superior to LT. An even further advancement is achieved by the three-parameter CT function, defined in section 2.3. Here the curvature can be made asymmetrical, so that any overcatch is punished even more severely than the corresponding undercatch. Moreover, the CT instrument is defined to nest the FQ and LT instruments. Thus, we can ascertain that

Theorem 1 *The three parameter convex tax instrument (CT) is weakly superior in maximising expected present value for all* $s_0 \in [0, \infty)$ *compared to fixed quotas FQ and linear taxation LT, i. e.*

$$\begin{cases} V^{CT}(s_0) \geq V^{LT}(s_0) \\ V^{CT}(s_0) \geq V^{FQ}(s_0) \end{cases}$$

for all $s_0 \in [0, \infty)$ *.*

Since the quadratic tax (QT) instrument only nests the LT instrument (and not FQ), it follows that

Corollary 2 *The quadratic tax instrument (QT) is weakly superior in maximising expected present value for all* $s_0 \in [0, \infty)$ *compared to linear taxation LT, i. e.*

$$V^{QT}(s_0) \geq V^{LT}(s_0)$$

for all $s_0 \in [0, \infty)$ *.*

5 Numerical Example

The purpose of this section is to illustrate the size of eventual gains when moving from an optimal linear tax (LT) to an optimal quadratic tax (QT), with the deterministic case serving as a benchmark (i.e., FQ control applied when the regulator has information of stock and cost).

In my numerical example fish commands price $p = 1$, and the discount factor $\rho = 0.9$. I adapt the parameter values and the stock-recruitment model that Clark and Kirkwood (1986) used in their numerical example, $(1 - \exp(-2s))$, which has a stable equilibrum at $x = 0.797$. Since extinction probabilities are of great interest and concern (see next section), I want to use that example but slightly extend it to include the possibility of resource collapse. Hence, I choose to specify the model as

$$G(s) = (1 - \exp(-2s))(1 - \exp(-10s)). \tag{19}$$

This model has a stable natural equilibrium at $x = 0.796$ and an unstable equilibrium point at $x = 0.0776$.[11] Thus, the population is doomed to extinction if the stock ever falls below the critical depensation level given by the unstable equilibrium point. Referring to the resource model (14), and the current value of the fishery (17), Table 1 shows the parameter values I have selected for the stochastic variables

The following figures are parametric plots with s_0 as the varying parameter. They use expected recruitment $E\{x_1\}$ as the abscissa function, given

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

Stochastic variable	Lognormal distribution	Mean value	Standard deviation
z	$f(z)$	$\overline{z} = 1$	$\sigma_z = 0.4$
c	$\theta(c)$	$\overline{c} = 0.1$	$\sigma_c = 0.1$

Table 1: Specification of the selected stochastic variables in the resource model (14) and in the equation (17) for the current value of the fishery.

by

$$E\{x_1\} = E\{x_1|\, s_0\} = E\{z_0 G(s_0)\} = \overline{z} G(s_0) = G(s_0). \tag{20}$$

Figures 2, 3 and 4 displays solutions of the functional equation (16) of 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 selected. Known costs for the QT and LT system, are costs given by its mean value $\overline{c}$. As said, 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 corresponding 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

$$E\left\{s_1^{\mathcal{R}*}\,|s_0\right\} = E\left\{\max\left(0, x_1 - H_1^{\mathcal{R}}\left(x_1, c, p, \mathfrak{u}_1^{\mathcal{R}*}(s_0)\right)\right)|s_0\right\} \tag{21}$$

where $\mathfrak{u}_1^{\mathcal{R}*}(s_0)$ is the obtained optimal argument functions that are depicted in Figure 4 and defined as

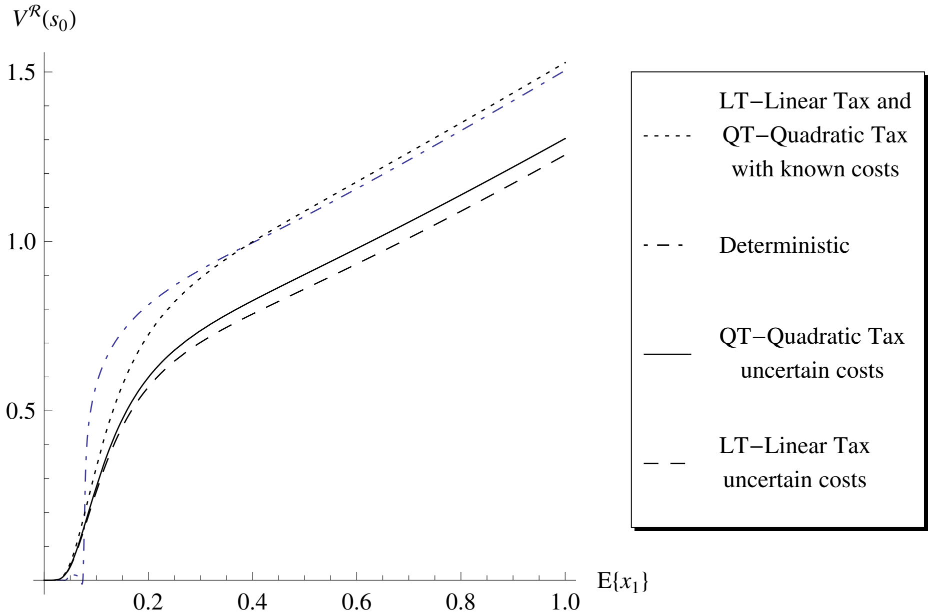

Figure 2: Parametric plot of the optimal expected present value versus expected recruitment. The legend indicates to which instrument the various curves belong, ranked after the ordinate value at the end of the abscissa axis.

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

In addition, Table 1 list the optimal present value $V^{\mathcal{R}}\left(E\left\{s_\infty^{\mathcal{R}*}\right\}\right)$ and the 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.

Notice in Figure 3 how the constant escapement policy emerges for the

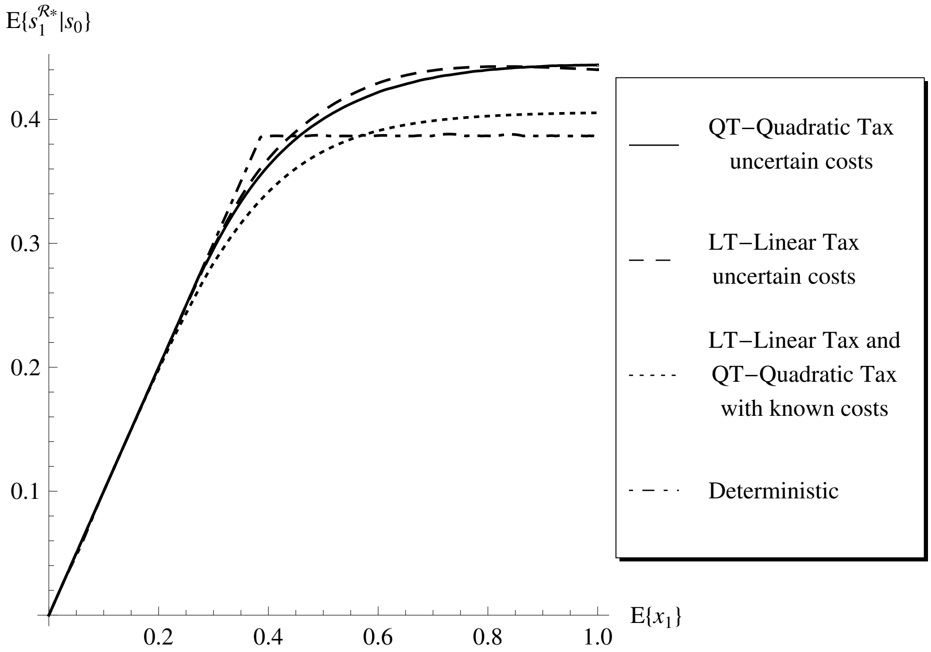

Figure 3: Optimal expected escapement versus expected recruitment. The legend indicate to which instrument the various curves belong, ranked after the ordinate value at the end of the abscissa axis.

		FQ-Deterministic	LT / QT σ_c=0.	LT σ_c=0.1	QT σ_c=0.1
Expected present value	$V^{\mathcal{R}}\left(E\left\{s_\infty^{\mathcal{R}*}\right\}\right)$	1.096	1.105	0.9051	0.9430
Expected recruitment level	$G\left(E\left\{s_\infty^{\mathcal{R}*}\right\}\right)$	0.5273	0.5186	0.5620	0.5533

Table 2: Expected present value and expected recruitment level at the stationary expected escapement level $E\left\{s_\infty^{\mathcal{R}*}\right\}$.

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.

With linear landing fees and known costs, the threshold for when harvesting should be allowed is very low (Figure 3). 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 QT regulation to approximate the 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: with only stock uncertainty the optimal landing fee is independent of $E\{x_1\}$[12]. Weitzman (2002) finds an analytical expression for such a constant landing tax when 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 the 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, as seen in Table 1, a higher expected present value.

The effect that "only knowing x_1 up to probability" makes the fishery

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

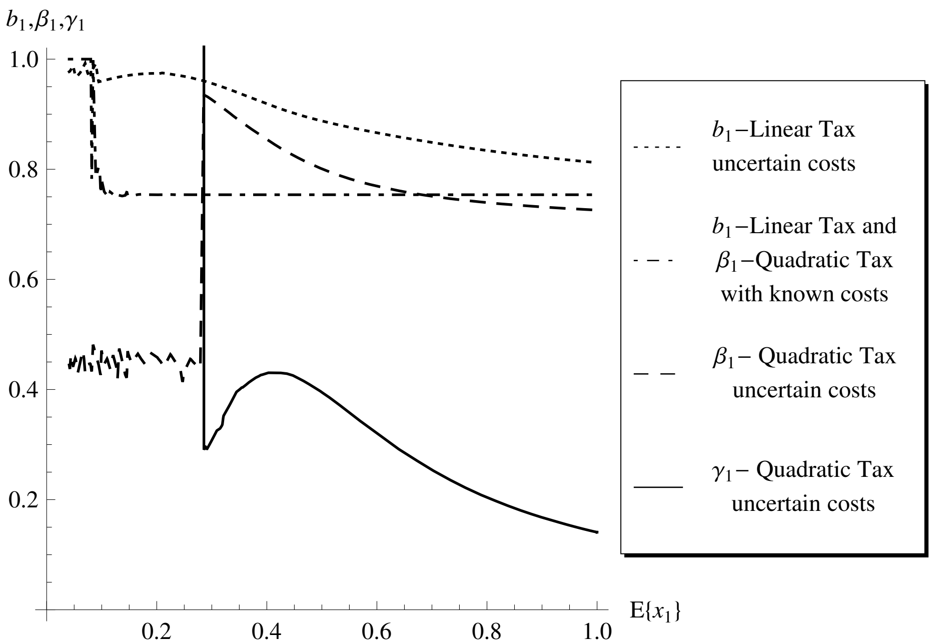

Figure 4: Optimal instrument parameter values vs expected recruitment. The legend indicates to which parameter described in section 2 the various curves belong, ranked after the ordinate value at the end of the abscissa axis.

more valuable is peculiar. 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 case.

The introduction of cost uncertainty when regulating with the LT and QT 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 is higher than its "known costs" counterpart which reflects a more cautious policy. Furthermore, the threshold for when the fishery should open increases with the cost uncertainty level.

For the QT 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 clearly shows 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 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 QT system is superior to the LT system. This is for instance reflected in Figure 2 and by the stationary expected present value (in Table 1) being higher for the QT 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 the sustainability of the fish stock. Such a "preservation value" would have been given a higher weight in the above calculations if the discount factor had been assumed to be closer to *one*. My next focus is an investigation on how instruments fare in terms of extinction probabilities.

6 The Probability of Extinction

The resource model (19) 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 of 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 $\underline{x}_2$:

$$\Pr(x_2 \leq \underline{x}_2) = \Psi(\underline{x}_2) := 1 - \int_{\underline{x}_2}^{\infty} \psi(x_2)\, dx_2 \tag{22}$$

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

$$\psi(x_2 \,|c) = \int_0^{\infty} \psi(x_2 \,|x_1, c)\, g(x_1)\, dx_1 \tag{23}$$

where $g(x_1)$ is the probability density function for x_1 for a given s_0, as defined in (18) and

$$\psi\left(x_2\left|x_1,c\right.\right) := \frac{dz_1\left(x_1,x_2,c\right)}{dx_2} f\left(z_1\left(x_1,x_2,c\right)\right) \tag{24}$$

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

$$z_1\left(x_1,x_2,c\right) = \frac{x_2}{G\left(x_1 - H_1^{\mathcal{R}}\left(x_1,c,\mathfrak{u}^{\mathcal{R}}\right)\right)} \tag{25}$$

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

$$\psi\left(x_2\right) = \int_0^{\infty} \psi\left(x_2\left|c\right.\right)\theta\left(c\right)dc \tag{26}$$

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

Figure 5 show the probability of extinction on a logarithmic scale as a function of expected recruitment $E\{x_1\}$ when respective optimal policies are employed. The two upper curves in Figure 5 reveal that the higher expected present value I found in the last section for the fishery due to asymmetric information of costs in the LT case presents itself at the expense of an increased extinction probability.

As mentioned the LT (and the equivalent QT with $\gamma_1 = 0$) regime with known costs can be very effectively instilled. Optimal parameter settings

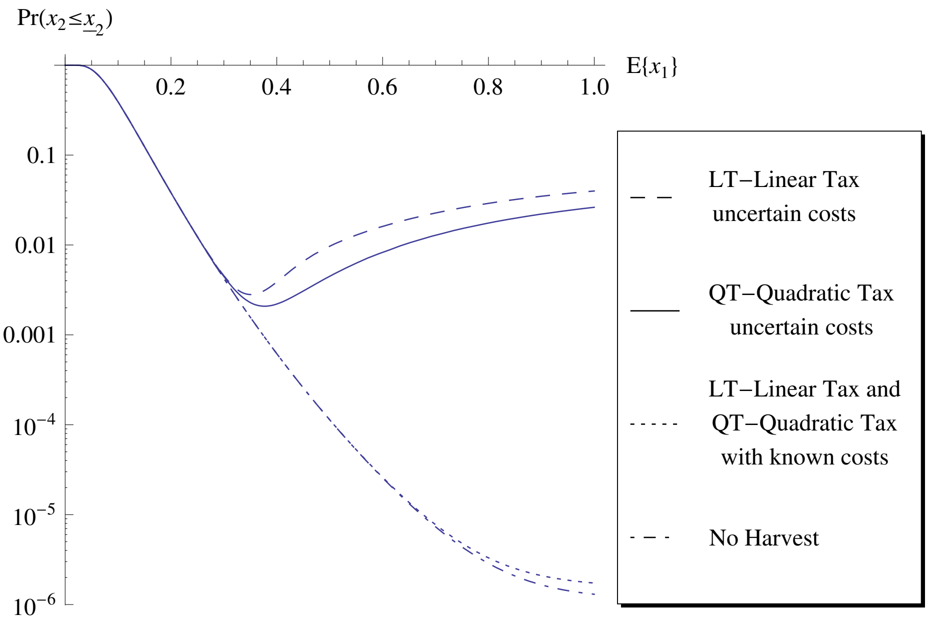

Figure 5: Probability for extinction after optimal harvesting for each system, respectively. The legend indicates to which instrument the various curves belong, ranked after the ordinate value at the end of the abscissa axis. The last curve is for when no harvesting takes place by the industry.

will block the harvest if the stock size is slightly below the optimal level, and as we see in the lower part in Figure 5 the result is an extinction risk $\Pr(x_2 \leq \underline{x}_2)$ that is only slightly higher than the risk associated with no harvesting at all. The distinctness is only recognisable in the figure for high values of $E\{x_1\}$. The increased extinction probability associated with the increased stock uncertainty is minimal for the LT regime (on the logarithmic scale), and while the QT system still dominates, its comparable advantage over LT regulation is much less.

7 Summary and Conclusion

This paper has compared various tools for managing fisheries under asymmetric information about fish stocks and of effort costs. I reviewed four instruments: quantity control (FQ), linear taxes (LT), convex taxation (CT) and quadratic taxation (QT). The generic convex tax tool (CT) is a design that was defined to nest both a linear tax b and a fixed quota q and to form, with a shape parameter a, all strictly convex tax shapes between those two extremes. Quadratic taxation (QT) is a second order approximation of CT and nests the linear tax (LT).

The most commonly used tool is quantity control (FQ). Chu (2009) estimated that several hundred stocks in 18 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 privatising the right to catch a fixed quota (FQ) is that the incentive to race for fish for strategic reasons may vanish. The control method is by many authors criticised for having negative social effects (Merayo et. al, 2018) and for generating incentives to discard fish (Kristofersson & Rickertsen, 2009).

A linear landing tax (LT) is an alternative proposed by Weitzman (2002), among others. When harvesting costs depend on the stock, a linear landing tax more or less directly controls the size of the breeding stock. Most fishery models predict that a relatively stable reproducing fish stock enhances efficiency. On closer scrutiny, this explains why price control might dominate quantity regulation in the fishery case. 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. This is confirmed by Hansen et al. (2013) in the case when resouce extiction is at stake. That result has also been confirmed by the results in Figure 5: the risk with linear taxes is only meagerly higher than the risk associated with no harvesting at all.

The merits of a linear landing tax instrument notwithstanding, it will not secure accuracy of the wanted escapement target. Uncertainty in the industry's costs of effort and/or the price of fish will diminish the linear tax instrument's potential advantage. The reason is that the expected escapement target in this case must be set, for the sake of precaution, at a higher level. Here we showed that in Figure 4, by observing the upper curve and compare it to the curve for linear tax with known costs (that is equal for all $x_1 \left(= E\left\{x_1\right\}\right)$). In its turn this gives an expected outcome which also might be less than with a fixed quota, as demonstated by Hannesson and Kennedy (2005). With both ecological and economic uncertainty, therefore, either the

LT or FQ instrument can dominate the other dependent on parameter values.

This paper's focus, however, was on the existence of a third alternative that might outperform both of the above. As noted in Theorem 1, the generic convex tax instrument (CT) is weakly superior to the other management tools. The size of the effect of moving to convex taxation can only be investigated with numerical simulations. Since the optimal form of the convex tax is difficult to determine, I applied a quadratic tax (a second order approximation) in the analysis. Since this quadratic tax (QT) only nests the LT system, QT can for sure only dominate the LT system (Corollary 2). The purpose of my numerical example (section 5) thus became an illustation of the size of the gains in value (section 5) and in decreased extiction probability (section 6) when moving from linear to a non-linear regulation.

Jensen et al. (2017) demonstrates the nature of the difference between flow externalities in static pollution models and stock externalities in dynamic fishery models. While the shadow price changes over time in a dynamic model, if left undisturbed, it will go asymptotically towards a steady-state equilibrium. Then by assuming that the fish stock has reached equilibrium, a representative model can be static. A recent paper by Berglann (2012), that employs a simple static model of pollution, shows that a regulator only needs to know the marginal damage caused by the industry to be able to levy a strictly convex tax on total emissions. This tax can be shared among parties by incorporating a *share quota* parameter in the tax function.

It might be possible to modify a static fishery model so that heterogenous vessels are levied equal marginal profit rates across firms. A similar share quota parameter may then be 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 profit for each vessel then becomes a strictly decreasing function of the individual share of the quota, these shares might be wanted and tradable. Then, by employing a market with a fixed supply of shares, competitive behaviour will ensure an *ex post* equilibrium where fishers acquire optimal share holdings. For a suitable profit function, the distribution of total profit may therefore be optimal. To show that such a profit function might exist can be a task for future research.

As Berglann (2012) demonstrates, the scheme may be as potentially easy to implement as an individual transferable quota (ITQ) regime. The ITQ regime will then correspond to an individual transferable expected quota (ITEQ) in the convex tax regime. The flexibility of such a quota might 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.

An additional motivating factor for considering convex tax 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.[13] For instance, the "deemed value" system employed in New Zealand to manage (multispecies) fisheries is a quota-tax system that allows each

[13] 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.

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 vessel's catch exceeds its quota holding (Stewart & Leaver, 2015; Holland & 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 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 comprised 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 compared to the biased outcome that may occur by employing the "deemed value" method.

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