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ANALYSIS

Asymmetric information and uncertainty: The usefulness of logbooks as a regulation measure ☆

Frank Jensen [a,*], *Niels Vestergaard* [b]

[a] *Akf, Institute of local government studies Denmark, Nyropsgade 37, 1602 Copenhagen V, Denmark*
[b] *University of Southern Denmark, Department of Environmental and Business Economics, Niels Bohrs Vej 9, 6700 Esbjerg, Denmark*

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ABSTRACT

In many fisheries managed by quota systems fishermen are required to keep a logbook containing information about catches. No well functioning enforcement system is set up in connection with the logbooks, since the purpose is to assist biologists in making stock assessments. In this paper we consider a case where three market failures (a stock externality problem, a stock uncertainty problem and problems with measuring individual catches) arise simultaneously. It is shown that a stock tax and a tax on voluntary self-reported catches may solve these three problems. By taxing voluntary self-reported catches we make use of logbook information. It is shown using an analytic model that it will be in the interest of risk-averse fishermen to report part of their catch voluntarily even without an enforcement policy. In addition, it is shown that the tax structure can secure optimal expected individual catches, and empirical simulations show that the tax payment is relatively low. Thus, the tax system may be useful in practical fisheries management.

1. Introduction

Property rights have become the conventional wisdom for the best way to manage fishing industries. This debate, once thought closed, has recently been reopened. Weitzman (2002) argues that taxes on catches are preferred to individual transferable quotas (ITQs) under uncertainty about the biological relation (environmental uncertainty), because it is possible with taxes to reach the desired escapement level of recruits. A tax system is also analysed in Jensen and Vestergaard (2002). The point of departure for Jensen and Vestergaard (2002) is that within fisheries a moral hazard problem arises because individual catches are unobservable. For example, an ITQ system creates incentives to exceed the quota because problems with illegal landings and discard arise. Thus, Jensen and Vestergaard (2002) analyse economic uncertainty (imperfect

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* *Corresponding author*. Fax: +45 33152875.
E-mail addresses: fje@akf.dk (F. Jensen), nv@sam.sdu.dk (N. Vestergaard).

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information about catches) and, in addition to solve this uncertainty, the mechanism proposed also solves the stock externality problem. The mechanism proposed in Jensen and Vestergaard (2002) is a stock tax and it is necessary to tax the fish stock because individual catches are unobservable. In this paper the analysis in Jensen and Vestergaard (2002) and Weitzman (2002) is generalised. The paper analyses an incentive scheme that can be applied both in the presence of environmental uncertainty (stock uncertainty) and economic uncertainty (imperfect information about catches).

Three market failures arise when imperfect information about catches, stock uncertainty and stock externality problems occur simultaneously.[1] It is a well-known general result within economics that if multiple market failure problems interact, multiple policy instruments must be used to secure a first-best optimum. Analyses of stock uncertainty and problems with measurement of individual catches have usually been accomplished separately within fisheries economics. The so-called stochastic bioeconomics (see Andersen and Sutinen, 1984 for an overview and Reed, 1979 for an original contribution) analyse expected optimal exploitation of the fisheries resource in the light of stock uncertainty, while, as mentioned above, Jensen and Vestergaard (2002) analyse a stock tax as a solution of problems with imperfect information about catches.

The purpose of this paper is to combine a stock tax and a tax on self-reported catches (e.g. logbooks) to solve the stock externality problem, the problem of imperfect information about catches and the stock uncertainty problem.[2] In the fisheries economic literature no attempt has, to our knowledge, been made to solve several market failures that arise simultaneously and, therefore, this paper is a novel contribution to this literature.[3] As mentioned above the mechanism proposed in this paper combines a resource stock tax and a tax on self-reported catches to solve several market failures that arise simultaneously. Thereby, it is implicitly argued that taxes are preferred to individual quotas when several market failures arise because an ITQ system is only designed to solve the stock externality problem.

A stock tax addresses the stock externality problem directly. This is not accomplished with ITQs and taxes on catches. These instruments only address the resource flow, not the resource stock itself, and, therefore, problems with illegal landings are not solved. Contrary to a stock tax, a tax on voluntary self-reported catches only addresses the flow from the resource stock, not the stock itself. However, if we have stock uncertainty and risk-averse fishermen, the stock tax does not secure an optimum. Therefore, it is necessary to have an additional regulatory instrument and this instrument can be a tax on voluntary self-reported catches. Thus, a tax on the resource flow combined with a tax on the resource stock can solve all market failure problems including problems with uncertain stock size.

If we use a stock tax alone in a situation with uncertain fish stocks and risk-averse fishermen we reach a second-best optimum. In this situation it is not possible to reach a full optimum. However, if we in addition to the stock tax impose a tax on voluntary self-reported catches a first-best optimum is reached. In this optimum it is not possible to increase welfare by altering policy instruments.

The result that several market failures can be corrected by the use of several instruments generalises to other common-pool resources. For example, a privately owned forest should be harvested such that the present value of future net benefits is maximised. At least two market failures can be imagined in the case of privately owned forests. First, there can be a difference between the private and social discount rate. Second, uncertain property rights especially in developing countries can lead to overharvesting of forests. A combination between public ownership and international agreements that may involve side payments from the developed to the undeveloped countries may solve these problems.

The use of an incentive scheme based on voluntary self-reported catches is also a novel thought within the fisheries economic literature. A common procedure when managing fisheries is that fishermen shall keep a logbook to record the quantity of each species caught. However, in many fisheries there is no well functioning enforcement system to control that the information in the logbooks is correct.[4] Instead the purpose with logbooks is to assists biologists in making stock assessments. In this paper we propose to make use of the logbook information by taxing voluntary self-reported

[1] A market failure is defined as a factor that prevents markets from reaching a first-best optimum. It can be argued that uncertainty about stock size and asymmetric information about catches is not a market failure and that the stock externality problem is the only market failure that arises. However, within welfare economics uncertainty and asymmetric information are labelled market failures (see for example Layard and Walters, 1978). The reason for this is that with uncertainty and asymmetric information markets do not reach a first-best optimum.

[2] The idea of the paper is taken from the work by Xepapadeas (1995) on non-point pollution. However, three important differences arise from Xepapadeas (1995). First, Xepapadeas (1995) uses a static model, while the model in this paper is dynamic. Second, the tax structure is simulated in this paper in order to obtain a rough indicator for the size of the tax payment. Third, Xepapadeas (1995) makes use of an enforcement policy, in order to secure self-reporting. In this paper it is shown that reporting part of the catches is optimal even without an enforcement policy.

[3] Roughgarden and Smith (1996) and Sethi et al. (2005) consider the case where three kinds of uncertainty arise simultaneously. These three kinds of uncertainty are environmental variability that influences the growth of fish stocks, stock measurement errors and inaccurate implementation of harvest quotas. However, the authors do not analyse how these three kinds of uncertainty may be solved by using multiple policy instruments. Instead, they consider how the common recommendation in stochastic bioeconomics about constant escapement is modified by multiple uncertainties. Thereby, the analysis in Roughgarden and Smith (1996) and Sethi et al. (2005) differs from the analysis in this paper.

[4] In some fisheries an enforcement system of individual quotas is constructed by cross-checking logbooks and sales notes at first-hand marketing levels. However, such an enforcement system is costly and for this reason it is important to construct incentive schemes that solve problems with unobservable individual catches. This paper presents such an incentive scheme.

catches.[5] In this way our analysis is very useful in practical fisheries management. In Hansen et al. (2003) a mechanism that secures truthful revelation of catches is constructed. However, the mechanism in Hansen et al. (2003) makes use of self-reported catches before a fishing season begins and, thereby, truthful revelation ex ante is considered. Thus, the mechanism in Hansen et al. (2003) analyse truthful revelation of expected catches. In this paper we use logbook information and, thereby, voluntary self-reported catches ex post are analysed. Thus, our mechanism differs from the one proposed in Hansen et al. (2003).

The paper is organised as follows. In Section 2 the model is presented, while Section 3 analyses optimal self-reporting by fishermen under stock certainty. Section 4 examines stock uncertainty, while some simulations are presented in Section 5. Some discussion points and a conclusion regarding the suggested tax mechanism are presented in Section 6.

2. The model

Consider a fishery consisting of n fishermen where a central authority (society) imposes a total allowable catch (TAC) on the industry. Each year, t, society calculates a target stock size for the end of the year, x_{t+1}^*. On the basis of this target year-end stock size, society calculates the optimal TAC, H_t^*. The optimal target year-end stock size and the optimal TAC can now be announced. Regulation is necessary to secure x_{t+1}^* and H_t^*.

Individual catches for fisherman i at time t, h_{it}, are assumed to be unobservable to society due to illegal landings.[6] However, individual catches are known by the fisherman. Therefore, h_{it} is a function of a random variable, θ_{it}, such that h_{it} (θ_{it}) and θ_{it} are not known by society, but are known by the fisherman. In the following notation θ_{it} is suppressed, but we assume that θ_{it} follows a normal distribution.[7]

A further assumption is that there is no enforcement system in connection with individual catches. As mentioned in the introduction, this corresponds to the common practise that fishermen shall keep a logbook containing information about catches. Instead of enforcement with respect to catches, a tax system is imposed and this system is analysed as an alternative to an enforcement policy. In very general terms the tax is a function of end-year stock size, x_{t+1}, and voluntary self-reported catches in logbooks, s_{it}, and, therefore, the tax system may be written as $T_{it}(x_{t+1}, s_{it})$. By making the tax payment a function of voluntary self-reported catches, the information in logbooks is used.

It is also assumed that the fisherman receives the same price for all landings and a single-species assumption is adopted. With a single-species assumption we assume no by-catches of undesirable species. A normal assumption in fisheries economics is that each individual fisherman disregards resource conservation measures leading to the open-access (stock externality) problem (see Clark, 1990). However, as pointed out by Jensen and Vestergaard (2002), this assumption is not reasonable when the tax is a function of year-end stock size. According to Jensen and Vestergaard (2002), the following function is, therefore, included as a restriction on the maximisation problem for fisherman i:

$$x_{t+1} = N_{it}(x_t, h_{it}, \boldsymbol{h}_{-it}) \tag{1}$$

where $\boldsymbol{h}_{-it}$ is a vector of catches for all other fishermen than i in the period between t and $t+1$.[8] Because the individual fisherman maximises profit at the beginning of the year, x_{t+1} is now the stock size at time $t+1$ as expected by the fisherman. $N_{it}(x_t, h_{it}, \boldsymbol{h}_{-it})$ is an expression for how fisherman i expects that the stock size at time $t+1$ is influenced by-catches and it is assumed that $\partial N_{it}/\partial h_{it}<0$. Furthermore, it is assumed that $\partial^2 N_{it}/\partial h_{it}^2>0$ and $\partial^2 N_{it}/\partial h_{it}\partial x_t<0$. $N_{it}(x_t, h_{it}, \boldsymbol{h}_{-it})$ may differ from the true resource restriction in society's maximisation problem. As explained by Jensen and Vestergaard (2002), individual fishermen may have incorrect expectations regarding how catches influence the stock size. Arnason (1990) builds a model where the true resource restriction is included in the maximisation problem of the fisherman. Thus, the analysis in this paper can be considered as more general than the analysis in Arnason (1990) because the possibility of incorrect expectations by the fisherman regarding the stock size is included.

The individual fisherman maximises the profit minus the tax payment in each time period[9] and, therefore, the maximisation problem of fisherman i may be written as:[10]

$$\max_{h_{it}, s_{it}} (p h_{it} - c_{it}(x_t, x_{t+1} - x_t, h_{it}) - T_{it}(x_{t+1}, s_{it})) \tag{2}$$

s.t.

$$x_{t+1} = N_{it}(x_t, h_{it}, \boldsymbol{h}_{-it}) \tag{3}$$

[5] One reviewer mentions that there can be measurement errors in estimating the size of catches by fishermen. The reason for this is that catches are not weighted, but estimated. However, fishermen have experienced in estimating catches and the uncertainty with respect to fishermen's measurement of catches is of minor importance compared to the problem society has in measuring catches due to illegal landings and discard. Therefore, we assume that individual fishermen can measure catches exactly in logbooks.

[6] Catches may also be unobservable due to discard. However, the stock tax proposed in this paper may also solve discard problems. Discard affects the stock size and, therefore, fishermen also pay tax of discard.

[7] It is assumed that no updating of θ_{it} takes place because the random variable changes every time period.

[8] It can be argued that $\boldsymbol{h}_{-it}$ is unknown to fisherman i due to illegal landings and at sea discards. However, based on own catches the fisherman may be able to estimate the catches of other fishermen even when illegal landings occur. Therefore, $\boldsymbol{h}_{-it}$ is included in (1).

[9] A possibility is that the tax is paid at the end of the year and ought, therefore, to be the discounted tax collected at the beginning of the year. However, in this paper we disregard discounting of tax payment. Furthermore, catches are captured continuously over the year and, therefore, payment of the tax on voluntary self-reported catches can be made continuously over the year.

[10] From (2) it is clear that it is assumed that the individual fisherman maximises current period profit only, i.e. fishermen are short-sighted. In the presence of (1) it may be argued that the individual fisherman ought to maximise the present value of future profits as in Arnason (1990). However, an assumption about short-sighted individual fishermen is common in fisheries economics (see Clark, 1990). An extreme case with short-sighted fishermen arises with the open-access assumption. With open-access only the current period profit is relevant. Furthermore, below we will argue that it makes no difference if we maximise present value of future profits. An argument for short-sighted fishermen is that $x_{t+1}=N_{it}(x_t,h_{it},\boldsymbol{h}_{-it})$ is only included because stock size is taxed. Thus, because x_{t+1} are taxed fishermen are still short-sighted as normally assumed in fisheries economics.

where p is the output price and $c_{it}(x_t, x_{t+1}-x_t, h_{it})$ is the cost function.[11] It is assumed that $\partial c_{it}/\partial x_t<0$, $\partial c_{it}/\partial h_{it}>0$, $\partial^2 c_{it}/\partial h_{it}^2$-0, $\partial^2 c_{it}/\partial x_t^2>0$ and $\partial^2 c_{it}/\partial h_{it}\partial x_t>0$. The maximisation in (2) occurs with respect to the catches (h_{it}) and voluntary self-reported catches (s_{it}). In (2) ph_{it} is the revenue, $c_{it}(x_t, x_{t+1}-x_t, h_{it})$ is the production costs, and $T_{it}(x_{t+1}, s_{it})$ is the tax payment.

Substituting (3) into (2) yields the following profit function for fisherman i:

$$\underset{h_{it},s_{it}}{\mathrm{Max}}(ph_{it}-c_{it}(x_t, N_{it}(x_t, h_{it}, \boldsymbol{h}_{-it})-x_t, h_{it})-T_{it}(N_{it}(x_t, h_{it}, \boldsymbol{h}_{-it}), s_{it})). \quad (4)$$

With regard to society, a stochastic version of a management model in Clark (1990) is adopted to analyse the welfare optimisation problem. Society maximises the expected value of future resource rents from $t=0, \ldots\ldots, \infty$. Therefore, according to Clark (1990) the maximisation problem of society may be written as:

$$\underset{h_t,T_{it},x_{t+1},x_t}{\mathrm{Max}}\left(E\left(\sum_{i=1}^{n}\sum_{t=0}^{\infty}(ph_{it}-c_{it}(h_{it}, x_t, x_{t+1}-x_t))\rho^t\right)\right) \quad (5)$$

s.t.

$$F(x_t)-E\left(\sum_{i=1}^{n} h_{it}\right)+x_t = x_{t+1} \quad (6)$$

$$h_{it}, s_{it}\ \varepsilon\ \mathrm{argmax}(ph_{it}-c_{it}(x_t, N_{it}(x_t, h_{it}, \boldsymbol{h}_{-it})-x_t, h_{it}) \\ -T_{it}(N_{it}(x_t, h_{it}, \boldsymbol{h}_{-it}), s_{it})) \quad (7)$$

where $F(x_t)$ is the natural growth rate, $E(\cdot)$ is the expectation operator included because individual catches are unobservable, and ρ is a discount factor. (5) is an expression for the expected present value of total resource rent for all fishermen in all time periods. The policy instrument for society is the tax system, $T_{it}(x_{t+1},s_{it})$. (5) captures that this policy instrument shall be determined such that socially optimal individual catches are reached. However, in order to find the socially optimal tax system, the first-order condition with respect to h_{it}, x_t and x_{t+1} must be found. Thus, even though $T_{it}(x_{t+1},s_{it})$ is the only control variable, it is necessary to have a first-order condition for h_{it}, x_t and x_{t+1}.[12]

In (6), $x_{t+1}-x_t$, is the change in stock size between t and $t+1$ and (6) indicates that the change in stock size must equal the natural growth rate minus expected catches.[13] This equation is known as the resource restriction. (7) captures that in selecting h_{it}, x_{t+1}, x_t and $T_{it}(\cdot)$ society must accept the choice of the fishermen of catches and voluntary self-reported catches in logbooks. Therefore, the choice of catches and self-reported catches by the fisherman must be included in the maximisation problem of society. By assuming interior solutions for s_{it} and h_{it}, (7) can be replaced by the first-order conditions. With this procedure the maximisation problem may be solved with the Lagrange-method.

Before the maximisation problem is solved, it is useful to substitute (6) into the objective function and, therefore, the maximisation problem of society may be written as:[14]

$$\underset{h_{it},T_{it},x_t}{\mathrm{Max}}\left(E\left(\sum_{i=1}^{n}\sum_{t=0}^{\infty}\left(ph_{it}-c_{it}\left(h_{it}, x_t, F(x_t)-\sum_{i=1}^{n} h_{it}\right)\right)\rho^t\right)\right) \quad (8)$$

s.t.

$$h_{it}, s_{it}\ \varepsilon\ \mathrm{argmax}(ph_{it}-c_{it}(x_t, N_{it}(x_t, h_{it}, \boldsymbol{h}_{-it})-x_t, h_{it})-T_{it}(N_{it}(x_t, h_{it}, \boldsymbol{h}_{-it}), s_{it})). \quad (9)$$

Again (8) is an expression for the expected present value of resource rents of all fishermen in all time periods. By solving (8) subject to (9), the expected optimal catch level, h_{it}^*, the expected optimal stock size, x_t^*, and the tax system, $T_{it}(x_{t+1}, s_{it})$ can be found.

This set up is similar to the model in Jensen and Vestergaard (2002). However, in this paper there ∞ is an important difference compared to Jensen and Vestergaard (2002). Jensen and Vestergaard (2002) assume that stock size can be measured exactly, and, therefore, a stock tax is studied as a solution to problems with imperfect information about catches. In reality, there are measurement problems associated with obtaining a reliable measure for stock size, see Anon (2002). Therefore, stock size is assumed to be a stochastic variable in this paper. Hence, two market failures (apart from the stock externality problem) are analysed in this paper, imperfect information about individual catches and uncertainty about stock size, and these two market failures interact. When two market failures interact, it is in general necessary to use two policy instruments to correct these market failures. Based on Xepapadeas (1995), $T_{it}(x_{t+1}, s_{it})$, may be written as:

$$T_{it}(x_{t+1}, s_{it}) = g_{it}(s_{it})(x_{t+1}^*-x_{t+1}) + \tau_{it}s_{it}. \quad (10)$$

Thus, the tax consists of two elements. First, voluntary self-reported catches in logbooks, s_{it}, are taxed and τ_{it} is the tax rate per unit of individual, voluntary self-reported of catches, s_{it}, in the period between t and $t+1$.[15] It is assumed that $\tau_{it}>0$. It can be argued that taxation of catches in logbooks biases stock estimates. A normal procedure when estimating stock size is to use catches estimates from logbooks and taxation of these catches will bias stock estimates. However, stock size can also be estimated without logbook information. It is possible to estimate stock size by participating in random selected trips (an at-sea observer programme). Now logbook information can be taxed without biased stock estimates. Second, a stock tax based on the difference between the target

[11] Note that the development in stock size for the period between t and $t+1$ is included in the cost function. This assumption can be deduced from the model in Clark (1990) for TACs, where the integral of the objective function is defined for $t=0$ to the time when the quota is filled. The explanation for this assumption is that changes in stock size between discrete time periods will influence cost of harvesting fish throughout a stock increase or decrease between the discrete time periods t and $t+1$.

[12] The same trick is used in Xepapadeas (1995).

[13] We are interested in an ex ante optimum and, therefore, expected catches, not actual catches, are included in (6).

[14] Note that in (8) the objective function is no longer maximised with respect to x_{t+1} (compare (8) with (5)). This situation arises because the resource restriction is substituted into the objective function of society.

[15] With the formulation in (10) we assume that the fishermen know their catches before the end of the year. This is justified by the fact that the fishermen know their catches after the end of a fishing trip and, therefore, updating of yearly catches may occur.

year-end stock size and the expected stock size at the end of the year is imposed on the fisherman. Stock size is measured by biologists within the EU, see Anon (2002). However, measurement of stock size is imprecise and we, therefore, consider stock uncertainty in Section 4. The stock tax function, $g_{it}(s_{it})$, is specified as a function of the voluntary self-reported catches in logbooks of fisherman i. The stock tax function is announced at the beginning of the year, but the tax revenue is collected at the end of the year based on differences between the year-end stock size and the target year-end stock size.[16] It is assumed that $g_{it}{}'(s_{it})<0$ and $g_{it}{}''(s_{it})<0$, i.e. the stock tax is declining in self-reported catches.

It is also assumed that there is a relation between the voluntary self-reported catches and real catches, h_{it}, for fisherman i in the period between t and $t+1$. This relation is specified as $s_{it}=f_{it}(h_{it})$,[17] where $f_{it}{}'(h_{it})>0$ and $f_{it}{}''(h_{it})>0$.[18] It is assumed that function $f_{it}(h_{it})$ is known with certainty by the fishermen but is unknown for society. Thus, there is asymmetric information about $f_{it}(h_{it})$. Formally, this is captured by assuming that $f_{it}(h_{it})$ is governed by a random variable, ω_{it}, for society and we assume that ω_{it} follows a normal distribution. However, in the following notation ω_{it} is suppressed. By use of $f_{it}(h_{it})$ the stock tax function may be written as $g_{it}(s_{it})=g_{it}(f_{it}(h_{it}))=k_{it}(h_{it})$, where $k_{it}(h_{it})$ is the stock tax rate as a function of catches. The assumptions about $g_{it}(s_{it})$ and $f_{it}(h_{it})$ imply that $k_{it}{}'(h_{it})<0$ and $k_{it}{}''(h_{it})<0$. With $k_{it}(h_{it})$, $T_{it}(x_{t+1}, s_{it})$ may be written as:

$$T_{it}(x_{t+1},s_{it}) = T_{it}(x_{t+1},f(h_{it})) = k_{it}(h_{it})(x^*_{t+1}-x_{t+1}) + \tau_{it}f_{it}(h_{it}). \quad (11)$$

With this tax function, the maximisation problem of fisherman i may be written as:

$$\underset{h_{it}f_{it}}{\text{Max}}(ph_{it}-c_{it}(x_t, x_{t+1}-x_t, h_{it})-k_{it}(h_{it})(x^*_{t+1}-x_{t+1})-\tau_{it}f_{it}(h_{it})) \quad (12)$$

s.t.

$$x_{t+1} = N_{it}(x_t, h_{it}, \boldsymbol{h}_{-it}). \quad (13)$$

Because there is a relation between the voluntary self-reported catches in logbooks and real catches ($s_{it}=f_{it}(h_{it})$), maximisation with respect to self-reported catches, s_{it}, is the same as maximising with respect to $f_{it}(h_{it})$. Maximisation by choosing a function is well-known within economics, see Varian (1992).

Substituting (13) into (12) yields the following profit function for fisherman i:

$$\underset{h_{it}f_{it}}{\text{Max}}(ph_{it}-c_{it}(x_t, N_{it}(x_t, h_{it}, \boldsymbol{h}_{-it})-x_t, h_{it})-k_{it}(h_{it})(x^*_{t+1}-N_{it}(x_t, h_{it}, \boldsymbol{h}_{-it}))$$
$$-\tau_{it}f_{it}(h_{it})). \quad (14)$$

With two tax instruments, the maximisation problem of society is:

$$\underset{h_{it},x_t,x_{t+1},k_{it},\tau_{it}}{\text{Max}} \left(E\left(\sum_{i=1}^{n} \sum_{t=0}^{\infty} (ph_{it}-c_{it}(h_{it}, x_t, x_{t+1}-x_t))\rho^t\right)\right) \quad (15)$$

s.t.

$$F(x_t)-E\left(\sum_{i=1}^{n} h_{it}\right) + x_t = x_{t+1} \quad (16)$$

$$h_{it},f_{it}\ \varepsilon\ \text{argmax}(ph_{it}-c_{it}(x_t, N_{it}(x_t, h_{it}, \boldsymbol{h}_{-it})-x_t, h_{it})$$
$$-k_{it}(h_{it})(x^*_{t+1}-N_{it}(x_t, h_{it}, \boldsymbol{h}_{-it}))-\tau_{it}f_{it}(h_{it})). \quad (17)$$

(15) must be maximised with respect to the policy instruments, but it is only necessary to find the first-order condition with respect to $k_{it}(h_{it})$, because by using the first-order of the fisherman with respect to the self-reported catches, the optimal τ_i may be found. In addition, the optimal catches and stock sizes will be found.

By substituting (16) into (15) the following maximisation problem is obtained:

$$\underset{h_t,x_t,k_{it}}{\text{Max}}\ E\left(\sum_{i=1}^{n} \sum_{t=0}^{\infty} (ph_{it}-c_{it}(h_{it}, x_t, F(x_t)-\sum_{i=1}^{n} h_{it}))\rho^t\right) \quad (18)$$

s.t.

$$h_{it},f_{it}\ \varepsilon\ \text{argmax}(ph_{it}-c_{it}(x_t, N_{it}(x_t, h_{it}, \boldsymbol{h}_{-it})-x_t, h_{it})$$
$$-k_{it}(h_{it})(x^*_{t+1}-N_{it}(x_t, h_{it}, \boldsymbol{h}_{-it}))-\tau_{it}f_{it}(h_{it})). \quad (19)$$

By solving (18) subject to (19), the expected optimal values of catches, h_{it}^*, the expected optimal stock size, x_t^*, the self-report tax rate, τ_{it}^*, and the stock tax function, $k_{it}^*(h_{it})$, can be found.

The timing of decisions and informational assumptions is summarised in Fig. 1.

3. Full certainty

In this section it is shown that with full stock certainty it is optimal for fisherman i to report zero catches. In addition, the optimal stock tax function is calculated. The first-order condition of the maximisation problem for fisherman i with respect to f_{it} for the period t is:[19]

$$k'_{it}(h_{it})(x^*_{t+1}-N_{it}(h_{it}, \boldsymbol{h}_{-it}, x_t))-\tau_{it}\leq 0,\ f_{it}\geq 0. \quad (20)$$

[16] Note that if the actual stock size is larger than the optimal stock size, the stock tax in (10) will be a subsidy.

[17] This formulation is justified by the fact that under stock uncertainty and with risk-averse fishermen, it is optimal for the individual fisherman to report a part of their catch. Now we must expect that larger catches imply larger self-reported catches. This is exactly what $s_{it}=f_{it}(h_{it})$ captures.

[18] An alternative to this formulation is to make self-reported catches a function of an enforcement policy by society. This procedure is adopted in Xepapadeas (1995). In Xepapadeas (1995) enforcement levels become a control variable for society and self-reports occur only due to the presence of an enforcement policy. With the formulation in our paper the fishermen will self-report part of their catches voluntarily in logbooks without an enforcement policy if they are risk-averse.

[19] (20) also holds when the fisherman maximises present value of future profits. In this case a discount factor is included but this factor reduces away.

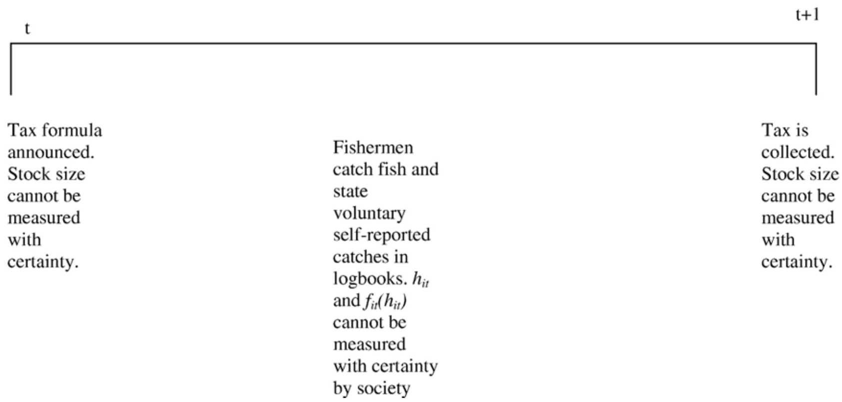

Fig. 1 – Timing of decisions.

In (20) $k_{it}'(h_{it})$ is included because $k_{it}(h_{it})$ can be expressed as $g_{it}(f_{it}(h_{it}))$.

By optimal selection of the stock tax function and self-report tax rate it can be secured that $N_{it}(h_{it}, \boldsymbol{h}_{-it}, x_t) = x_{t+1}^*$. In other words society adjust $k_{it}'(h_{it})$ and τ_{it} until $N_{it}(h_{it}, h_{-it}, x_t) = x_{t+1}^*$. Thereby, the stock externality problem is solved. In addition, it is assumed that $\tau_{it} > 0$ and, therefore, (20) can be reduced to:

$$-\tau_{it} < 0, f_{it} = 0. \tag{21}$$

From (21) it is seen that it is optimal for vessels not to reveal any information about their catches in logbooks. The explanation for this result is that without stock uncertainty, the fisherman is indifferent between paying the stock tax and the self-report tax. Thus, the fisherman might as well declare $f_{it} = 0$ and, thus, avoid the self-report tax payment.

The first-order condition of the maximisation problem of fisherman i (14) with respect to h_{it} in period t, noticing that $x_{t+1}^* = N_{it}(h_{it}, \boldsymbol{h}_{-it}, x_t)$ and $f_{it}'(h_{it}) = 0$, is:

$$p - \frac{\partial c_{it}}{\partial N_{it}}\frac{\partial N_{it}}{\partial h_{it}} - \frac{\partial c_{it}}{\partial h_{it}} + k_{it}(h_{it})\frac{\partial N_{it}}{\partial h_{it}} = 0. \tag{22}$$

(22) states that the marginal benefits (p) equal the marginal private costs. The marginal private costs consist of the marginal production costs ($\partial c_{it}/\partial h_{it}$), the marginal stock tax costs ($k_{it}(h_{it})\, \partial N_{it}/\partial h_{it}$) and the marginal user costs of the fish stock as perceived by the fisherman ($\partial c_{it}/\partial N_{it}\, \partial N_{it}/\partial h_{it}$).[20]

As mentioned in Section 2, (19) can be replaced by (22) in society's maximisation problem, if an interior solution for h_{it} exists. Furthermore, it is not necessary to take into account the first-order condition for f_{it}, because $f_{it} = 0$ in optimum. Therefore, the following expected Lagrangian can be set up for society:

$$\begin{aligned}\max_{h_{it}, x_t, k_{it}} L = &\Big(\Big(\sum_{t=0}^{\infty}\sum_{i=1}^{n}\Big) ph_{it} - c_{it}\Big(h_{it}, x_t, F(x_t) - \sum_{i=1}^{n} h_{it}\Big)\Big) \\ &+ \sum_{i=1}^{n}\sum_{t=o}^{\infty} \lambda_{it}\left(p - \frac{\partial c_{it}}{\partial N_{it}}\frac{\partial N_{it}}{\partial h_{it}} - \frac{\partial c_{it}}{\partial h_{it}} + k_{it}(h_{it})\frac{\partial N_{it}}{\partial h_{it}}\right)\Big)\Big)\rho^t.\end{aligned} \tag{23}$$

Because ρ^t is outside the parenthesis the expected Lagrangian in (23) can be written as:

$$\begin{aligned}\max_{h_{it}, x_{it}, k_{it}} L' = &E\Big(\sum_{i=1}^{n} ph_{it} - c_{it}\Big(h_{it}, x_t, F(x_t) - \sum_{i=1}^{n} h_{it}\Big)\Big) \\ &+ \sum_{i=1}^{n} \lambda_{it}\left(p - \frac{\partial c_{it}}{\partial N_{it}}\frac{\partial N_{it}}{\partial h_{it}} - \frac{\partial c_{it}}{\partial h_{it}} + k_{it}(h_{it})\frac{\partial N_{it}}{\partial h_{it}}\right)\Big).\end{aligned} \tag{24}$$

Noticing that $\partial x_{t+1}/\partial E(h_{it}) = -1$ ($x_{t+1} - x_t = F(x_t) - \sum_{i=1}^{n} h_{it}$ is the last term in the cost function), the first-order conditions of the Lagrangian for fisherman i in period t are:

$$\begin{aligned}\frac{\partial L'}{\partial h_{it}} = &\; p - E\left(\frac{\partial c_{it}}{\partial h_{it}} + \sum_{i=1}^{n}\frac{\partial c_{it}}{\partial x_{t+1}}\right) \\ &- \lambda_{it}\left(\frac{\partial^2 c_{it}}{\partial h_{it}^2} + \frac{\partial^2 c_{it}}{\partial N_{it}^2}\frac{\partial N_{it}}{\partial h_{it}} + \frac{\partial c_{it}}{\partial N_{it}}\frac{\partial^2 N_{it}}{\partial h_{it}^2} - k_{it}(h_{it})\frac{\partial^2 N_{it}}{\partial h_{it}^2} + k_{it}'(h_{it})\frac{\partial N_{it}}{\partial h_{it}}\right) \\ = &\; 0\end{aligned} \tag{25}$$

$$\begin{aligned}\frac{\partial L'}{\partial x_t} = &-E\left(\frac{\partial c_{it}}{\partial x_t} + \frac{\partial c_{it}}{\partial x_{t+1}}\frac{\partial x_{t+1}}{\partial F(x_t)}\frac{\partial F(x_t)}{\partial x_t}\right) \\ &- \lambda_{it}\left(\frac{\partial^2 c_{it}}{\partial N_{it}\partial x_t}\frac{\partial N_{it}}{\partial h_{it}} + \frac{\partial c_{it}}{\partial N_{it}}\frac{\partial^2 N_{it}}{\partial h_{it}\partial x_t} + \frac{\partial^2 c_{it}}{\partial h_{it}\partial x_t} - k_{it}(h_{it})\frac{\partial^2 N_{it}}{\partial h_{it}\partial x_t}\right) = 0\end{aligned} \tag{26}$$

$$\frac{\partial L'}{\partial k_{it}} = \lambda_{it}\frac{\partial N_{it}}{\partial h_{it}} = 0 \tag{27}$$

$$\frac{\partial L'}{\partial \lambda} = p - \frac{\partial c_{it}}{\partial N_{it}}\frac{\partial N_{it}}{\partial h_{it}} - \frac{\partial c_{it}}{\partial h_{it}} + k_{it}(h_{it})\frac{\partial N_{it}}{\partial h_{it}} = 0. \tag{28}$$

From (27) it follows that $\lambda_t = 0$ because $\partial N_{it}/\partial h_{it} < 0$. Therefore, (25) and (26) reduces to:

$$p - E\left(\frac{\partial c_{it}}{\partial h_{it}} + \sum_{i=1}^{n}\frac{\partial c_{it}}{\partial x_{t+1}}\right) = 0 \tag{29}$$

$$-E\left(\frac{\partial c_{it}}{\partial x_t} + \frac{\partial c_{it}}{\partial x_{t+1}}\frac{\partial x_{t+1}}{\partial F(x_t)}\frac{\partial F(x_t)}{\partial x_t}\right) = 0. \tag{30}$$

(29) expresses that the marginal social benefit (p) shall equal the expected marginal social costs. The expected marginal social costs consist of the expected marginal user costs ($E(\sum \partial c_{it}/\partial x_{t+1})$) and the expected marginal production costs ($E(\partial c_{it}/\partial h_{it})$). (30) states that the expected marginal benefit of stock size ($-E$

[20] If the fisherman maximises the present value of future profits the discount factor cancels out and (22) still holds.

$(\partial c_{it}/\partial x_t)$) shall equal the expected marginal social cost of stock size $(-E(\partial c_{it}/\partial x_{t+1}\partial x_{t+1}/\partial F(x_t)\partial F(x_t)/\partial x_t))$. Setting (29) equal to (28), the following stock tax is arrived at:[21]

$$k_{it} = \frac{Q}{\frac{\partial N_{it}}{\partial h_{it}}} \tag{31}$$

where $Q=\partial c_{it}/\partial h_{it}+\partial c_{it}/\partial N_{it}\ \partial N_{it}/\partial h_{it}-E(\partial c_{it}/\partial h_{it})-\sum E(\partial c_{it}/\partial x_{t+1})$ are the marginal social costs of illegal landings. Q reflects the difference in user costs between society and the fisherman ($\partial c_{it}/\partial N_{it}\ \partial N_{it}/\partial h_i$ are the marginal private user costs while $\sum E(\partial c_{it}/\partial x_{t+1})$ are the expected marginal social user costs).[22] When the fisherman has correct perceptions regarding the resource restriction and society has correct expectations regarding the catches of the fisherman, $Q=\sum_{j\neq i}\partial c_{jt}/x_{t+1}$. In this case the stock tax function is the user cost of the fish stock for society. The user cost captures that each individual fisherman does not take into account the effect that catches has on other fishermen and on future time periods. This is usually referred to as the stock externality in fisheries economics and, therefore, the stock tax corrects this externality. Note that the stock tax function may differ between fishermen with variations in the user cost of the fish stock for both the fisherman and society.

(31) is exactly the stock tax arrived at in Jensen and Vestergaard (2002). The tax arrived at in (31) uses the fish stock as tax base. The stock tax proposed in (31) secures optimal individual catches because the fishermen pay the full social costs that illegal landings generate (the difference in user cost of the fish stock).[23] Therefore, the stock tax can be seen as an argument for using taxes instead of ITQs to manage fisheries because taxes can solve the problem of measuring individual catches. Under the assumption that there is asymmetric information about catches due to illegal landings and at-sea discards ITQs cannot secure an expected optimum, but the stock tax in (31) secures such an expected optimum. From (31) it is clear that it is enough for society to determine the stock tax function when there is stock certainty if the purpose is to secure expected optimal individual catches. The reason for this result is, naturally enough, that the optimal, voluntary self-reported catches in logbooks are zero.

4. Uncertainty

The conclusions in the previous section depend on the assumption that stock size is known with certainty. In reality, this assumption is not very realistic because there is a considerable error associated with measuring stock size; see Anon (2002). Therefore, the case of stochastic stock size is now analysed. Stock size is, due to measurement problems, environment, climate and uncertainty in nature, assumed to be a stochastic variable so that $x_t=\bar{x}_t+\varepsilon_t$, where ε_t is a random variable and $\bar{x}_t$ is the mean stock size. The random variable is neither known by society nor the fishermen.[24] It is assumed that $E(x_t)=\bar{x}_t, E(\varepsilon_t)=0$ and $\sigma_{\varepsilon_t}^2=E(\varepsilon_t^2)$, where $\sigma_{\varepsilon_t}^2$ is the variance and, thereby, a normal distribution for the random variable is assumed. Now the perceived biological reaction function for the fisherman may be expressed as $N_{it}(h_{it}, \boldsymbol{h}_{-it}, x_t, \sigma_{\varepsilon_t}^2)$.[25] The expected social optimal stock size is called x_{t+1}^*. An assumption regarding the risk attitude of the individual fisherman is now necessary and it is assumed that fishermen are risk-averse with respect to stock size. Because fishermen are risk-averse with respect to stock size the following function can be formulated with respect to derivations of the expected optimal stock size from actual stock size:

$$\varphi_{it}(x_{t+1}^*-N_{it}(h_{it},\boldsymbol{h}_{-it},x_t,\sigma_{\varepsilon_t}^2)). \tag{32}$$

It is assumed that $\phi_{it}(0)=0$, ϕ_{it}', $\phi_{it}''>0$ and $\phi_{it}'''>0$. These assumptions reflect the risk-aversion of the fisherman with respect to stock size and because of these assumptions together with the assumptions about the cost function, the objective function for the fisherman has a shape that corresponds to risk-aversion. However, (32) is too general to give any quantitative expressions for the self-report tax rate and the stock tax function. Therefore, ϕ_{it} is expressed as a second-order approximation around the point where $x_{t+1}^*=N_{it}(h_{it}, \boldsymbol{h}_{-it}, x_t, \sigma_{\varepsilon_t}^2)$. With this second-order approximation, (32) may be expressed as:

$$\begin{aligned}\varphi_{it}(0) = {} & \varphi_{it}(x_{t+1}^*-N_{it}(h_{it},\boldsymbol{h}_{-it},x_t,\sigma_{\varepsilon_t}^2)) \\ & +\varepsilon_t\varphi_{it}'(x_{t+1}^*-N_{it}(h_{it},\boldsymbol{h}_{-it},x_t,\sigma_{\varepsilon_t}^2)) \\ & +\frac{\varepsilon_t^2}{2}\varphi_{it}''(x_{t+1}^*-N_{it}(h_{it},\boldsymbol{h}_{-it},x_t,\sigma_{\varepsilon_t}^2)).\end{aligned} \tag{33}$$

Because $E(\varepsilon_t)=0$ and $\sigma_{\varepsilon_t}^2=E(\varepsilon_t^2)$, (33) may be reduced to:

$$\begin{aligned}\varphi_{it}(0) = {} & \varphi_{it}(x_{t+1}^*-N_{it}(h_{it},\boldsymbol{h}_{-it},x_t,\sigma_{\varepsilon_t}^2)) \\ & +\frac{\sigma_{\varepsilon_t}^2}{2}\varphi_{it}''(x_{t+1}^*-N_{it}(h_{it},\boldsymbol{h}_{-it},x_t,\sigma_{\varepsilon_t}^2)).\end{aligned} \tag{34}$$

(34) is the expression for the risk-aversion with respect to the deviation between the expected optimal and actual stock size that is used in this paper.

Fisherman i is assumed to maximise the expected utility of profit in period t. Because ϕ_{it} captures the risk-aversion of an individual fisherman with respect to stock size, (34) can be substituted into (14). This yields the following expected utility of profit function, which shall be maximised with respect to f_{it} and h_{it}:

$$\begin{aligned}\underset{h_{it}f_{it}}{\mathrm{Max}} & (ph_{it}-c_{it}(x_t,N_{it}(x_t,h_{it},\boldsymbol{h}_{-it},\sigma_{\varepsilon_t}^2)-x_t,h_{it}) \\ & -k_{it}(h_{it})(\varphi_{it}(x_{t+1}^*-N_{it}(h_{it},\boldsymbol{h}_{-it},x_t,\sigma_{\varepsilon_t}^2)) \\ & +\frac{\sigma_{\varepsilon_t}^2}{2}\varphi_{it}''(x_{t+1}^*-N_{it}(h_{it},\boldsymbol{h}_{-it},x_t,\sigma_{\varepsilon_t}^2))-\tau_{it}f_{it}(h_{it})).\end{aligned} \tag{35}$$

[21] (31) will be the same if present value of future profits is maximised by the fisherman because the first-order condition (22) is the same.

[22] Note that (31) secures an expected optimum ex ante because h_{it} and $f_{it}(h_{it})$ are governed by a random variable for society. Forming an expectation with respect to the random variable is the best society can do. However, in general an inefficiency arises ex post because societies expectations with respect to the random variable differ from its realised values.

[23] The stock tax also solves problems with discard. Discard affects the difference between the actual and optimal stock size and, therefore, discard implies higher tax payment.

[24] No updating takes place because the random variable changes every time period.

[25] We only include the variance in the biological response function because a second-order approximation of $\phi_{it}(x_{t+1}^*-N_{it}(h_{it}, \boldsymbol{h}_{-it}, x_t, \sigma_{\varepsilon_t}^2))$ is conducted. With this approximation the variance is the highest moment.

The first-order condition with respect to f_{it} using that if $k_{it}(h_{it})$ and τ_{it} are set correct, $x^*_{t+1}=N_{it}(h_{it}, h_{-it}, x_t, \sigma_{\varepsilon_t}{}^2)$, is:

$$-k'_{it}(h_{it})\left(\frac{\sigma^2_{\varepsilon_t}}{2}\varphi''_{it}(0)\right)-\tau_{it}\leq 0, f_{it}\geq 0. \quad (36)$$

Because $k_{it}'(h_{it})<0$, $\tau_{it}>0$ and $\phi''>0$, it will be the case that:[26]

$$-k'_{it}(h_{it})\left(\frac{\sigma^2_{\varepsilon_t}}{2}\varphi''_{it}(0)\right)-\tau_{it}=0, f_{it}>0. \quad (37)$$

(37) states that the expected marginal benefit of self-reported catches expressed as marginal cost savings in the expected stock tax payment $\left(-k'_{it}(h_{it})\left(\frac{\sigma^2_{\varepsilon_t}}{2}\varphi''_{it}(0)\right)\right)$ shall equal the marginal self-report tax payment (τ_{it}).

From (37) it is clear that it is optimal for fisherman i to report part of their catches voluntarily in logbooks. In other words, the skipper of the vessel will be willing to adjust catches so that an expected social optimum is achieved and at the same time pay a tax based on the self-reported of part of the catches. In this way, the vessel reduces its uncertain stock tax payment if random effects cause $x_{t+1}<x^*_{t+1}$. Xepapadeas (1995) reaches a similar conclusion, but for different reasons. In Xepapadeas (1995) polluters are also willing to report part of their pollution, but this result arises because society imposes an enforcement policy. In this paper, the fishermen self-report a part of the catches voluntarily even if there is no enforcement policy. The explanation for this is that the fishermen prefer a certain self-report tax payment over the uncertain stock tax payment if they are risk-averse. Thus, risk-aversion together with uncertainty about stock size in itself secures that self-reports of a part of the catches voluntarily in logbooks are optimal.

Note that if the fisherman is risk-neutral ($\phi_{it}''=0$), he would be indifferent between the uncertain stock tax payment and the self-report tax payment. The result that $f_{it}>0$ is, therefore, driven by the risk-aversion of each individual fisherman. It is also clear that if the measurement error in stock size is large ($\sigma_{\varepsilon_t}{}^2$ is large), the voluntary self-reported catches will be large. The reason for this result is that if the measurement error is large, risk-averse fishermen will do more to avoid the uncertain stock tax payment.

Because $f_{it}>0$, (37) represents an interior solution and, therefore, (37) is a restriction on the maximisation problem for society. Assuming that an interior solution for h_{it} also exists, this first-order condition is also a restriction on the maximisation problem and from (35) this condition may, noting that $\phi_{it}(0)=0$, be expressed as:[27]

$$p-\frac{\partial c_{it}}{\partial h_{it}}-\frac{\partial c_{it}}{\partial N_{it}}\frac{\partial N_{it}}{\partial h_{it}} + k_{it}(h_{it})\left(\varphi'_{it}\left(\frac{\partial N_{it}}{\partial h_{it}}\right)+\frac{\sigma_{\varepsilon_t}}{2}\varphi'''_{it}\left(\frac{\partial N_{it}}{\partial h_{it}}\right)\right)-\tau_{it}f'_{it}(h_{it})=0. \quad (38)$$

(38) states that the marginal revenue shall equal the expected marginal private cost for fisherman i. The expected marginal private cost consists of the marginal harvest cost, the marginal user cost as perceived by the fisherman and the expected marginal tax payment.

Using (38) and (37), the following expected Lagrangian can be set up for society:

$$\begin{aligned}\max_{h_{it},x_t,k_{it}} L = E((&\sum_{i=1}^{n}\sum_{t=o}^{\infty} ph_{it}-c_{it}(h_{it},x_t,F(x_t)-\sum_{i=1}^{n}h_{it}))\\ &+\sum_{i=1}^{n}\sum_{t=0}^{\infty}\lambda_{it}(p-\frac{\partial c_{it}}{\partial N_{it}}\frac{\partial N_{it}}{\partial h_{it}}-\frac{\partial c_{it}}{\partial h_{it}}\\ &+k_{it}(h_{it})\left(\varphi'_{it}\left(\frac{\partial N_{it}}{\partial h_{it}}\right)+\frac{\sigma^2_{\varepsilon_t}}{2}\varphi'''_{it}\left(\frac{\partial N_{it}}{\partial h_{it}}\right)\right)-\tau_{it}f'_{it}(h_{it}))\\ &+\sum_{i=1}^{n}\sum_{t=0}^{\infty}\mu_{it}\left(k'_{it}(h_{it})\left(\frac{\sigma^2_{\varepsilon_t}}{2}\varphi''_{it}(0)\right)+\tau_{it}\right))\rho^t.\end{aligned} \quad (39)$$

Because ρ^t is multiplied on every term the expected Lagrangian may be written as:

$$\begin{aligned}\max_{h_{it},x_t,k_{it}} L = E(&\sum_{i=1}^{n} ph_{it}-c_{it}(h_{it},x_t,F(x_t)-\sum_{i=1}^{n}h_{it}))\\ &+\sum_{i=1}^{n}\lambda_{it}(p-\frac{\partial c_{it}}{\partial N_{it}}\frac{\partial N_{it}}{\partial h_{it}}-\frac{\partial c_{it}}{\partial h_{it}}+k_{it}(h_{it})(\varphi'_{it}\left(\frac{\partial N_{it}}{\partial h_{it}}\right)\\ &+\varphi'''_{it}\frac{\sigma^2_{\varepsilon_t}}{2}\left(\frac{\partial N_{it}}{\partial h_{it}}\right))-\tau_{it}f'_{it}(h_{it}))\\ &+\sum_{i=1}^{n}\mu_{it}\left(k'_{it}(h_{it})\left(\frac{\sigma^t_{\varepsilon_t}}{2}\varphi''_{it}(0)\right)+\tau_{it}\right)\end{aligned} \quad (40)$$

The first-order conditions with respect h_{it}, x_t, k_{it}, λ_{it} and μ_{it} for fisherman i in period t are:

$$\begin{aligned}\frac{\partial L}{\partial h_{it}} = p-E&\left(\frac{\partial c_{it}}{\partial h_{it}}+\sum_{i=1}^{n}\frac{\partial c_{it}}{\partial x_{t+1}}\right)\\ &-\lambda_{it}(\frac{\partial^2 c_{it}}{\partial h^2_{it}}+\frac{\partial^2 c_{it}}{\partial N^2_{it}}\frac{\partial N_{it}}{\partial h_{it}}+\frac{\partial c_{it}}{\partial N_{it}}\frac{\partial^2 N_{it}}{\partial h^2_{it}}-k_{it}(h_{it})\varphi''_{it}\left(\frac{\partial^2 N_{it}}{\partial h^2_{it}}\right)\\ &-k'_{it}(h_{it})\left(\varphi'_{it}\left(\frac{\partial N_{it}}{\partial h_{it}}\right)+\varphi'''_{it}\left(\frac{\partial N_{it}}{\partial h_{it}}\right)\frac{\sigma^2_{\varepsilon_t}}{2}\right)+\tau_{it}f''_{it}(h_{it}))\\ &+\mu_{it}k''_{it}(h_{it})\frac{\sigma^2_{\varepsilon_t}}{2}\varphi''_{it}(0)=0\end{aligned} \quad (41)$$

$$\begin{aligned}-E&\left(\frac{\partial c_{it}}{\partial x_t}+\frac{\partial c_{it}}{\partial x_{t+1}}\frac{\partial x_{t+1}}{\partial F(x_t)}\frac{\partial F(x_t)}{\partial x_t}\right)\\ &-\lambda_{it}(\frac{\partial^2 c_{it}}{\partial N_{it}\partial x_t}\frac{\partial N_{it}}{\partial h_{it}}+\frac{\partial c_{it}}{\partial N_{it}}\frac{\partial^2 N_{it}}{\partial h_{it}\partial x_t}+\frac{\partial^2 c_{it}}{\partial h_{it}\partial x_t}\\ &-k_{it}(h_{it})\left(\varphi''_{it}\left(\frac{\partial^2 N_{it}}{\partial h_{it}\partial x_t}\right)\frac{\sigma^2_{\varepsilon_t}}{2}\right))=0\end{aligned} \quad (42)$$

$$\frac{\partial L}{\partial k_{it}}=\lambda_{it}\left(\varphi'_{it}\left(\frac{\partial N_{it}}{\partial h_{it}}\right)+\varphi'''_{it}\left(\frac{\partial N_{it}}{\partial h_{it}}\right)\frac{\sigma^2_{\varepsilon_t}}{2}\right)=0 \quad (43)$$

$$\begin{aligned}\frac{\partial L}{\partial \lambda_{it}} = p&-\frac{\partial c_{it}}{\partial N_{it}}\frac{\partial N_{it}}{\partial h_{it}}-\frac{\partial c_{it}}{\partial h_{it}}\\ &+k_{it}(h_{it})\left(\varphi'_{it}\left(\frac{\partial N_{it}}{\partial h_{it}}\right)+\varphi'''_{it}\left(\frac{\partial N_{it}}{\partial h_{it}}\right)\frac{\sigma_{\varepsilon_t^2}}{2}\right)-\tau_{it}f'_{it}(h_{it})\\ &=0\end{aligned} \quad (44)$$

$$\frac{\partial L}{\partial \mu_{it}}=k'_{it}(h_{it})\left(\frac{\sigma^2_{\varepsilon_t}}{2}\varphi''_{it}(0)\right)+\tau_{it})=0. \quad (45)$$

From (43) it is obtained that $\lambda_{it}=0$ because $\varphi'_{it}\left(\frac{\partial N_{it}}{\partial h_{it}}\right)+\varphi'''_{it}\left(\frac{\partial N_{it}}{\partial h_{it}}\right)\frac{\sigma^2_{\varepsilon_t}}{2}>0$. In this case (41) and (42) reduces to:

$$p-E\left(\frac{\partial c_{it}}{\partial h_{it}}+\sum_{i=1}^{n}\frac{\partial c_{it}}{\partial x_{t+1}}\right)+\mu_{it}k''_{it}(h_{it})\frac{\sigma^2_{\varepsilon_t}}{2}\varphi''_{it}(0)=0 \quad (46)$$

[26] The same conclusions and expressions hold when fishermen maximise present value of future profits because the discount factor reduces away.

[27] Exactly the same considerations as in Section 3 hold when the fisherman maximises present value of future profits.

$$-E\left(\frac{\partial c_{it}}{\partial x_t}+\frac{\partial c_{it}}{\partial x_{t+1}}\frac{\partial x_{t+1}}{\partial F(x_t)}\frac{\partial F(x_t)}{\partial x_t}\right)=0. \tag{47}$$

(46) states that the marginal social benefit equals the expected marginal social costs. The expected marginal social costs consist of the expected marginal production costs and the expected marginal user costs as perceived by society while the marginal social benefit consist of the price and the saving in marginal stock tax payment $\left(\mu_{it}k''_{it}(h_{it})\frac{\sigma^2_{\varepsilon_t}}{2}\varphi''_{it}(0)\right)$. (47) states that the expected marginal social benefit of stock size equals the expected marginal social costs.

Combining (46) and (44) yields the following expression for the stock tax function:[28]

$$k_{it}(h_{it})=\frac{Q-\tau_{it}f'_{it}(h_{it})-\mu_{it}k''_{it}(h_{it})\frac{\sigma^2_{\varepsilon_t}}{2}\varphi''_{it}(0)}{\varphi'_{it}\left(\frac{\partial N_{it}}{\partial h_{it}}\right)+\varphi'''_{it}\left(\frac{\partial N_{it}}{\partial h_{it}}\right)\frac{\sigma^2_{\varepsilon_t}}{2}} \tag{48}$$

where Q is defined in (31). Comparing (48) with (31) we see that $\varphi'_{it}\left(\frac{\partial N_{it}}{\partial h_{it}}\right)+\varphi'''_{it}\left(\frac{\partial N_{it}}{\partial h_{it}}\right)\frac{\sigma^2_{\varepsilon_t}}{2}$ and $\tau_{it}f'_{it}(h_{it})+\mu_{it}k''_{it}(h_{it})\frac{\sigma^2_{\varepsilon_t}}{2}\varphi''_{it}(0)$ enters in (48). $\varphi'_{it}\left(\frac{\partial N_{it}}{\partial h_{it}}\right)+\varphi'''_{it}\left(\frac{\partial N_{it}}{\partial h_{it}}\right)\frac{\sigma^2_{\varepsilon_t}}{2}$ is the marginal risk-aversion and $\tau_{it}f'_{it}(h_{it})+\mu_{it}k''_{it}(h_{it})\frac{\sigma^2_{\varepsilon_t}}{2}\varphi''_{it}(0)$ is the marginal value of an increase in the self-reporting tax payment in terms of reduced stock tax payment. The stock tax is, therefore, the expected marginal social cost of optimal catches shared by the marginal risk-aversion. It is natural that Q is corrected by the marginal risk-aversion and $\tau_{it}f'_{it}(h_{it})+\mu_{it}k''_{it}(h_{it})\frac{\sigma^2_{\varepsilon_t}}{2}\varphi''_{it}(0)$ because there is stock uncertainty.

From (45) the tax rate on self-reported catches may be found as:[29]

$$\tau_{it}=-k'_{it}(h_{it})\frac{\sigma^2_{\varepsilon_t}}{2}\varphi''_{it}(0). \tag{49}$$

The self-report tax rate, thus, consists of three elements: the marginal stock tax function, the variance of the uncertain stock size and the second-order derivative of the risk-aversion function. The tax structure represented by (48) and (49) will secure optimal expected individual catches and this paper can, therefore, be seen as an argument for using taxes over ITQs to regulating fisheries because a tax system can solve problems with several market failures.[30] With ITQs it is not possible to secure optimal expected individual catches because of illegal landings and discards while a combination between the stock tax and the self-report tax suggested in this paper secures such an expected first-best optimum. Note also that the tax system in (48) and (49) is preferred over taxes on catches alone. Taxes on catches only solve the stock externality problem while the stock externality problem, problems with illegal landings and stock uncertainty problems are solved with the dual tax system proposed in this paper.

It is also useful to highlight how changes in various variables and functions influence the stock tax function and self-report tax rate. This is done by performing comparative statics, and the result of the comparative static analysis is sketched in Table 1. The expressions for the comparative static results can be calculated from (48) and (49) and can be found in Appendix.

From Table 1 it is clear that if x_t increases, the stock tax function and the self-report tax rate decrease. The explanation for this is that if the stock size increases, expected optimal catches can be increased and, therefore, the tax payment can be decreased. From the comparative static analysis it is also clear that if the target year-end stock size increases the stock tax function and the self-report tax rate must also be increased (Table 1). The reason for this is that expected optimal catches must be reduced if x_{t+1} shall be increased. It is also stated that the stock tax function and the self-report tax rate are increased if h_{it} is increased. This is explained by the fact that an increase in expected catches implies an increase in the information problem that arises due to imperfect information about catches. An increase in the total risk-aversion function ($\phi_{it}(0)$) implies a decrease in the stock tax function and an increase in the self-report tax rate. The explanation for this result is that if the total risk-aversion increases, it becomes more attractive for the fishermen to increase their self-reported catches in logbooks. Finally, it is also seen that if the variance increases the stock tax rate decreases and the self-report tax rate increases. This conclusion arises because if the variance increases, the measurement error associated with the stock increases and, therefore, the fishermen wish to report a larger share of their catches.

A question that arises is whether the tax system proposed in this paper is too complex to be implemented in practical fisheries management. (48) and (49) require knowledge of individual cost functions, individual risk-aversion functions and individual response to changes in stock size and these are huge information requirements. To our knowledge no attempts have been made to estimate the risk-aversion of individual fishermen. However, this information can be collected in surveys and, in addition, other attempts to regulate in an optimal fashion also raise huge information requirements. For example, an ITQ system requires that a dynamic optimization problem is solved and this is a difficult task. If a survey is used a procedure could be to form groups of fishermen with similar characteristics. In addition, proxies for the necessary data can be used. Information about the stochastic properties of the stock can be found in Anon (2002). Then, the stock tax function and the self-report tax rate can be calculated and announced to the fishermen before a fishing period is started. After the fishing period, the tax payment is calculated and the tax rates and functions are announced for the next period. It can be argued that this system is not more complex than the ration system used in Denmark; see Jensen (2002). In Denmark a ration is allocated to each individual fisherman each year and this ration varies each year because of variations in the EU determined TAC. A ration system is an example of limited access regulation. Calculating optimal rations also requires substantial information. An advantage of the proposed incentive scheme is that it makes use of logbook information. In many individual quota systems fishermen are asked to keep a logbook containing

[28] Again the same expressions hold if a dynamic fisherman model is used.

[29] As in the case of k_{it}, this self-report tax formula does not change if the fishermen maximise present value of future profits. Note also that (48) and (49) secures an ex ante expected optimum. Therefore, an ex post inefficiency may arise because of wrong expectations.

[30] The optimality of the tax system does not require that the fisherman shall understand the optimisation problem of society. All that is required is that the fisherman shall react in a rational way and this way is described by profit maximisation.

Table 1 – The signs of the comparative static expressions

	Stock tax rate (k_{it})	Harvest tax rate (τ_{it})
Beginning of the year stock size (x_t)	–	–
End-year stock size (x_{t+1})	+	+
Individual harvest (h_{it})	+	+
Risk-aversion function ($\phi_{it}(0)$)	–	+
Variance in measuring stock size (σ_{ε_i})	–	+

information about their catches, but no enforcement system is associated with these logbooks. Logbooks information is usually used to assists biologists in assessing fish stocks. In this paper we use logbook information by taxing self-reported catches in logbooks. Thus, the tax system proposed in this paper is not impossible to implement in practical fisheries management and it is, therefore, important to highlight whether the taxes are unrealistically high, and examining this question is the purpose of the next section.

5. Simulations

Some simulations for the cod fishery in Kattegat are now presented. Kattegat is a small sea east of Denmark with a small population of cod. The motivation is to obtain a very rough indicator for the magnitude of the stock tax function and the self-report tax rate. Jensen and Vestergaard (2002) estimate a pure stock tax function for cod in Kattegat. A conclusion in Jensen and Vestergaard (2002) is that the stock tax rate function is very low compared to the sales price — maximally 10%. The simulations in this paper extend the empirical analysis in Jensen and Vestergaard (2002), because the focus is on calculating the optimal stock tax functions and self-report tax rates in the presence of uncertainty about the stock.

As in Jensen and Vestergaard (2002) individual tax rates and functions have been calculated for six groups of vessels:

- Netters under 20 GT
- Netters over 20 GT
- Danish Seiners
- Trawlers under 50 GT
- Trawlers between 50 GT and 199 GT
- Trawlers over 200 GT

Some assumptions are necessary for the simulations to be conducted. First, it is necessary to assume full information about catches for society. Second, it is necessary to assume that voluntary self-reported catches in logbooks constitute a fixed part of the catches each year. Therefore, the functional relation $s_i=\alpha h_i$ is postulated and α is set to 0.30. Third, it is assumed that the fishery is always in steady-state and long-run economic yield is maximised. This implies that $x_{t+1}=x_t=x$. Theses assumptions is motivated by a desire to keep the simulations as simple as possible. If the first-order conditions for the fisherman are disregarded, the maximisation problem for society may be written as $\max(\sum_{i=1}^{n} ph_i - c_i(x,h_i))$s.t. $F(x)-\sum_{i=1}^{n} h_i = 0$. The restriction may be solved for x to yield $x=M(h_i, h_{-i})$. Now $M(h_i, h_{-i})$ is an expression for how the steady-state stock size is related to catches and $\partial M/\partial h_i$ is a biological response function. The biological response function indicates how the steady-state stock responds to changes in individual catches. $M(h_i, h_{-i})$ may be substituted into the objective function of society and the first-order condition for fisherman i with respect to h_i states that $p-\partial c_i/\partial h_i - \partial c_i/\partial M \partial M/\partial h_i - \sum_{j\neq i}\partial c_j/\partial M \partial M \partial h_i = 0$. The expression $\partial c_i/\partial M \partial M/\partial h_i - \sum_{j\neq i}\partial c_j/\partial M \partial M \partial h_i$ is the user cost of the fish stock. With respect to fisherman i, f_i and h_i are the control variables and the maximisation problem may be written as

$$\max(ph_i - c_i(N_i(h_i,\boldsymbol{h}_{-i}),h_i) - k_i(h_i)((\varphi_i(x^* - N(h_i,\boldsymbol{h}_{-i},\varepsilon_i))$$
$$-\frac{\sigma^2_{\varepsilon_i}}{2}\varphi_i''(x^* - N_i(h_i,\boldsymbol{h}_{-i},\varepsilon_i))) - \tau_i f_i(h_i))$$

The first-order conditions with respect to h_i and f_i are

$$p-\partial c_i/\partial h_i - \partial c_i/\partial N_i \partial N_i/\partial h_i$$
$$+k_i(h_i)\left(\varphi_i'(\partial N_i/\partial h_i) + \frac{\sigma^2_{\varepsilon_i}}{2}\varphi_i'''(\partial N_i/\partial h_i) - \tau f_i'(h_i)\right)$$
$$=0 \text{ and } k_i'(h_i)\frac{\sigma_{\varepsilon_i}}{2}\varphi_i''(0) + \tau_i = 0.$$

On the basis of these conditions and the functions presented below the tax rates and functions can now be simulated.

The simulation requires knowledge of:[31]

a. $M(h_i, \boldsymbol{h}_{-i})$
b. $c_i(h_i, x)$
c. $N_i(h_i, \boldsymbol{h}_{-i})$
d. ϕ_i
e. σ_ε

With respect to $M(h_i, \boldsymbol{h}_{-i})$ a logistic growth function has been estimated, while the cost function has the following form:

$$c_i(x,h_i) = \alpha_i + \frac{\beta_i h_i^2}{x}. \quad (50)$$

Individual cost functions have been estimated for the average vessel within the six groups.

Information about $N_i(h_i, \boldsymbol{h}_{-i})$ is not directly obtainable, but it is assumed that $N_i(h_i, \boldsymbol{h}_{-i})=DM(h_i, \boldsymbol{h}_{-i})$ and the simulations are conducted for:

- D=0.8
- D=0.6
- D=0.4

What is new compared to Jensen and Vestergaard (2002) is that an estimate for ϕ_i and σ_ε is necessary. Information about

[31] All details regarding the simulations are available by contacting the authors.

Table 2 – Self-report tax rates for the six groups of vessels, DKK per tonne

		1991	1992	1993	1994	1995	1996	1997
Netters under 20 GT	D=0.8	3.03	2.54	3.19	4.29	4.89	2.34	7.87
	D=0.6	6.07	5.07	6.36	8.57	9.78	4.68	15.71
	D=0.4	12.10	10.10	12.69	17.10	19.50	9.34	31.35
Netters over 20 GT	D=0.8	9.02	7.53	9.45	12.74	14.53	6.96	23.36
	D=0.6	17.95	14.99	18.83	25.37	28.92	13.86	46.51
	D=0.4	35.57	29.70	37.3	50.27	57.29	27.47	92.15
Danish Seiners	D=0.8	6.06	5.07	6.36	8.56	9.76	4.68	15.70
	D=0.6	13.10	10.94	13.74	18.52	21.11	10.11	33.95
	D=0.4	24.11	20.13	25.29	34.08	38.85	18.62	62.46
Trawlers under 50 GT	D=0.8	4.55	3.80	4.77	6.43	7.33	3.51	11.78
	D=0.6	9.08	7.58	9.52	12.83	14.63	7.01	23.51
	D=0.4	18.09	15.11	18.97	25.56	29.15	13.96	46.85
Trawlers between 50 GT and 199 GT	D=0.8	3.63	3.03	3.81	5.13	5.85	2.80	9.41
	D=0.6	7.25	6.05	7.60	10.24	11.68	5.59	18.77
	D=0.4	14.43	12.05	15.13	20.39	23.25	11.14	37.37
Trawlers over 200 GT	D=0.8	3.65	3.05	3.83	5.16	5.89	2.82	9.46
	D=0.6	7.91	6.05	9.08	9.88	9.88	4.73	18.02
	D=0.4	14.59	12.19	15.30	20.62	23.51	11.26	37.80

ϕ_i and σ_ε is not directly obtainable and, therefore, reasonable functional forms and parameters must be selected. The following form of ϕ_i is selected:

$$\varphi_i = a(N_i(h_i, \boldsymbol{h}_{-i}) - x) + b\frac{\sigma_{\varepsilon_t}^2}{2}(N_i(h_i, \boldsymbol{h}_{-i}) - x^2). \tag{51}$$

Now the parameters a and b are chosen such that a 50% reduction in the stock tax in Jensen and Vestergaard (2002) is obtained. It is, therefore, assumed that a=1.9998 and b=0.0001. With respect to the variance, this is assumed to be small and, therefore, σ_ε=500 tonnes. Based on these functions the tax rates and functions can be calculated by inserting actual values for the variables h_i, $\boldsymbol{h}_{-i}$, x and s_i. By using actual values an estimate for what the tax rate and functions that secure the optimal catches in each year given the actual chosen variables is obtained.

It has already been mentioned that the simulations depart from a function of ϕ_i that leads to a 50% reduction in the stock tax function in Jensen and Vestergaard (2002). Therefore, presentation of self-report tax rates is enough. For the period 1991–1997, these are presented in Table 2.

From Table 2 it is seen that the variable self-report tax rate is low compared to the sales price. With a sales price between 8200 and 13,500 DKK per tonne, the self-report tax rate is maximally 0.5% of the sales price. The variation in tax rates between vessel groups is low, which could suggest a uniform tax. However, the simulations are based on a very simple assumption about $N_i(h_i, h_{-i})$, so this conclusion is not very useful. The self-report tax rate decreases in D (the share of the true resource restriction that the fisherman includes). This conclusion is not surprising, because an increase in D decreases the market failure. The variation in the tax rates over time can be explained by variations in self-reported catches. If the self-reported catches are large, as in the early years, the tax rate becomes low.

But how sensible is the conclusion that the self-report tax rate is low to changes in the parameters. Jensen and Vestergaard (2002) show that a stock tax function is not very sensible to changes in the cost parameters. For this reason only sensibility analysis on ϕ_i and σ_ε is performed in this paper. Note that the parameter a in ϕ_i will not influence the self-report tax rate because this parameter is not included in ϕ_i''. Therefore, b is varied with ±50%. The results are presented in Table 3. Because of lack of variations in the tax rates between vessel groups and years only the results for D=0.8, Netters under 20 GT and 1997 are presented.

It is seen that the self-report tax rate increases with b. The reason for this is that an increase in b, increases the risk-aversion. Therefore, the fisherman prefers the certain self-report tax payment and the tax rate is increased. Despite this fact the increase in the tax rate is low even for high increases in b.

But what about σ_ε? In Table 4 the results obtained by varying σ_ε with ±50% are reported.

Naturally the self-report tax rate increases with an increase in σ_ε. The increase is larger than the increase associated with an increase in b. The reason for this is that the stock tax function is unaffected by an increase in σ_ε. However, even by varying σ_ε with ±50%, the self-report tax rate still constitutes a very low share of the sales price.

To conclude, from Tables 2–4 it is seen that the self-report tax rate is very low and, therefore, a combination of a stock

Table 3 – Sensibility analysis for ϕ_i. D=0.8, Netters under 20 GT, 1997, DKK per tonne

	Tax rates
Main case	7.87
+50%	11.79
−50%	5.90

Table 4 – Sensibility analysis for σ_{ε}., D=0.8, Netters under 20 GT, 1997, DKK per tonne

	Tax rates
Main case	7.87
+50%	17.69
−50%	1.97

and a self-report tax may be a useful combination of management tools within fisheries.

6. Conclusion and discussion

In this paper, a stock tax function and a self-report tax rate have been combined to solve the stock externality problem, the problems with measurement of stock size and the problems with asymmetric information about individual catches. Information about voluntary self-reported catches is available in logbooks. In the quota systems used in many countries fishermen shall keep a logbook with information about catches, but no well functioning enforcement system is set up in connection with the logbooks. Instead the purpose of the logbooks is to assists biologists in making stock assessments. In this paper we tax the voluntary self-reported catches in the logbooks. The stock and self-report tax system can be designed such that expected optimal individual catches are secured. This cannot be accomplished within an ITQ system. Assume that a TAC is determined and this TAC is distributed to fishermen as ITQs. Now trade among quotas between fishermen will secure that the stock externality problem is solved. However, the problem of measuring individual catches is not solved because of the well-known problems of compliance with individual quota systems. Therefore, this paper indirectly argues that taxes may be preferred to ITQs to manage fisheries. However, the paper only gives one argument for taxes. The issue of the choice between price and quantity regulation is by no means solved with the contribution in this paper because other kinds of uncertainty and asymmetric information can arise within fisheries.

Two points are worth mentioning. First, the analysis in this paper is based upon an assumption that stock size is a random variable. In Section 4 the risk-aversion function was approximated with a second-order approximation around the optimal point. If this approximation shall be precise it requires that the random variation in stock size (the variance with respect to measuring the uncertain stock size) is small, but in reality the random variation in stock size may be large; see Anon (2002). However, the second-order approximation is only conducted in order to analyse the tax functions and rates with mathematics. The conclusion in the case where the measurement error associated with the stock size is large is that fishermen will increase the self-reported catches if they are risk-averse. However, this conclusion can only be arrived at by conducting formally an approximation of the risk-aversion function. Second, the analysis assumes risk-aversion among fishermen and this assumption can also be discussed. If vessels are risk-neutral, the fisherman will be indifferent between the stock tax payment and the self-report tax payment. Therefore, if the fishermen are risk-neutral the stock tax alone can secure expected optimal individual catches.

A criticism of the mechanism proposed in this paper could be that it does not secure budget-balance. This criticism is part of the motivation for the work by Xepapadeas (1991), who proposes a random penalty mechanism to solve non-point pollution problems. Even though it is relevant to discuss this mechanism for a renewable resource, a fairly simple solution to the budget-balance problem is to pay back the social benefit from falling in line with the optimal catches to the industry. In other words, the social benefit from acting optimally is distributed back to, for example, the fishermen. In this manner, budget-balance can be secured.

Furthermore, the information requirements of the proposed tax mechanism could be discussed. This point is also part of the motivation for the work by Xepapadeas (1991). Within fisheries economics, taxes have traditionally been criticised for posing excessive information requirements, see Arnason (1990). The information requirements mentioned by Arnason (1990) can be seen from the model in this paper, because the user costs enter in the stock tax function and the user costs vary over time. However, the tax structure proposed in this paper raises even greater information requirements because society must have information about the individual risk-aversion. This information can, however, be obtained in surveys. Furthermore, in practice the information requirements are not larger than any necessary information needed when the ambition is to regulate in an optimal fashion.

The discussion of information problems is related to the analysis by Cabe and Herriges (1992), who mention a problem in connection with non-point pollution. The tax mechanism proposed within the non-point pollution literature will only work if producers perceive they have a significant influence on the ambient concentration at the damage site. For the model in this paper, this means that fishermen must react to the stock tax by taking some account of their effect on the stock. If the fishermen do not react in this way, the tax would be ineffective — the fishermen would interpret it as a lump-sum tax, which does not influence the marginal incentive to catch illegally. Note, however, that the tax will work if other criteria are used to determine the quota (e.g. biological or political). All that is required is that individual catches are determined.

The mechanism proposed in this paper reaches expected optimal individual catches. It is an expected optimum because h_{it} and $f_{it}(h_{it})$ are governed by a random variable. Society forms expectations with respect to the random variables and bases the tax mechanism on this expectation. In general, society's expectations of the variables differ from the realised value and, thus, an inefficiency arises ex post. However, reaching an expected optimum ex ante in the light of asymmetric information is common in economics. Given asymmetric information about catches and the self-report function, society cannot do anything better than reaching an expected optimum.

Another criticism that could be raised of the mechanism proposed in this paper is that optimal entry and exit are not secured (see Hansen et al., 2003). Thus, the optimal number of fishermen is not reached. To see this, assume that stock is perfect measurable and that the stock tax in Jensen and Vestergaard (2002) is imposed on the fishermen. This tax secures expected optimal individual catches, but does not secure the optimal amount of vessels. The reason for this is that the tax payment per vessel does not correspond to the reduction in costs of illegal landings if the marginal vessel were to exit. The same point holds for the combination between a stock tax and a self-report tax suggested in this paper due to the stock tax part of the mechanism. A solution to the entry and exit problem is to lump-sum transfer part of the tax revenue back to the fishermen in order to satisfy the optimal entry and exit conditions (see Hansen et al., 2003).

Despite these discussion points, combining several policy instruments to the solution of several market failure problems within fisheries is an important area for future research, because several market failure problems arise simultaneously in reality. For example, the optimal combination of instruments to the solution of problems with stock externalities, congestion and asymmetric information could be studied.

Appendix A

It is assumed that the sign of the partial derivative of Q with respect to a variable is the same as the sign of the partial derivative of the social user cost with respect to the same variable. Because of this assumption $\partial Q/\partial h_{it}<0$ since $\partial^2 c_{it}/\partial h_{it}\partial x_{t+1}>0$, while $\partial Q/\partial x_t>0$ since $\partial^2 c_{it}/\partial x_1^2<0$. Furthermore, because of the same fact $\partial Q/\partial x_{t+1}<0$.

By differentiating the stock and the self-report tax in the text (32) and (33) the following results are obtained:

$$\frac{\partial k_{it}}{\partial x_t}=\frac{\frac{\partial Q}{\partial x_t}\left(\varphi_{it}'\left(\frac{\partial N_{it}}{\partial h_{it}}\right)+\frac{\sigma_{\varepsilon_t}^2}{2}\varphi_{it}'''\left(\frac{\partial N_{it}}{\partial h_{it}}\right)\right)-\varphi_{it}'''\left(\frac{\partial N_{it}}{\partial h_{it}}\right))-\varphi_{it}''\left(\frac{\partial^2 N_{it}}{\partial h_{it}\partial x_t}\right)Q}{\left(\varphi_{it}'\left(\frac{\partial N_{it}}{\partial h_{it}}\right)+\varphi_{it}'''\frac{\sigma_{\varepsilon_t}^2}{2}\left(\frac{\partial N_{it}}{\partial h_{it}}\right)\right)^2}<0 \quad \text{(A1)}$$

$$\frac{\partial \tau_{it}}{\partial x_t}=-\frac{\partial k_{it}'}{\partial x_t}\frac{\sigma_{\varepsilon_t}^2}{2}\varphi_{it}''(0)<0 \quad \text{(A2)}$$

$$\frac{\partial k_{it}}{\partial x_{t+1}}=\frac{\frac{\partial Q}{\partial x_{t+1}}\left(\varphi_{it}'\left(\frac{\partial N_{it}}{\partial h_{it}}\right)+\frac{\sigma_{\varepsilon_t}^2}{2}\varphi_{it}'''\left(\frac{\partial N_{it}}{\partial h_{it}}\right)\right)}{\left(\varphi_{it}'\left(\frac{\partial N_{it}}{\partial h_{it}}\right)+\varphi_{it}'''\frac{\sigma_{\varepsilon_t}^2}{2}\left(\frac{\partial N_{it}}{\partial h_{it}}\right)\right)^2}>0 \quad \text{(A3)}$$

$$\frac{\partial \tau_{it}}{\partial x_{t+1}}=-\frac{\partial k_{it}'}{\partial x_{t+1}}\frac{\sigma_{\varepsilon_t}^2}{2}\varphi_{it}''(0)>0 \quad \text{(A4)}$$

$$\frac{\partial k_{it}}{\partial h_{it}}=\frac{\frac{\partial Q}{\partial h_{it}}\left(\varphi_{it}'\left(\frac{\partial N_{it}}{\partial h_{it}}\right)+\frac{\sigma_{\varepsilon_t}^2}{2}\varphi_{it}'''\left(\frac{\partial N_{it}}{\partial h_{it}}\right)\right)-\varphi_{it}'''\left(\frac{\partial N_{it}}{\partial h_{it}}\right))-\varphi_{it}''\left(\frac{\partial^2 N_{it}}{\partial h_{it}^2}\right)Q}{\left(\varphi_{it}'\left(\frac{\partial N_{it}}{\partial h_{it}}\right)+\varphi_{it}'''\frac{\sigma_{\varepsilon_t}^2}{2}\left(\frac{\partial N_{it}}{\partial h_{it}}\right)\right)^2}>0 \quad \text{(A5)}$$

$$\frac{\partial \tau_{it}}{\partial h_{it}}=-k_{it}''\frac{\sigma_{\varepsilon_t}^2}{2}\varphi_{it}''(0)>0 \quad \text{(A6)}$$

$$\frac{\partial k_{it}}{\partial \varphi_{it}}=\frac{-\varphi_{it}''\left(\frac{\partial N_{it}}{\partial h_{it}}\right)Q}{\left(\varphi_{it}'\left(\frac{\partial N_{it}}{\partial h_{it}}\right)+\varphi_{it}'''\frac{\sigma_{\varepsilon_t}^2}{2}\left(\frac{\partial N_{it}}{\partial h_{it}}\right)\right)^2}<0 \quad \text{(A7)}$$

$$\frac{\partial \tau_{it}}{\partial \varphi_{it}}=-k_{it}'\frac{\sigma_{\varepsilon_t}^2}{2}\varphi_{it}'''(0)>0 \quad \text{(A8)}$$

$$\frac{\partial k_{it}}{\partial \sigma_{\varepsilon_t}}=\frac{-\frac{1}{2}\varphi_{it}''\left(\frac{\partial N_{it}}{\partial h_{it}}\right)Q}{\left(\varphi_{it}'\left(\frac{\partial N_{it}}{\partial h_{it}}\right)+\varphi_{it}'''\frac{\sigma_{\varepsilon_t}^2}{2}\left(\frac{\partial N_{it}}{\partial h_{it}}\right)\right)^2}<0 \quad \text{(A9)}$$

$$\frac{\partial \tau_{it}}{\partial \sigma_{\varepsilon_t}}=-k_{it}'\frac{\sigma_{\varepsilon_t}^2}{2}\varphi_{it}''(0)>0 \quad \text{(A10)}$$

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