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The Welfare Gain from Switching to Tax Regulation of Fisheries[1]

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Abstract: Theoretical papers find that taxes are preferred over individual transferable quotas (ITQs) when fisheries regulators are uncertain about either biological growth or the extent of non-compliance with regulations. However, the size of the welfare gain from switching to taxes has not previously been investigated empirically. Based on estimated profit and growth functions, we simulate this gain for the Danish cod fishery in the Kattegat and find a welfare gain of less than 2%. We also develop a simple indicator which can be used to approximate the welfare gain of switching to tax regulation for other fisheries. The value of the indicator is calculated for a number of fisheries worldwide for which the necessary data have been published and we find that the gain from a switch to taxes is typically between 1.5% and 2.5% (in no case greater than 4.2%). We, therefore, conclude that the switch to tax regulation of fisheries, which has been recommended in prior theoretical literature, is of little practical importance.

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1. Introduction

Fisheries are an example of a renewable resource where overexploitation may result if the harvest is not properly regulated. To address this problem, fisheries are being regulated worldwide and in almost all cases some kind of quota regulation is used, while taxes or landing fees have hardly ever been applied (see Costello and Deacon, 2007).

Much classical work on the regulation of fisheries assumes that the regulator has full knowledge of biological and economic conditions[2], but this assumption is, of course, unrealistic. The implications of uncertainty about the stock size (biological uncertainty) for optimal extraction of a fish resource was first studied by Reed (1979)[3] using a stochastic stock-growth model.[4] The importance of uncertainty about illegal landings (compliance uncertainty) was originally investigated by Sutinen and Andersen (1985).[5] Recently, Weitzman (2002) used a stochastic stock-growth model to show that taxes are preferred over individual transferable quotas (ITQs) under biological uncertainty when no economies of scale in harvest are assumed. Hansen and Jensen (2016) show that under negative economies of scale, ITQs may be preferred over taxes, but only if the marginal cost of the harvest is large compared to the marginal cost of the stock size. Finally, Hansen et al (2008) also use a stock-growth model to show that taxes are preferred over ITQs under compliance uncertainty irrespective of the assumption about the degree of economies of scale. Thus, the prior theoretical literature suggests that a potential welfare gain from switching to taxes may exist in many fisheries currently using quantity regulation.

Despite these theoretical results, we are not aware of any empirical studies that have estimated the size of the potential welfare gains from switching to taxes.[6] Thus, we do not know

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[2] As an example full certainty is assumed in the path-breaking article by Clark and Munro (1975) where optimal extraction of a renewable resource is analysed and by using a capital theoretical approach Clark and Munro (1975) reach a golden rule for exploiting a renewable resource.

[3] An overview over the literature on biological uncertainty is provided by Andersen and Sutinen (1984).

[4] In fisheries economics there is a lot of confusion about the definitions of various growth models but in this paper we chose to distinguish between stock-recruitment and stock-growth models. A stock-recruitment model is normally used by biologists to describe the relation between a spawning stock biomass and new cohorts of fish. In contrast, a stock-growth model captures that the growth of a fish stock in a given time period depend on the total recruitment (both the recruitment of a new cohort of fish and the growth of existing cohorts of fish). With these definitions the models in Reed (1979), Weitzman (2002), Hansen and Jensen (2016) and Hansen et al (2008) are stock-growth models but the term stock-recruitment models are used in all these studies. However, to avoid any confusion we use the term of stock-growth models in this paper.

[5] The literature on compliance uncertainty considers optimal enforcement when there is non-compliance with fisheries regulations. Apart from biological uncertainty and compliance uncertainty, the fisheries economic literature has also considered price uncertainty (see Andersen, 1982).

[6] To our knowledge the only prior paper that quantifies the effects of various kinds of uncertainty for the choice between taxes and ITQs is Hannesson and Kennedy (2005) but here hypothetical values for the uncertainties and the parameter values are used.

how large the potential welfare gains are or what parameters are critical for the size of the gain. We, therefore, address the following research questions in this paper:

> Does switching to tax regulation for typical fisheries result in a welfare gain, and if so, how large is this gain?

To address this research question, we estimate core biological and economic relationships for the Danish cod fishery in the Kattegat. This fishery is well suited for our empirical investigation because long time series of both biological and economic data are available. In particular, we are able to estimate the degree of economies of scale as well as the size of both biological and compliance uncertainty. Using these estimates, we construct a simulation model based on a feed-back rule approach[7], which is used to simulate the welfare gain of switching to tax regulation.

When estimating the cost function, we find negative economies of scale for the Danish cod fishery in the Kattegat, which implies that ITQs may be preferred over taxes. However, we find a welfare gain from switching to tax regulation of 2.8% if the regulator uses uniform regulation, while the welfare gain of taxes decreases to 1.6% if the regulator instead adjusts the regulatory instruments (tax rates or quotas) to include information about the last period´s escapement.[8] Thus, even though there is a welfare gain of switching to taxes for the Danish cod fishery in the Kattegat, it is quite small.

The modelling and simulation procedure we apply requires a considerable amount of information. However, by using extensive sensitivity analysis, we show that the size of the welfare gain from a switch to tax regulation can be approximated reasonably well by a simple indicator. Calculating the value of this indicator only requires knowledge about the standard deviation of the escapement (the stock size) and the escapement level at the maximum sustainable yield and this information can be obtained by estimating a natural growth function. Many regulators will, therefore, be able to calculate the indicator value for a particular fishery they regulate. We have calculated the value of the indicator for a number of fisheries worldwide, where we have been able to find the necessary information in published papers. Our survey of studies covers a broad spectrum of fisheries and in all cases we find a small welfare gain, usually between 1.5% and 2.5% (in no case greater than 4.2%), from switching to tax regulation.

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[7] See e.g. Clark (1990) for a definition of a feed-back rule.

[8] This is the current procedure in Danish fisheries regulation as is the case in many other fisheries as well.

Thus, it is possible to answer the research question we pose and our conclusion is that the size of the welfare gain of switching to tax regulation is likely to be small for most fisheries. The recommendation to switch to tax regulation under compliance and biological uncertainty in the existing theoretical literature is, therefore, of little practical relevance. Instead, regulators should focus on other less dramatic and more beneficial management reforms such as switching from biological management objectives (maximum sustainable yield) to economic objectives (maximum economic yield) or switching from individual non-transferable quotas (INTQs) to ITQs. However, for fisheries with a very large biological uncertainty and/or a very small escapement level at the maximum sustainable yield, the welfare gain from switching to taxes may be substantial. Though we did not find any fisheries of this kind in the literature survey, we cannot exclude that such fisheries may exist. Furthermore, by using the indicator developed in the paper, regulators should be able to approximate the gain from switching to tax regulation for any specific fishery. Thus, providing an indicator that regulators can use for a specific fishery is another important result of this paper.

The paper also provides two methodological contributions to the fisheries economic literature:

1. We derive and estimate a relatively simple but theoretically consistent industry profit function that enables the identification of the degree of economies of scale.

2. We use feed-back rules instead of the usual value function approach to simulate the welfare of various regulatory instruments.

A theoretically consistent empirical model that enables the estimation of the degree of economies of scale may be of interest to other researchers. This may also be the case for the feedback rule we use because it facilitates the evaluation of regulatory instruments under sophisticated management strategies. Such strategies that take escapement levels of previous periods into account are common practice in fisheries regulation (see, e.g. ICES, 2013).

The paper is organized as follows. In section 2, we briefly summarize the most important theoretical results in the existing literature, while section 3 presents a general simulation model that is used to quantify the welfare gain of taxes. The specific functional forms used in the simulations are discussed in section 4, while the estimation results for the Danish cod fishery in the

Kattegat are described in section 5. The simulation results are presented in section 6 and section 7 concludes the paper.

2. Prior literature on taxes versus ITQs in fisheries

In the fisheries economic literature, three recent theoretical papers use a dynamic stock-growth model to investigate the implications of uncertainties regarding the choice between tax and ITQ regulation.[9] Weitzman (2002) investigates this choice under biological uncertainty, but assumes no economies of scale (the average cost of harvest only depends on the size of recruitment). The regulator determines the value of a regulatory instrument (a tax or a total quota) before knowing the size of the recruitment, while the representative fisherman observes the recruitment when deciding how much to harvest. This asymmetry in the information about the size of the recruitment generates a difference in welfare between taxes and ITQs. The regulator's problem is to induce the fisherman to harvest an optimal proportion of the recruitment and if the actual recruitment is lower than the expected recruitment it is optimal to reduce the total harvest below the expected optimal value. With ITQs, this is not possible because the total quota is set prior to observing the actual recruitment. Under tax regulation, on the other hand, an optimum can be reached by decentralizing the harvesting decision to the fisherman who observes the actual recruitment prior to making harvesting decisions. Thus, Weitzman (2002) shows that under biological uncertainty, taxes are always preferred over ITQs under no economies of scale.

Hansen and Jensen (2016) extend the analysis by Weitzman (2002) on biological uncertainty to include both positive and negative economies of scale. Specifically, Hansen and Jensen (2016) show that under negative economies of scale the pro-tax result in Weitzman (2002) may break down if the marginal cost of harvest is large compared to the marginal costs of stock size.[10]

The implications of compliance uncertainty (uncertainty about illegal landings) on the choice between taxes and ITQs have been studied by Hansen et al. (2008) who include the possibility of illegal landings in a stochastic stock-growth model. The main result in Hansen et al

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[9] Departing from Weitzman (1974) several papers use a static, steady-state equilibrium model to analyze the implications of uncertainty about prices (benefits) and costs. This literature is represented by Koenig (1984a) and (1984b), Anderson (1986), Androkovich and Stollery (1991), Jensen and Vestergaard (2003) and Hansen (2008). However, these studies are not directly relevant for our paper because a steady-state equilibrium is assumed.

[10] Note that the marginal cost of stock size can be labelled the marginal cost of recruitment or escapement depending on the time in a year where the stock size is measured. However, in this paper we use the term the marginal cost of stock size to be consistent with Clark (1990).

(2008) is that under compliance uncertainty taxes are preferred over ITQs for all possible assumptions about the degree of economies of scale.

To conclude, the existing theoretical literature suggests that taxes may be preferred over ITQs for fisheries under both biological uncertainty and compliance uncertainty. Under biological uncertainty, this pro-tax result holds under weakly positive economies of scale, while taxes are preferred over ITQs for any assumptions about the degree of economies of scale under compliance uncertainty. However, to our knowledge, no papers have empirically quantified the size of the welfare gain of switching to tax regulation. In order to investigate this issue, we must construct and estimate a parametric model for a given fishery that incorporates biological uncertainty, compliance uncertainty and the degree of economies of scale. In the next section, we develop such a simulation model, while the appropriate functional forms are specified and estimated for the Danish cod fishery in the Kattegat in the following sections. Finally, the model is used to simulate the size of the welfare under both tax and ITQ regulation.

3. A general simulation model

In this section, we specify a model of a fishery characterized by a growth function, an industry profit function and a penalty function. After this, fishermen's behavior is discussed and, finally, the objectives of the regulator and a feed-back rule are presented. In the following sections, parametric functional forms of the model are specified and estimated.

The growth function and biological uncertainty

We use the dynamic stock-growth model originally introduced by Reed (1979)[11] where the growth of a fish stock and harvest occurs in distinct time periods. Let R_t denote the recruitment (the size of the fish stock available at the beginning of a fishing season t).[12] Furthermore, let S_t be the escapement (stock size available at the end of a fishing season after fishermen have completed the harvest activities). Finally, H_t denotes the fisherman´s aggregate harvest during a fishing season,

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[11] The dynamic stock-growth model from Reed (1979) is used to analyze the choice between taxes and ITQs in Weitzman (2002), Hansen et al (2008) and Hansen and Jensen (2016).

[12] Our use of the term recruitment for the size of a fish stock at the beginning of a fishing season can be questioned. For fisheries biologists, recruitment is the size of a new cohort of fish generated by a spawning stock biomass and fisheries economists normally use stock size for what we refer to as recruitment. However, in the fisheries economic literature on the implications of a stochastic stock size for fisheries management it is common to define recruitment as the fish stock at the beginning of a fishing season (see e.g. Reed, 1979 and Weitzman, 2002). Since we assume that the recruitment is stochastic this tradition is followed in the present paper.

which is the sum of the legal harvest (H_{Lt}) and the illegal harvest (H_{Lt}). We assume that harvesting is the only variable that affects the fish stock during a fishing season so that:

$$S_t = R_t - H_t \tag{1}$$

Between fishing seasons the fish stock can grow and this growth is described by a stock-growth relation. Formally, we let R_t be a function of the escapement (S_{t-1}) and a stochastic variable (ε_t) that captures random variations in the growth (due to, for example, changes in climatic conditions). Thus, the growth function is given by:

$$R_t(S_{t-1}, \varepsilon_t) \tag{2}$$

We assume that the stochastic variable, ε_t, is observable by the fisherman when making harvest decisions, while the regulator only knows a distribution of ε_t when the regulations are determined at the beginning of a fishing season.[13] The standard derivation of ε_t is a measure for the size of the regulator's biological uncertainty. Because of the asymmetry of information, the welfare with taxes and ITQs may differ.

The industry profit function

The fishing industry is modelled as a representative fisherman who maximizes the industry profit. We let π denote the marginal industry profit of harvest during a fishing season, which is defined as the difference between the marginal revenue and the marginal costs at a particular point in time. The cost of the harvest often depends on the size of the fish stock because of search costs, which reflect that it becomes increasingly difficult to locate fish before harvesting as the stock size falls.[14] We let x denote the size of the fish stock at the moment of time when fishing occurs (so that $x = R_t$ at the beginning of a fishing season, $x = S_t$ at the end of a fishing season and $S_t < x < R_t$ during a

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[13] The information structure assumed in this paper is consistent with the literature on the choice between taxes and ITQs for fisheries (see e.g. Weitzman, 2002). The idea is that fishermen experience the costs associated with the fishing activity. For this reason the fishermen are better informed about ε_t when making harvesting decisions during the season than the regulator when he makes regulatory decisions prior to the fishing season.

[14] An alternative explanation for why costs increase as stocks decrease is that the density of fish falls as the stock size decline (see e.g. Clark, 1990).

fishing season). The dependency of the marginal industry profit on the stock size is captured by $\pi(x)$ and, due to search costs, we expect that $\frac{\partial \pi}{\partial x} > 0$.

The marginal industry profit at a particular point in time during a fishing season also depends on the accumulated legal and illegal harvest from the beginning of the current fishing season simply because of either positive or negative economies of scale.[15] Let h_{Lt} be the amount of accumulated legal harvest (from the start of a fishing season) and let h_{It} be the accumulated illegal harvest. Given this dependency on the accumulated harvest, the marginal industry profit function can be expressed as:[16]

$$\pi(x, h_{Lt}, h_{It}) \tag{3}$$

At any point in time during a fishing season, the current stock size is equal to the recruitment minus the accumulated legal and illegal harvest up to this point in time so that:

$$x \ = R_t - (h_{Lt} + h_{It}) \tag{4}$$

By inserting (4) into (3) and integrating the resulting expression from R_t to $R_t - H_{Lt} - H_{It}$ we get the following total industry profit function:

$$\Pi(H_{Lt}, H_{It}, R_t) = \int_{R_t - H_{Lt} - H_{It}}^{R_t} \pi(x_t, h_{Lt}, h_{It})dx \tag{5}$$

In (5) $\Pi(H_{Lt}, H_{It}, R_t)$ is a total profit function for an entire fishing season depending on the legal and illegal harvest (H_{Lt} and H_{It}) and the recruitment (R_t).

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[15] Our formulation of the marginal profit function implies a separation of the degree of economies of scale and stock effects which are important for the choice between taxes and ITQs (see Hansen and Jensen, 2016). This separation is not always explicit in the existing fisheries economic literature (see Clark, 1990 for an example) but we follow Hansen and Jensen (2016) and allow for both positive and negative economies of scale. In contrast Weitzman (2002) and Hannesson and Kennedy (2005) assume that marginal industry profit only depends on x corresponding to an assumption about zero economies of scale.

[16] Note that using a marginal profit function to derive a total profit function is a bit untraditional in economics since we normally use the total function to find a marginal function (see Varian, 1992). However, departing from a marginal profit function ensures that both positive and negative economies of scale are incorporated in a linear marginal profit function in a theoretical consistent way.

The penalty function and compliance uncertainty

Under both tax and quota regulation, we include the possibility of illegal harvest, and to reduce the size of this activity, the regulator undertakes inspections and imposes fines. Inspections and fines make illegal behavior less attractive and we characterize this as an enforcement policy. We assume that the enforcement policy generates an expected fine payment, P, imposed on the fishermen leading to an expected penalty function. The expected penalty function is assumed to depend on the size of the illegal harvest during a fishing season so that we obtain:

$$P(H_{It}, a_t) \tag{6}$$

It is assumed that $\frac{\partial P}{\partial H_{It}} > 0$ and $\frac{\partial^2 P}{\partial {H_{It}}^2} > 0$ which capture the assumption that the marginal expected penalty is positive and increases with the size of illegal harvest. Note that under both tax and ITQ regulation, the extent of illegal landings is determined by the representative fisherman who takes the expected penalty function in (6) into account. Following Hansen et al (2008) the expected penalty also depends on an exogenous parameter, a_t, which we interpret as enforcement efficiency. The representative fisherman can observe the realized value of a_t when making harvest decisions, while the regulator only knows a distribution of the enforcement efficiency.[17] Thus, there is asymmetric information about a_t and uncertainty about the enforcement efficiency is labeled compliance uncertainty, which may generate a difference in the welfare between tax and ITQ regulation. We assume that the standard error of a_t is a measure of the size of the compliance uncertainty.

The representative fisherman

We make the standard assumption that the representative fisherman ignores the resource restriction[18] and uses the legal and illegal harvest as control variables. The fisherman maximizes the

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[17] The information structure assumed in this paper is consistent with the prior literature on enforcement uncertainty (see Hansen et al, 2008). Here it is assumed that individual fishermen know the size of their total illegal harvest while the regulator only observes the part of illegal harvest that is detected by inspectors. Therefore, the individual fishermen are better informed about the actual probability of detection. After individual fishermen's expected penalty functions are aggregated to reach an industry penalty function this information asymmetry is captured by assuming that the enforcement efficiency, a_t, in (6) is unobservable by the regulator but observable by the fishermen.

[18] See e.g. Clark (1990).

industry's profit in each time period less the expected penalty payments subject to the regulations and given the realized values of the two stochastic variables which he observes. Under ITQ regulation, the profit is maximized subject to the restriction that legal landings must be less than or equal to the quota (Q_t). Therefore, the fisherman solves the following problem under quota regulation:

$$\underset{H_{Lt}, H_{It}}{Max} \left(\Pi_t(H_{Lt}, H_{It}, R_t(S_{t-1}, \varepsilon_t)) - P(H_{It}, a_t)\right) \tag{7}$$

s.t.

$$H_{Lt} \leq Q_t \tag{8}$$

In the following, we assume that the quota restriction given by (8) is binding.

Under taxes (with tax rate Φ_t on legal harvest), the representative fisherman subtracts the tax payment on legal landings from the industry profit. The fisherman, therefore, solves the following problem:

$$\underset{H_{Lt}, H_{It}}{Max} \left(\Pi_t(H_{Lt}, H_{It}, R_t(S_{t-1}, e_t)) - \Phi_t H_{Lt} - P(H_{It}, a_t)\right) \tag{9}$$

With these specifications of the fisherman´s decisions, we include the possibility of both biological uncertainty (captured by the stochastic variable, ε_t) and compliance uncertainty (captured by the stochastic variable, a_t) in the model.

The regulator and a feed-back rule

The regulator maximizes social welfare, which we define as the industry profit before tax and penalty payment. Thus, the regulator treats tax and penalty payments as pure transfers.[19] In addition, the maximization problem for the regulator is more complicated than the problem for the fisherman because the regulator takes the resource restriction into account, which leads to

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[19] For simplicity we assume that the regulator disregards a possible double dividend arising from collecting public revenue.

interactions between time periods. Finally, the regulator only knows the distributions of a_t and e_t, which implies that an expectation of social welfare over the current and future values of the two random variables is maximized. Thus, the regulators problem can be expressed as:

$$\underset{Z_t}{Max}\begin{pmatrix} E_{a_t,\varepsilon_t}\left[\Pi(H_{Lt}^Z(Z_t), H_{It}^Z(Z_t), R_t(S_{t-1},\varepsilon_t))\right]+ \\ dE_{a_t,\varepsilon_t}\left[V^*(F(R_t(S_{t-1},\varepsilon_t)-H_{Lt}^Z(Z_t)-H_{It}^Z(Z_t),\varepsilon_{t+1}))\right] \end{pmatrix} \qquad (10)$$

s.t.

$$R_t = S_{t-1} + R_t(S_{t-1}, e_t) \qquad (11)$$

where $0 < d \leq 1$ is the discount factor and E is an expectation operator. In (10) only S_{t-1} is observable, while Z_t is the value of the regulatory instrument (the total quota, Q_t or the tax, Φ_t). $H_{lt}^Z(Z_t)$ and $H_{it}^Z(Z_t)$ is the aggregated legal and illegal harvest given by the solution to the fisherman's maximization problems ((7) - (8) or (9)). Thus, $H_{lt}^Z(Z_t)$ and $H_{it}^Z(Z_t)$ represent the fisherman´s response functions to the regulator's choice of the value of the regulatory instrument.

We now let $V^*(.)$ be the expected discounted sum of the expected welfare in all future time periods given optimal values of the regulatory instruments, which implies that:

$$V^*(S_t) = \underset{Z_{t+1}^*, Z_{t+2}^*, \ldots}{ArgMax} E\left[\sum_{\tau=t+1}^{\infty} d^{\tau-t-1}\Pi(H_{L\tau}^Z, H_{I\tau}^Z, R_\tau)\right] \qquad (12)$$

The problem in (10) and (11) is a dynamic programming problem that can be solved numerically using standard recursive methods (see Conrad and Clark, 1991) to yield an approximation of $V^*(.)$ defined in (12). However, we follow a different approach by using a feed-back rule, which is a functional relation between the value of a decision maker's control variable in a given time period (here the tax or the total quota) and the previous period's values of the state variables (here the escapement). In fisheries economics, feed-back rules have almost exclusively been used to find optimal adjustment paths for total quotas over time[20] and to our knowledge, these rules have not

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[20] See Clark (1990) and Sandal and Steinshamn (1997)

been used to compare regulatory instruments before. However, using feed-back rules to compare regulatory instruments has some important advantages which will become clear below.

We can now reformulate the regulator´s problem in (10) and (11) to find a feed-back rule, $Z^{*}(S_{t-1})$, that maximizes the expected welfare:

$$\underset{Z\ (.)}{Max}\ E\left[\sum_{t=1}^{T}\Pi(H_{L\tau}^{Z}(Z^{*}(S_{t-1})),H_{I\tau}^{Z}(Z^{*}(S_{t-1})),R_{\tau})/T\right]\ \text{for}\ T\rightarrow\infty \tag{13}$$

s.t.

$$R_{t}=S_{t-1}+R_{t}(S_{t-1},e_{t})+e_{t} \tag{14}$$

Sandal and Steinsham (1997) have shown that the solution obtained by maximizing (10) subject to (11) is equivalent to the result of maximizing (13) subject to (14). This implies that any set of control variables ($Z_{t+1}^{*},Z_{t+2}^{*},...$) that is a solution to (10) subject to (11) for every future time period can be found by using a (possibly quite complex) feed-back rule, $Z\ (.)$, that solves (13) subject to (14).

The optimal feedback rule found by maximizing (13) subject to (14) may be approximated by using a Taylor-series expansion given as:

$$Z(S_{t-1})\approx\sum_{g=0}^{G}a_{g}(S_{t-1})^{g} \tag{15}$$

where G is the number of polynomial elements included in the feed-back rule. Equation (15) implies that the optimization problem can be solved numerically using standard routines for a given T and G. Note that Sandal and Steinshamn (1997) have shown that the approximation error decreases as G increases.

The feed-back rule in (15) has a nice intuitive interpretation since G reflects the regulator’s reactions to information about the previous period´s escapement. With $G=0$, the regulator does not include information about the previous period’s escapement at all and the tax rate or total quota is fixed at a uniform level. This solution is relevant when it is difficult to adjust total quotas or taxes (e.g. for political reasons) or when the estimates of the escapement are very uncertain.[21] $G > 0$ illustrates the situations where the value of the regulatory instruments is adjusted in response to the previous period´s escapement. In particular, $G = 1$ implies that the tax or the total quota is a linear function of the last period's escapement, S_{t-1}, which corresponds to a first-order Taylor approximation in (15). When $G = 2$, the tax or total quota is a quadratic function of S_{t-1}, which corresponds to a second-order Taylor approximation.

The theoretical results in Weitzman (2002), Hansen and Jensen (2016) and Hansen et al (2008) are derived under the assumption that $G=0$. Thus, the simulation results for $G > 0$ allow us to derive welfare implications of more sophisticated regulatory rules where the regulatory instrument is adjusted in response to shifts in the escapement conditions. Such sophisticated regulatory practices are common in fisheries regulation (see, e.g. ICES, 2013).

4. Specific functional forms

In this section, we specify the assumed functional forms for the growth function, the profit function and the penalty function, which will be used in the simulations of the model from section 3.

The growth function and biological uncertainty

We follow the main tradition in the fisheries economic literature and assume a growth function based on the total biomass (e.g. Conrad and Clark, 1991).[22] Arnason et al (2004) compare various specifications of the growth functions and conclude that a standard logistic specification gives the best statistical fit for almost all fish species. We, therefore, use a logistic growth function given as:

$$R_t(S_{t-1}, e_t) = rS_{t-1}(1 - \frac{S_{t-1}}{K}) + e_t \tag{16}$$

where r is the intrinsic growth rate and K is the carrying capacity. Following Weitzman (2002), ε_t enters additively in (10) [23] and it is assumed that ε_t follows a normal distribution. From section 3, we have that the regulator specifies the taxes or ITQs prior to observing the realization of ε_t and instead the regulator's decisions are based on a prior distribution over ε_t.

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[21] With a very uncertain escapement measure, this variable cannot be used to adjust regulations.

[22] Biologists often use the spawning stock biomass instead of the total biomass (see e.g. ICES, 2013).

[23] Hoel and Karp (2001) have investigated the implications of multiplicative uncertainty in a stock externality model by using simulations and show that taxes is always preferred over quotas. Due to the similarities between a stock externality model and a fisheries model we believe that this result also holds for fisheries.

The industry profit function

Many empirical specifications of profit functions implicitly assume zero economies of scale.[24] However, the degree of economies of scale is potentially important for the choice between taxes and ITQs[25] so we want to estimate this degree empirically.[26] To obtain a parsimonious specification of a profit function, we assume that the marginal industry profit is a linear function of the legal and illegal harvest and the stock size so that: [27]

$$\pi(h_{L\tau}, h_{I\tau}, x_\tau) = p - c - bx_\tau - k(h_{L\tau} + h_{I\tau}) \qquad (17)$$

where p is the output price and c, b and k are cost parameters. c is a constant marginal cost of harvest, which is expected to be positive, while b captures the marginal cost of the stock size, which is expected to be zero or negative.[28] Finally, k indicates the degree of economies of scale and if $k=0$, (17) reduces to the linear specification used by Weitzman (2002) with no economies of scale. However, (17) also allows positive economies of scale ($k<0$) and negative economies of scale ($k>0$).

The total industry profit function, derived by integrating (17) (see section 3), is: [29]

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[24] In micro-economics it is common to define the degree of economics of scale in relation to the size of a production plant (see e.g. Varian, 1992). However, in the literature on regulation of natural monopolies economics of scale is normally defined in relation to the output level (see e.g. Joskow, 2005). We follow the latter tradition in this paper and measure the degree of economics of scale in relation to the size of harvest (output).

[25] See Hansen and Jensen (2016)

[26] A common specification of the total profit function in the fisheries economic literature is $\Pi_t(H_{Lt}, H_{It}, R_t) = p\left[H_{Lt} + H_{It}\right] - \frac{d\left[H_{Lt} + H_{It}\right]}{R_t}$, where $d \geq 0$ is a cost parameter (see e.g. Conrad and Clark, 1991 and Arnason et al, 2004). The corresponding marginal profit function, $\pi(h_{L\tau}, h_{I\tau}, x_\tau) = p - \frac{d}{x_\tau}$, is independent of h_t implying that zero economies of scale is implicitly assumed (see Hansen and Jensen, 2016 for a discussion).

[27] Note that we assume that the marginal cost of legal and illegal harvest is identical. This assumption can, of course, be questioned but due to lack of data we cannot identify the marginal cost of illegal harvest separately.

[28] The assumption that $b \leq 0$ is consistent with the with the traditional fisheries economic literature (see Conrad and Clark, 1991 and Arnason et al, 2004). To see this, assume that the total profit function is given by $\Pi_t(H_{Lt}, H_{It}, R_t) = p\left[H_{Lt} + H_{It}\right] - \frac{d\left[H_{Lt} + H_{It}\right]}{R_t}$. Now the marginal costs of stock size become $\frac{\partial \Pi_t(H_{Lt}, H_{It}, R_t)}{\partial R_t} = \frac{d\left[H_{Lt} + H_{It}\right]}{(R_t)^2}$ and with $d \geq 0$ we have the same assumption about sign of the marginal stock costs as in our paper.

[29] See the appendix A for a derivation of (18).

$$\begin{aligned}&\Pi_t(H_{Lt},H_{It},R_t) = p\left[H_{Lt}+H_{It}\right]-c\left[H_{Lt}+H_{It}\right]\\&-b\left[(H_{Lt}+H_{It})R_t-½(H_{Lt}+H_{It})^2\right]-k\left[½(H_{Lt}+H_{It})^2\right]\end{aligned}\tag{18}$$

where the total revenue is $p\left[H_{Lt}+H_{It}\right]$ and the total cost is $c\left[H_{Lt}+H_{It}\right]+b(H_{Lt}+H_{It})R_t -$ $½b(H_{Lt}+H_{It})^2 +$ $k\left[½(H_{Lt}+H_{It})^2\right]$. Equation (18) is a novel specification of a total profit function for fisheries, but we find the formulation attractive since it is relatively simple but, at the same time, allows for both positive and negative economies of scale in a theoretically consistent way captured by the fisherman's profit maximizing behavior during the fishing season.

The penalty function and compliance uncertainty

In the simulations, we use a quadratic specification of the expected penalty function given as:

$$P(H_{It},a_t) = \frac{a_t}{2}(H_{It})^2 \tag{19}$$

We assume that a_t follows a uniform distribution[30] and, from section 3, the regulator must base his decisions on the prior distribution over a_t. In contrast, the representative fisherman observes the realization of a_t before deciding on the size of the illegal harvest.

5. The Danish cod fishery in the Kattegat and parameter estimation

In this section we describe the Danish cod fishery in the Kattegat, the data we use in the paper, and the estimation results for the natural growth, the cost and the expected penalty function.

The fishery and the data

The Danish cod fishery in the Kattegat is a small-scale fishery where approximately 64 vessels participated in 2014. The cod fish stock is mainly exploited by Danish Seiners and for the entire

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[30] The assumption about a uniform distribution can be questioned but another distribution (such as a normal distribution) will decrease the welfare loss of both taxes and ITQs under compliance uncertainty. Thus, a uniform distribution maximizes the welfare loss of taxes and ITQs.

data period, the fishery has been regulated with individual quotas.[31] However, the total quota for Danish fishermen must be in line with the total allowable catches (TACs) set by the EU.

The Danish cod fishery in the Kattegat is well suited to the simulation of the model developed in the previous sections because:

1. We have a long data series for biological variables (1971-2011).
2. We have a reasonably long time series for economic variables (1995-2011).
3. There is very little inflow and outflow of cod between the Kattegat and other fishing areas.
4. The cod stock in the Kattegat is almost exclusively exploited by Danish fishermen (see ICES, 2013).[32]
5. ICES (1997) and (2008) have estimated the size of the illegal harvest for the fishery and indicated confidence intervals for these estimates.

We use the escapement observations (S_t) from ICES (2013) and the total harvest (H_t) is defined as the sum of the legal and illegal harvest. The legal harvest (H_{Lt}) is defined as the registered landings by Danish vessels in EU harbors,[33] while the illegal harvest (H_{It}) is assumed to be 20% of the total harvest during the entire data period. This illegal harvest share corresponds to the estimates of illegal landings for the Danish cod fishery in the Kattegat by ICES (1997) and (2008).[34] The time series for the natural growth ($G(S_t)$) is calculated by using the definition $G(S_t) = S_{t+1} - S_t + H_t$ where by definition $S_{t+1} = R_t$. Figure 1 illustrates the development in the escapement, the total harvest and the natural growth for cod in the Kattegat for the period 1971 to 2011.[35]

Figure 1: Escapement, total harvest and natural growth for cod in the Kattegat, 1971-2011.

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[31] Between 1971 and 2006 the Danish cod fishery in Kattegat was regulated with INTQs but ITQs were introduced in 2006.

[32] Between 1971 and 2012 the legal harvest of cod in Kattegat by non-Danish vessels (almost exclusively Swedish vessels) only constituted between 2.8 and 3.9 % of the total harvest. In appendix B we discuss how the Swedish vessels have been treated in the simulations.

[33] See ICES (2013)

[34] Despite the change in regulation from INTQs to ITQs in 2006, ICES (1997) and (2008) estimate that the illegal harvest constitute 20% of the total harvest for Danish vessels fishing cod in Kattegat between 1971 and 2007.

[35] See appendix B for details.

From Figure 1, we see that the escapement, the aggregated total harvest and the natural growth decline over time. This development has been attributed to overexploitation.[36]

When calculating the total industry revenue (*TR*), we use income data for Danish vessels fishing cod in the Kattegat (Anon, 1997 - 2013). The total industry costs of harvesting cod (*TC*) are calculated as a share of the total costs of harvesting all fish species by using the harvest share of Danish vessels fishing cod from Anon (1997) and Anon (2013). The total industry costs of harvesting cod are adjusted to include remuneration to the skipper and capital costs (see appendix B for details). The industry profit for the Danish cod fishery in the Kattegat (π) is the total industry revenue minus the total industry costs. Figure 2 shows the industry revenue, the industry costs and the industry profit for the Danish cod fishing in the Kattegat for the period 1995 to 2011.[37]

Figure 2: The total revenue, the total costs and the total profit for the Danish cod fishing industry in the Kattegat, 1995-2011.

Figure 2 shows that the downward trend in biological indicators from Figure 1 is reflected in the economic indicators and, in fact, at the end of the data period, the industry profit is negative.

Parameter estimation

By using these time series, we have estimated the natural growth function, the profit function and the expected penalty function specified in section 4 for the Danish cod fishery in the Kattegat. The results of the estimations are reported in Table 1.

Table 1: Parameter estimates for the Danish cod fishery industry in the Kattegat

The logistic growth function in (16) is estimated by using OLS on the time series for the escapement and the natural growth in Figure 1. Following Arnason (2004) and Agnarsson (1999) we estimate $R_t(S_{t-1}, e_t) = rS_{t-1} - f(S_{t-1})^2 + e_t$ and by using (16) it is obtained that $K = \frac{r}{f}$. The estimation results are reported in the first column of Table 1 and we see that both r and f are

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[36] The European Union (EU) has concluded that the cod stock in Kattegat is overexploited (see ICES, 2013). This is consistent with the observed increasing natural growth in proportion to the stock size as the latter declines (see Figure 1). Note that the growth and the total harvest are almost identical in Figure 1 for each time period which suggests that we may have underestimated the illegal harvest. Despite this fact we use the illegal harvest shares from ICES (1997) and (2008) since these are the only estimates we are aware of for the Danish cod fishery in Kattegat.

[37] See appendix B for details.

significant with the expected signs. The explained proportion of the variation in data is substantial and by looking at the Durbin Watson (DW) test we detect no autocorrelation because the actual DW test is above critical DW test level. The unexplained variation in the recruitment, R_t, is captured by a stochastic variable, e_t and as mentioned in section 4, the estimated standard derivation of e_t is a measure of the size of biological uncertainty. Many other papers have estimated logistic growth functions for cod fish stocks in other areas[38] and both the intrinsic growth rate and the biological uncertainty in Table 1 are similar to these estimates[39], so the estimated parameter values seem plausible.

Turning to the industry profit function in (18), we have calculated the price (*p*) as a weighted average of the sales prices for the whole time period where the harvest shares of cod are used as weights.[40] We estimate the cost function by using OLS on the time series for costs presented in Figure 2. The estimation results are reported in the second column of Table 1. We find that *c* is significant with the expected positive sign. The estimated marginal cost of stock size (*b*) is also significant and negative as expected, while *k* is significant and positive. The positive value of *k* indicates that the fishery is characterized by negative economies of scale, which implies that ITQs may potentially outperform taxes. Our specification explains a large part of the variation in the data and we detect no autocorrelation (the critical DW test level is below the actual DW test). Thus, overall, the estimated industry cost function seems well specified and the estimated parameter values are theoretically consistent and plausible. Because the formulation in (18) is a novel specification of a cost function, we cannot compare the parameter estimates with other estimates from the literature.

Finally, we have calibrated the penalty function ((19)) because we do not have a time series that makes it possible to estimate an expected penalty function. However, ICES (1997) and (2008) estimate that illegal landings constitute approximately 20% of the total landings for the Danish cod fishery in the Kattegat. Furthermore, it is estimated that the span of illegal harvest may vary between 10% and 30%.[41] Therefore, we set the average value of a_t so that the mean illegal

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[38] See e.g. Arnason et al (2004), Marato and Moran (2004) and Kugarajh et al (2006).

[39] The carrying capacity is a measure for the size of the fish stock and, therefore, *K* cannot be compared between fishing areas. However, even though the value of the biological uncertainty depends on the size of the fish stock, this uncertainty can be compared between fishing areas because the measurement error of the escapement is expected to decrease with the size of the escapement.

[40] See appendix B for details.

[41] Similar illegal harvest shares and spans of the shares is found for other cod fisheries and other fish species by Banks et al (2000), Triumble et al (1993), Sullivan et al (1993) and Svelle et al (1997).

harvest is 20% of the total harvest and, then, we impose a variance of a_t that generates realizations of illegal landings following a uniform distribution between 10% and 30%. This variance is our measure of the size of compliance uncertainty and the results of this calibration of a_t are reported in the third column of Table 1.

6. Simulation results

In this section, we first present the results of the simulation of the welfare gains from switching to tax regulation for the Danish cod fishery in the Kattegat. Then, we use the simulation model to calibrate and validate a simple indicator of the welfare gain from switching to taxes. Finally, we use the indicator to find the suggested welfare gains of switching to tax regulation for a number of fisheries around the world for which the necessary data is available in published studies.

For the simulations, we use the model presented in section 3 and the functional forms and parameter estimates from section 4 and 5. To conduct the simulations, we use SAS-NLP for 1000 time periods[42] and, for simplicity, we assume no discounting of future welfare and only compare steady-state equilibria under taxes and ITQs.[43]

The main results

In this section, we present the results of the simulations for tax and ITQ regulation for the Danish cod fishery in the Kattegat under pure biological uncertainty (only uncertainty about ε_t), pure compliance uncertainty (only uncertainty about a_t), and combined uncertainty (uncertainty about both ε_t and a_t). These results are summarized in Table 2.

Table 2: Effect of taxes and ITQs for the Danish cod fishery industry in the Kattegat

Consider, first, pure biological uncertainty when $G = 0$ in Table 2. Here we see that taxes are preferred over ITQs even though we have found negative economies of scale for the Danish cod fishery in the Kattegat. This implies that the marginal cost of stock size dominates the marginal cost of harvest (see section 2). Table 2 also shows that the welfare gain of switching to tax under pure biological uncertainty is 2.77 %.

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[42] The programme for conducting the simulations is available from the authors upon request

[43] We iterate the size of the initial escapement until it is equal to the mean escapement level in the following 1000 periods to ensure that the simulations is initiated in a steady-state equilibrium.

Next we consider pure compliance uncertainty and $G = 0$ in Table 2. Here the differences in the welfare gain between tax and ITQ regulation are much smaller than under pure biological uncertainty (a relative gain of 0.15%). Now consider combined uncertainty with $G = 0$. From Table 2 it is clear that the welfare gain of taxes under combined uncertainty is only slightly higher than the gain under pure biological uncertainty. Thus, biological uncertainty and compliance uncertainty interact positively to increase the welfare gain of taxes, but due to the small gain under pure compliance uncertainty, the size of this interaction is very small. Thus, for practical policy purposes, compliance uncertainty is not important for the choice between taxes and ITQs for the Danish cod fishery in the Kattegat.

Finally, we investigate the welfare gain from switching to taxes when the regulator uses more advanced regulatory practices that use information about the previous period's escapement ($G > 0$). When $G = 1$, the welfare gain of taxes under combined uncertainty decreases to 1.62% and this gain is virtually unchanged for $G > 1$ (see Table 2). From Table 2, it is clear that there is an increase in welfare under ITQs when moving to $G=1$, while the welfare is approximately unchanged under tax regulation. Thus, allowing the regulator to use information about the previous period´s escapement improves the performance of ITQ regulation, while this is not the case for taxes. It is, also, clear that more advanced feedback rules than $G = 1$ do not give additional improvements in the performance of ITQs (comparing $G > 1$ with $G=1$). Thus, the overall conclusion from Table 2 is that the welfare gain of taxes under both compliance and biological uncertainty is between 2% and 3% with uniform regulation. This gain is reduced substantially if the regulator can adjust regulation in response to information about the previous period´s escapement.

Sensitivity analysis[44]

To investigate the robustness of the main result, we have conducted several sensitivity analyses by varying all parameter values by +/- 50%.[45] Note that varying *p* and *c* gives exactly the same

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[44] In this section we present the results of varying the parameter values. However, we have also investigated the implications of using another specification of the cost function given as $C(R_t, H_{It}, H_{Lt}) = \frac{c(H_{It} + H_{Lt})^2}{R_t}$. With this functional form we find a welfare gain of taxes on approximately 5% under combined uncertainty with $G = 0$. However, when $G > 0$ there is almost no difference in the welfare between taxes and ITQs and, therefore, the result reported in Table 2 are also robust to changes in the functional form for the cost function.

[45] In fisheries economics a parameter variation on +/- 20% is common (see Anderson, 1982) but we chose a larger variation for two reasons. First, we want to investigate if a low welfare gain of taxes arises even with extreme parameter values. Second, the outcome of the model is used to generalize the results to other fisheries making a large parameter variation useful.

results[46] and, therefore, we only present the results for p in this section. The results of the sensitivity analysis for $G = 0$ are presented in Table 3.

Table 3: Sensitivity analysis, relative industry welfare gain of taxes (%) under uniform regulation (G = 0).

Consider first the results for pure biological uncertainty reported in Table 3. Here we see that, for all parameter variations, there is a positive welfare gain of switching to taxes even though we have negative economies of scale. This implies that the marginal cost of harvest is dominated by the marginal cost of stock size. However, varying the parameters values in the industry profit function (p, b and k) has almost no effect on the welfare gain of taxes, which implies that the low welfare gain from taxes reported in Table 2 is not driven by the parameters in the cost function. However, varying the parameter values in the natural growth function (r, K and biological uncertainty) influences the size of the welfare gain of taxes substantially. Reducing the intrinsic growth rate (r) by 50% causes the welfare gain from switching to taxes to increase to approximately 4%. Increasing biological uncertainty by 50% increases the gain to 6.39% and if the carrying capacity (K) is decreased by 50%, the welfare gain of taxes increases to 12.39%. Thus, we can conclude that a variation in the parameters in the growth function for the Danish cod fishery in the Kattegat may potentially imply a large welfare gain of switching to taxes.

Next we turn to the sensitivity analysis for pure compliance uncertainty in Table 3. For all parameter variations in the industry profit function (p, b and k), the natural growth function (r and K) and the expected penalty function (compliance uncertainty), the welfare gain of switching to taxes is extremely low. Only when the size of the compliance uncertainty is increased by 50% is there a noticeable increase in the relative welfare gains (to 0.3%), but the absolute welfare gain is still very small. Furthermore, the simulations for combined uncertainty do not change the conclusions reached under pure biological and compliance uncertainty. Thus, for the Danish cod fishery in the Kattegat, the pro-tax result in Hansen et al (2008) for compliance uncertainty is irrelevant for practical policy purposes.[47]

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[46] Simply because reducing the price has the same effect on marginal profit as increasing the constant in the marginal cost function.

[47] Our results for pure compliance uncertainty are based on the illegal landing shares on 20% in ICES (1997) and (2008). However, Banks et al (2000), Triumble et al (1993), Sullivan et al (1993) and Svelle et al (1997) find similar illegal landing shares for other cod fisheries and other fish species and this may indicate a low welfare gain of taxes for other fisheries. However, both the profit function and the growth function may differ between fishing areas and fish

In Table 4, we present the sensitivity analysis when assuming that *G = 1* under combined uncertainty.

Table 4: Sensitivity analysis, relative industry welfare gain of taxes (%) under linear regulation in last periods escapement (G = 1).

By comparing the results in Table 4 and Table 3, we see that the welfare gains from switching to taxes are significantly reduced for all parameter variations when the regulator uses the previous period´s escapement levels in the regulatory rule. The largest welfare gain from switching to taxes in Table 4 is 6.41%, which arises with a 50% decrease in *K*. Thus, more advanced regulatory rules reduce the welfare gain from switching to taxes significantly over the span of variations in all parameter values.

An operational indicator of the welfare gain from switching to taxes

The simulation model we have constructed requires more information than fisheries regulators typically have. However, the simulation model allows us to validate a simple indicator that can be used to approximate the welfare gain from switching to taxes, while at the same time requiring less information than what is needed for the simulation model.

From the sensitivity analysis presented in Table 3, it is clear that the parameters in the natural growth function (*r*, *K* and σ^2) are critical for the size of the welfare gain from switching to taxes. Furthermore, since welfare gain is substantially more sensitive to variation in *K* than in *r* we propose the following indicator:[48]

$$\text{Indicator} = \frac{\sigma^2}{S_{MSY}} * 100 \qquad (20)$$

where σ^2 is the size of the biological uncertainty (defined as the standard error of e_t) and $S_{MSY} = \frac{K}{2}$ is the escapement level at maximum sustainable yield. The advantage of using this indicator is that

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species so we only get a very rough indication of the possibility of generalizing the result for compliance uncertainty to other fisheries.

[48] That this indicator provides a good approximation for the welfare gain of taxes may be seen from the Pearson correlation coefficients, *d*, for the observations in Table 3. Under pure biological uncertainty we obtain a significant value of *d* on 0. 64. For combined uncertainty we reach that *d* = 0.60 and again this value is significant. Given the low variation in both the welfare gain of taxes and the size of the indicator these values of *d* is very high indicating that the indicator is a good approximation for the welfare gain of taxes.

it only requires the estimation of a natural growth function for a given fishery since values for σ^2 and S_{MSY} are found from this function. The disadvantage of using the indicator is that it does not include information about other parameters of which especially *r* may be critical since this parameter has a significant influence on the welfare gain of taxes.

To investigate the validity of using (20) to approximate the welfare gain of taxes, we use the simulation model for *G=0* to generate observations of the gains for different hypothetical indicator values consisting of +/- 50% variation in all other parameter values. By doing this, we construct a span of the welfare gains from taxes that, for each possible value of the indicator, captures a large span of potential variation in all other parameters. This span is illustrated in Figure 3, which shows the upper and lower bound of welfare gains from switching to taxes as a function of the indicator value.[49]

Figure 3: Upper and lower bounds for the welfare gain from switching to tax regulation as a function of indicator values.

Based on Figure 3, the welfare gain of taxes is easy to approximate for any fishery where a logistic growth function has been estimated. After estimating this growth function, the regulator can calculate the indicator value in (20) and, given the indicator value, the regulator can identify an upper and lower bound for the welfare gain from switching to taxes by using Figure 3.[50]

Generalization of our main result

Turning to the research question, we can now use the indicator to approximate the spans of likely welfare gains from switching to tax regulation for actual fisheries around the world. Specifically, we have identified 11 published studies (including our own) that have both estimated a natural

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[49] A more complex indicator (e.g. including *r* in the calculation) would reduce the span of possible gains around the mean values shown in Figure 3, but at the cost of reduced practical applicability.

[50] Note that Figure 3 is constructed by assuming uniform regulations that are not adjusted to information about previous period´s escapement (G= 0). If the regulator adjust the taxes and ITQs using the previous periods escapement (G > 0)) the mean welfare gains of taxes is reduced and the span of these gains around the mean is reduced compared to those indicated in Figure 3.

growth function and reported the values of σ^2 and S_{MSY}.[51] Table 5 gives an overview of the 11 studies that we have been able to include in the survey.

Table 5: Indicator values for studies estimating a natural growth function.

We see that the fisheries included in the literature survey vary substantially with respect to both the degree of biological uncertainty (σ^2) and the escapement level at maximum sustainable yield (S_{MSY}). However, despite this fact, the variation in the value of the indicator is quite small. For the redfish fishery in Australia, the anchory fishery in Korea and the blacktip sawtail fishery, the value of the indicator is low, while the highest value of the indicator is obtained for the North East Arctic cod fishery.

In Figure 3, we have inserted the values of the indicator reported in Table 5. The numbers in Figure 3 (1-10) refer to the study number in Table 5 and the vertical line indicates the span of the welfare gains predicted for this fishery by using the indicator. Figure 3 shows that the welfare gain from switching to taxes is positive for all the fisheries included in our literature survey. For some fisheries, the predicted gain is below 1%, while the gain is between 1.5% and 2.5% for most fisheries. The largest predicted welfare gain from taxes is obtained for the North-East arctic cod fishery with an upper bound on the welfare gain of 4.2%. The gains in Figure 3 are relatively small compared to the gains from other much less dramatic regulatory reforms. For example, Waldo et al (2016) study the welfare gain from different regulatory changes in five Nordic countries and find that switching from biological objectives (maximum sustainable yield) to economic objectives (maximum economic yield) for determining a total quota for cod yields a welfare gain of 31% in the Icelandic fishery. This study also finds that switching from INTQs to ITQs in the Swedish fishery would generate a welfare gain of 15%.

Based on the literature survey, the conclusion is, therefore, that the welfare gains from switching to taxes in fisheries are generally small (an average gain of around of 2%) when the regulator is confronted with biological uncertainty. However, the span of gains generated by the literature survey may not cover all fisheries and we cannot rule out that a significant welfare gain from switching to taxes may arise in some fisheries. Specifically, for a small fishery (a low S_{MSY})

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[51] We have found many empirical papers that estimate a logistic growth function but do not report σ^2. However, σ^2 is normally generated as a byproduct when estimating a natural growth function so it is likely that the indicator can be identified for most fisheries around the world.

with substantial measurement problems associated with the escapement (a large σ^2), the welfare gain may be substantial. By calculating the indicator in (20) and using Figure 3, a regulator can obtain a rough estimate of the potential gain from switching to tax regulation for the particular fishery he is managing. This rough estimate could, then, serve as a basis for deciding whether further investigation of such a regulatory change should be undertaken.

7. Conclusion

Theoretical contributions within fisheries economics have shown that taxes may be preferred over ITQs under various forms of uncertainty. However, no attempts have been made to empirically quantify the size of the potential welfare gain of switching to taxes. In this paper, we have estimated profit, penalty and growth functions as well as the size of both biological uncertainty and compliance uncertainty for the Danish cod fishery in the Kattegat. Based on these estimations, we simulate the welfare gain of switching to tax regulation and find that the gain under compliance uncertainty is negligible, while the gain under biological uncertainty is small (typically less than 2%) for the Danish cod fishery in the Kattegat.

We also develop a simple indicator that can be used to approximate the welfare gain of taxes for fisheries when limited information makes it impossible to use a simulation model like the one presented here. The indicator only requires information about the natural growth function and we have calculated indicator values for a number of fisheries worldwide. We find that the welfare gain from a switch to taxes for these fisheries typically lies between 1.5% and 2.5% (in no case greater than 4.2%). Therefore, we can conclude that the recommended switch to tax regulation in the prior theoretical literature is of little practical relevance. Generally, regulators should investigate the potential gains from implementing other less dramatic and more beneficial management reforms before considering a switch to tax regulation.

We have also provided two methodological contributions to the fisheries economic literature that may be of interest to other researchers. First, we derive and estimate a relatively simple, but theoretically consistent, industry profit function which allows for both positive and negative economies of scale. This specification may be relevant for other fisheries where the degree of economies of scale is important. Second, we use feed-back rules instead of the usual value function approach to simulate the welfare under both taxes and ITQs. The feedback rule makes it possible to evaluate the welfare of sophisticated regulatory strategies where taxes and ITQs are adjusted to information about the escapement levels in previous periods.

In this paper, we only investigate biological uncertainty and compliance uncertainty but, according to Jensen (2008), there may also be substantial uncertainty about costs and revenues in a given fishery. From the analysis in this paper, we cannot rule out that the welfare gains from switching to tax regulation are high under economic uncertainty. Investigating the empirical implications of economic uncertainty is an obvious area for future research.

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Figure 1: Escapement, total harvest and natural growth for cod in the Kattegat, 1971-2011.

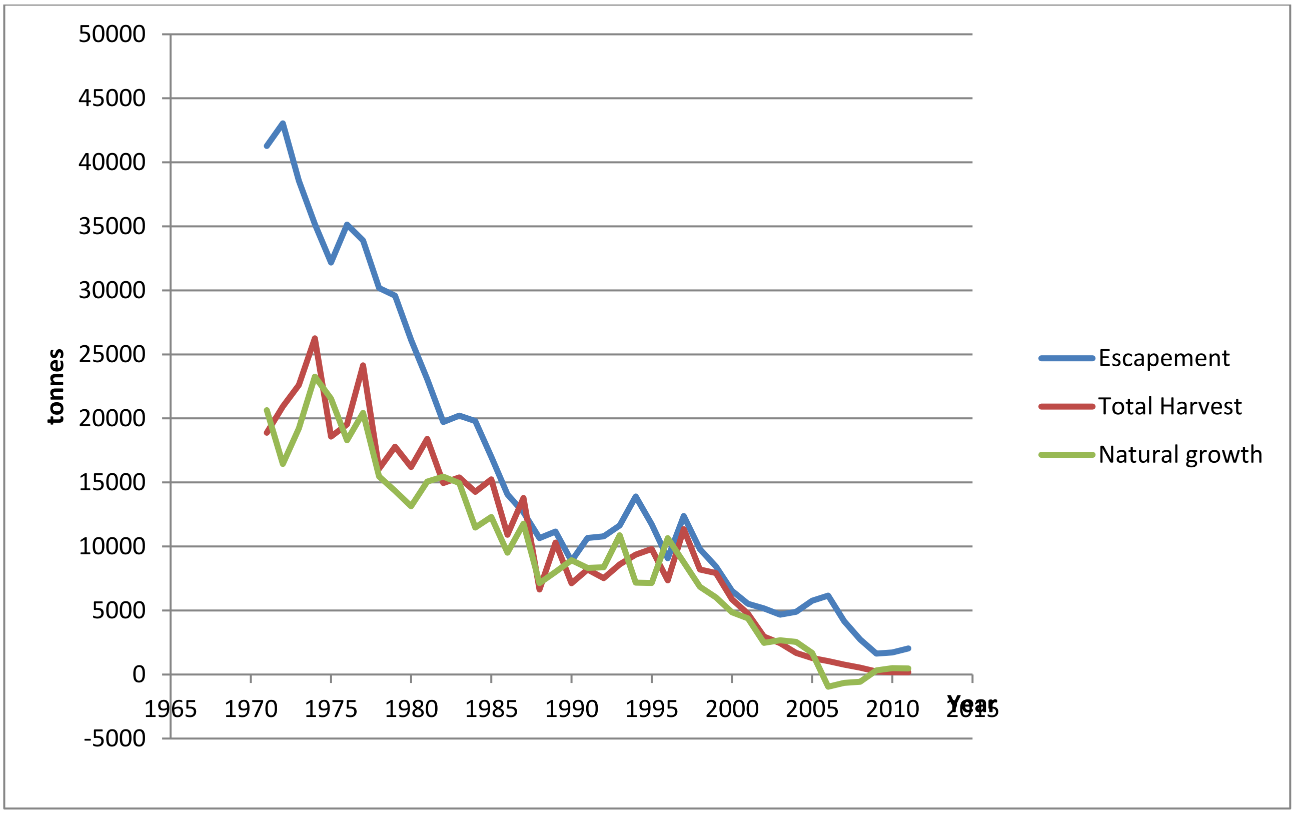


Figure 2: The total revenue, the total costs and the total profit for the Danish cod fishing industry in the Kattegat, 1995-2011.

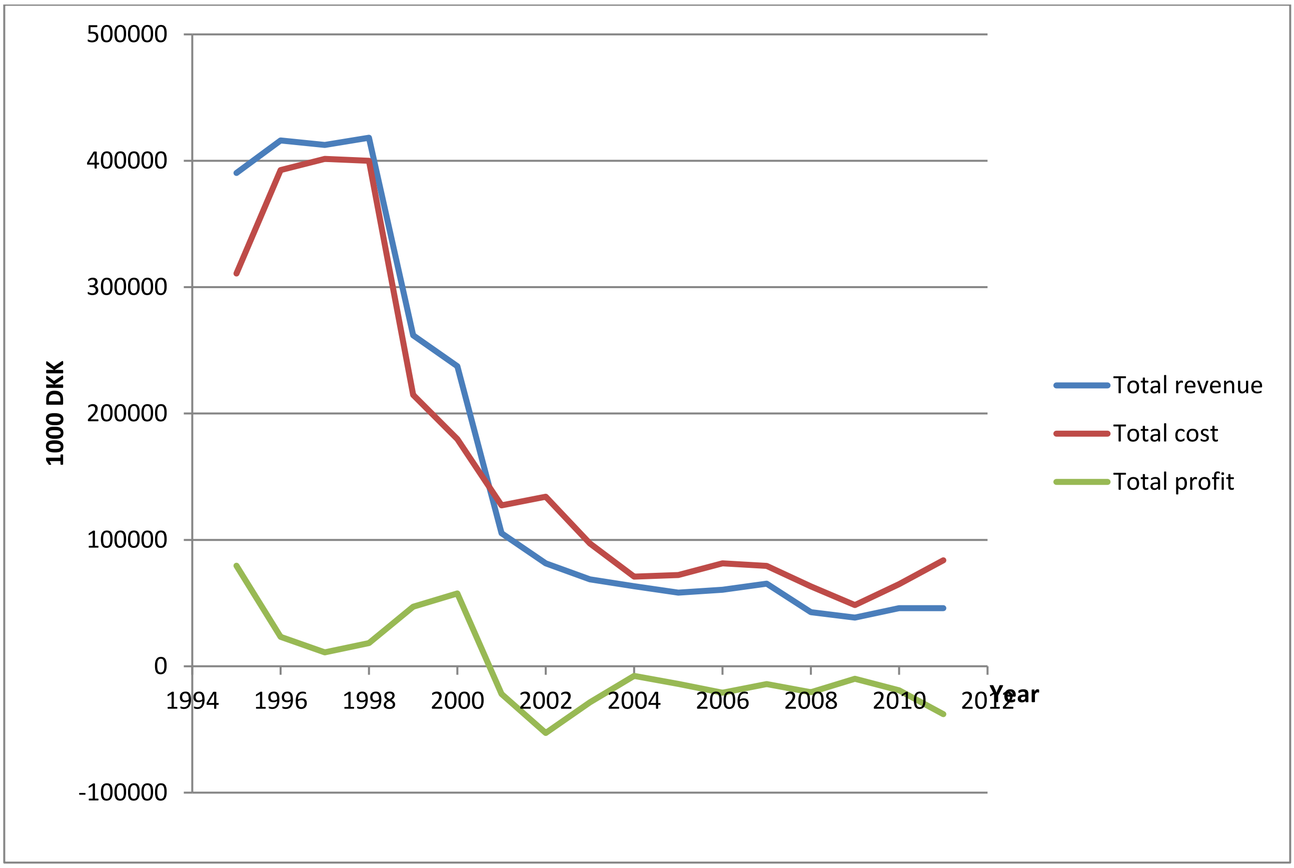
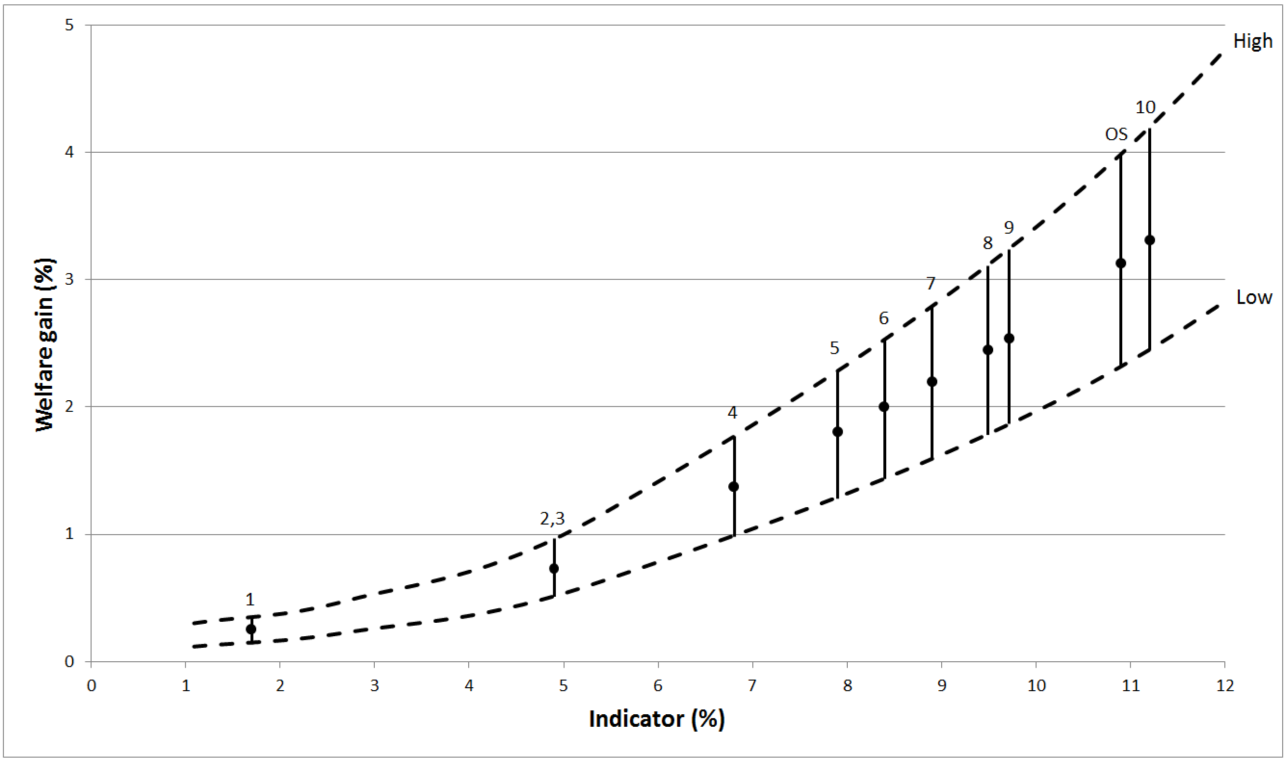


Figure 3: Upper and lower bounds for the welfare gain from switching to tax regulation as a function of indicator values.



Note: The regulator uses uniform regulation (G=0). The numbers above the vertical line in the figure refer to the study number in Table 5. OS refers to the study in our paper and is found by using σ^2 and S_{MSY} as presented in Table 1.

Table 1: Parameter estimates for the Danish cod fishery industry in the Kattegat

Natural growth function (Equation (16))		**Industry profit function** (Equation (18))		**Penalty function** (Equation (21))	
Parameter	Estimate (standard error)	Parameter	Estimate (standard error)	Parameter	Calibrated
r	0.86* (0.0596)	p (1000 DKK/tons)	10.74 (calculated)	Mean a_t (calibrated to generate 20% mean illegal catch in tons)	$1.78*10^{-6}$
f	0.0000074* (0.00000161)	c (1000 DKK)	31.52* (9.912)	Span of a_t (calibrated to generate 10%-30% span in generated illegal catch in tons)	$18.92*10^{-7}$ – $2.68*10^{-6}$
$K=r/f$ (tons)	116.263 (calculated)	b (1000 DKK/tons)	-0.084* (-0.0302)		
Standard error of e_t (Biological uncertainty in tons)	6.325	k (1000 DKK/tons)	0.015* (0.00493)		
R^2=0.96 DW=1.88 (critical value 1.128)		R^2=0.94 DW=1.29 (critical value 0.864)			

Note: * indicate significance at a 5%-level.

Table 2: Effect of taxes and ITQs for the Danish cod fishery industry in the Kattegat

	ITQs, annual means			**Taxes, annual means**			**Welfare gain of taxes (%)**
	Optimal aggregated welfare (million DKK/ year)	**Optimal aggregated total harvest (1000 tonnes)**	**Optimal escapement (1000 tonnes)**	**Optimal aggregated welfare (million DKK/ year)**	**Optimal aggregated total catch (1000 tonnes)**	**Optimal escapement (1000 tonnes)**	
Pure biological uncertainty							
G = 0 (uniform regulation)	164,86	23.23	75.12	169,43	23.76	74.66	2.77
Pure compliance uncertainty							
G = 0 (uniform regulation)	167.87	23.70	74.58	168.13	23.76	74.66	0.15
Combined uncertainty							
G=0 (uniform regulation)	164.80	23.25	75.12	169.43	23.76	74.66	2.83
G=1 (linear regulation in last period's escapement	166.73	23.49	74.33	169.43	23.76	74.66	1.62
G=2 (quadratic regulation in last period's escapement)	166.73	23.53	74.36	169.43	23.76	74.66	1.62
G=3 (third degree regulation in last period's escapement)	166.75	23.53	74.35	169.43	23.76	74.66	1.61

Table 3: Sensitivity analysis, relative industry welfare gain of taxes (%) under uniform regulation (G = 0).

	Pure biological uncertainty			**Pure compliance uncertainty**			**Combined uncertainty**		
	Parameter value +50%	Benchmark (Table 1)	Parameter value -50%	Parameter value +50%	Benchmark (Table 1)	Parameter value -50%	Parameter value +50%	Benchmark (Table 1)	Parameter value -50%
Industry profit function									
p (price)	2.77	2.77	2.77	0.15	0.15	0.15	2.82	2.83	2.83
b (marginal stock cost)	2.55	2.77	2.89	0.29	0.15	0.05	2.74	2.83	2.88
k (economies of scale)	2.66	2.77	2.88	0.14	0.15	0.15	2.72	2.83	2.94
Natural growth function									
r (intrinsic growth rate)	2.23	2.77	4.08	0.10	0.15	0.28	2.31	2.83	3.98
K (carrying capacity)	2.14	2.77	12.39	0.95	0.15	0.14	2.23	2.83	12.35
σ^2 (standard error of e_t)	6.39	2.77	0.67				6.39	2.83	0.78
Penalty function									
Span of a_t				0.08	0.15	0.43	2.94	2.83	2.58

Table 4: Sensitivity analysis, relative industry welfare gain of taxes (%) under linear regulation in last period's escapement (G = 1).

	Parameter value +50%	Benchmark (Table 1)	Parameter value -50%
Industry profit function			
p (price)	1.62	1.62	1.62
b (marginal stock cost)	1.65	1.62	1.57
k (economies of scale)	1.67	1.62	1.65
Natural growth function			
r (intrinsic growth rate)	1.57	1.62	1.65
K (carrying capacity)	0.77	1.62	6.41
σ^2 (standard error of e_t)	2.03	1.62	1.11
Penalty function			
Span of a_t	1.57	1.62	1.65

Table 5: Indicator values for studies estimating a natural growth function.

Study number	Authors	Fishery	σ^2 ((standard error of e_t in 1000 tons)	$S_{MSY} = \frac{K}{2}$ (escapement at maximum sustainable yield in 1000 tons)	The value of the indicator
1.	Liu et al (2011)	Blacktip Sawtail Catsshark in Taiwan	0.012	0.7	1.7
2.	Chen et al (1997)	Redfish in Australia	2,057	41,917	4.9
3.	Dong and Lee (2003)	Anchory fishery in Korea	1,073	21,713	4.9
4.	Velazques et al (2013)	Jumbo squid fishery in the Central Gulf of California	1,098	16,131	6,8
5.	Agnarsson (1999)	Norwegian spring-spawning herring	3620	46,000	7.9
6.	White et al (2011)	Boarfish in Northeast Atlantic	513	6,143	8.4
7.	Rogers-Benneth et al (2003)	Red sea urchins in Northern Califronia	375	4,192	8.9
8.	Kateregga and Sterner (2008)	Lake Victoria fish stocks	191	2,013	9.5
9.	Khan (2007)	Bangladesh shrimp fishery	8,829	90,913	9.7
10.	Ussif et al (2003)	North-East arctic cod stock	5,900	52,690	11.2
OS (own study)	Jensen and Hansen (2017)	Danish cod fishery in the Kattegat	6,325	58,132	10.9