DEPARTMENT OF FOOD AND RESOURCE ECONOMICS
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IFRO Working Paper

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2018 / 05

IFRO Working Paper 2018 / 05

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JEL-classification: Q22, D80, H20, H23

Published: May 2018

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A First-Best Optimal Solution to Multiple Objectives with Fisheries Regulation

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Key words: Stock externalities, double-dividend, uncertainty, taxes, quotas,

JEL codes: Q22, D80, H20, H23

Abstract: Part of the existing economic literature on fisheries regulation focuses on addressing several objectives with one instrument. In an extension of this literature we investigate the following three objectives of fisheries regulation: A) Correcting a stock externality; B) Raising public funds, and; C) Solving problems with uncertainty. We analyze the implications of combining a non-linear tax on harvest and individual transferable quotas to address these three objectives and argue that a tax alone can fulfill all three objectives simultaneously. This result can be related to the theory on a first-best and a second-best optimum which state that the number of objectives must be identical to the number of instruments if a first-best optimum shall be reached. We show that one instrument (a tax based on the size of the harvest in this case) is enough to achieve a first-best optimum.

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1.Introduction

Actual fisheries management around the world involves the use of multiple regulatory instruments. For example, in the European Union, fisheries are regulated with total allowable catches (a total quota), licenses, effort regulation, minimum mesh sizes, discard bans, decommission schemes and minimum prices (Holden and Garrod, 1996). At the Member State level, Denmark, for example, has introduced individual transferable quotas (ITQs), effort regulation, minimum landing sizes, discard bans and marine protected areas (Andersen et al., 2010). The use of multiple instruments in actual fisheries regulation means there is a need for an economic discussion of this policy practice.

From an economic perspective, multiple market failures constitute one justification for using multiple regulatory instruments.[2] Within fisheries, several market failures arise simultaneously including stock externalities[3], CO_2 emissions[4], congestion[5], by-catches[6], high-grading[7], substitution between quota and non-quota species[8] and other values from fish stocks than fisherman-related resource rents.[9] Another efficiency-related argument for regulation is that taxes imposed to solve externalities may generate double-dividends (Brendemoen and Vennemo, 1996).[10] Proponents of the double-dividend hypothesis assert that the tax revenue collected when correcting market failures can be used to reduce the size of other distortionary taxes.[11] An implication of a double-dividend is that the tax revenue collected by correcting a stock externality in fisheries should be given a positive weight in a welfare function (the objective function of a regulator).

[2] Non-economic justifications for using multiple instruments can also be provided and actual fisheries regulation is often determined with reference to non-economic objectives. In principle, non-economic objectives should be taken into account when discussing the use of multiple instruments. However, this paper is written within a welfare-economic tradition and, therefore, we will only discuss efficiency-related arguments for regulation.
[3] See Smith (1968) and (1969).
[4] See Waldo et al. (2016).
[5] See Brown (1974).
[6] See Boyce (1996).
[7] See Anderson (1994) and Arnason (1994).
[8] See Asche et al. (2007).
[9] See Stage (2015).
[10] Another example is minimizing the efficiency loss arising from governmental failures.
[11] A similar argument can be found in the literature on recovery of regulatory costs in fisheries (see e.g. Kaufmann and Green, 1997). Here it is argued that the fishermen shall cover the costs of regulation implying that regulatory costs enters with a negative sign in a regulator´s objective function. One example of regulatory costs which have been analyzed is compliance and enforcement costs (see e.g. Sutinen and Andersen, 1985).

For the analysis below we will use three related concepts repeatedly and it is, therefore, important to define these concepts.[12] First, objectives cover the overall goals with undertaking public policies. Typical examples of objectives in fisheries regulation include maximum sustainable yield, maximizing the resource rent and correcting market failures (see e.g. Anderson, 1977). Second, instruments are the regulatory measure that is used to reach the objectives. In a fisheries context, examples of instruments are taxes, total quotas and subsidies (see e.g. Anderson, 1977). Last, regulatory variables are the units according to which the objectives and/or instruments are defined and harvest, stock size and input use are good examples for fisheries (see e.g. Anderson, 1977).

From general economic theory the concepts of a first-best and second-best optimum can be used to discuss multiple objectives and instruments.[13] According to Lipsey and Lancaster (1956) a first-best optimum represents a situation where all conditions for a social optimum is satisfied.[14] In a second-best optimum one or several restrictions exist, implying that one or several optimality conditions cannot be fulfilled. Thus, an efficiency loss arises but given the restrictions this loss is minimized. Boadway and Bruce (1984) apply the theory on a first-best and a second-best optimum to a discussion of the relation between the number of instruments and objectives. Specifically, Boadway and Bruce (1984) argue that a first-best optimum can be reached if the number of objectives and instruments are identical while we only can reach a second-best optimum if the number of objectives is larger than the number of instruments. The explanation for this result is easiest to understand if we impose two simplifying assumptions: A) The objectives are totally independent in the sense that fulfilling one objective has no effect on fulfilling the other objectives, and, B) The possible instruments adopted can only affect one objective. Under these assumptions it is easy to see that in order to obtain a first-best optimum we need one instrument for each objective and by using fewer instruments we can only reach a second-best optimum.[15] Below we will refer to this result as the first-best and second-best rule in Boadway and Bruce (1984).

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[12] See Boadway and Wildasin (1984) for a carefully discussion of these three conecpts.
[13] Tinbergen´s rule can also be used to justify the relation between the number of objectives and instruments (see Tinbergen, 1952).
[14] The conditions for an optimal solution is efficiency in exchange, efficiency in production and total efficiency (see e.g. Boadway and Bruce (1984).
[15] This result generalizes to the situation where the instruments affect the objectives in fixed proportions (see Boadway and Bruce, 1984).

This paper applies the theory on a first-best and a second-best optimum to fisheries regulation and discusses whether the number of objectives must be identical to the number of instruments in order to achieve a first-best optimum. In a fisheries model, we analyze the following three objectives: A) Correcting a stock externality; B) Raising public funds, and; C) Solving problems with uncertainty. The discussion of these three objectives is based on a dynamic model of fisheries regulation where adjustment towards a steady-state equilibrium and discounting is incorporated. We introduce two instruments: A) A non-linear tax on harvest, and, B) An ITQ system. These instruments are analyzed under both full certainty and cost uncertainty. We show that that the non-linear tax may generate a first-best optimum while this is not true for the quota.[16] Thus, contrary to the first-best and second-best rule in Boadway and Bruce (1984) several objectives (correcting stock externalities, raising public funds and solving cost uncertainty) can be reached in a first-best optimal way with one instrument. The explanation for this result is that all objectives can be related to the same regulatory variable (harvest) so one instrument (a non-linear marginal tax on harvest) can be adjusted to reflect all three objectives. Thus, we reach a modified version of the first-best and second-best rule in Boadway and Bruce (1984) stating that the number of objectives must be identical to the number of instruments defined by using independent variables.

This paper contributes to three strands of economic literature. The first strand is the existing fisheries economic literature preforming analysis of regulation of multiple externalities. Apart from a stock externality, congestion[17], high-grading[18], by-catches[19] and substitution between quota and non-quota species[20] is discussed. The literature investigates how an ITQ system shall be adjusted in a second-best optimal way to incorporate the effect of additional externalities. In our paper we reach a similar result since we show that an ITQ system cannot reach a first-best optimum. However, we also argue that a first-best optimum can potentially be reached with a non-linear tax and this represent a novel contribution to the existing fisheries economic literature on regulation of multiple externalities.

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[16] We assume that the quota is grandfathered away. Under auctions a tax and a quota gives identical results.
[17] See e.g. Smith (1969) and (1969), Clark (1980), Boyce (1992) and (1996), Danielson (2000) and Huang and Smith (2014).
[18] See e.g. Arnason (1994), Anderson (1994) and Turner (1997).
[19] See e.g. Boyce (1996), Segerson (2007) and Abbott and Wilen (2009).
[20] See e.g. Hutniczak (2014), Asche et al. (2007), Ekerhovd (2007), Jensen (2000), Pascoe et al. (2007), Branch and Hilborn (2008) and Pascoe et al (2010).

The second strand can be labelled the fisheries economics literature on price versus quantity regulation. This literature has its roots in the seminal papers on flow pollution by Weitzman (1974), Adar and Griffin (1976) and Yohe (1978). By extending the work by these authors the fisheries economic literature study the second-best issue of choosing between a uniform tax and a quota to solve a stock externality problem under various forms of uncertainty.[21] The main result in this literature is that it depends on the characteristics of a given, actual fishery whether a uniform tax or a quota generates the highest efficiency. Our contribution to this literature is to show that a non-linear marginal tax can correct an externality problem under uncertainty in a first-best optimal way.

The third strand can be labelled the environmental economics literature on price and quantity regulation under uncertainty. Some papers in this literature investigate various regulatory systems without introducing self-reporting,[22] while others seek to design regulatory systems that induce truthful self-reporting of private information.[23] It is argued that it requires two regulatory instruments[24] to reach a first-best optimal solution for regulation of externalities under uncertainty. In this paper, we argue that a single instrument (a non-linear tax) is enough to correct an externality under uncertainty, which represents a contribution to the literature on price and quantity regulation.

The last strand is the principal-agent literature on the regulation of externalities (Jebjerg and Lando, 1997; Laffont and Tirole, 1993; Jensen and Vestergaard, 2001). This literature focuses on both correcting externalities and collecting information from private agents. It is common to include a double-dividend arising from environmental taxation in the regulator´s objective function and non-linear taxation is often recommended as policy instrument. The main result in the principal-agent literature is that a tax on pollution can be adjusted in a second-best optimal way to secure correct revelation of private information. In this paper, we also include a double-dividend and study non-linear taxation, but instead of designing regulation to collect private information, we focus on reaching a first-best optimum under the assumption that truthful revelation of information occurs.

[21] See Koenig (1984a) and (1984b), Hansen (2008), Weitzman (2002), Hannesson and Kennedy (2005), Hansen et al. (2008) and (2013).
[22] See Roberts and Spence (1976) and Weitzman (1978).
[23] See Kwerel (1977) and Dasgupta et al. (1980).
[24] We interpret self-reporting as a regulatory instrument.

The paper is organized in four main sections. Section 2 presents a model of fisheries regulation under full certainty, while cost uncertainty is considered in section 3. A discussion of the assumptions and main results in the paper can be found in section 4, while section 5 concludes the paper.

2.A dynamic model with full certainty

In this section, we present a dynamic model of fisheries regulation with full certainty about all relevant parameters, variables and functions. In the model, we consider a fishing industry which consists of a fixed number of fishermen. Following Clark (1980), we capture the behavior of the fishing industry with a representative fisherman.[25] Furthermore, a regulator wishes to correct a stock externality and takes adjustments towards a steady-state equilibrium and discounting into account. The regulator also wants to use regulation to raise public funds and this may be justified with a double-dividend that may arise when regulating fisheries (see e.g. Bovenberg, 1994). The double-dividend hypothesis state that the public funds raised by regulating externalities can be used to reduce other distortionary taxes. Thus, regulation has two objectives: A) To increase the efficiency in the regulated sector by correcting market failures, B) To decrease the inefficiency loss in other sectors by reducing taxes. It is well known that, under full certainty and without a double-dividend, a uniform tax and a quota are equivalent when correcting the stock externality that may arise in fisheries, which implies that only one instrument is needed. With a double-dividend the tax and quota are still equivalent if the quotas are auctioned away. However, when the quotas are grandfathered away, a tax is preferred over a quota if a double-dividend is taken into account. In this paper, we assume grandfathering as the allocation rule for a total quota.

Under full certainty, we assume that the regulator calculates a non-linear marginal tax rule defined by using harvest as regulatory variable (labelled a marginal tax) and a corresponding non-linear quota rule (a quota) and that these two instruments are designed so that the desired outcome is reached. The regulator announces the marginal tax and/or the quota prior to a fishing period, which the representative fisherman reacts to during the period. Regarding quantity regulation, we can

[25] To justify this model set-up we can imagine either a fishing industry that consists of a number of given homogeneous fishermen or an average fisherman where the other fishermen are equally distributed around the average fisherman.

imagine that the regulator imposes a total quota on the representative fisherman. This structure is identical to the situation in which the regulator distributes a total quota to a given number of fishermen as ITQs (Clark, 1980). Now trade with ITQs will ensure that the quota price becomes equal to the value of the optimal marginal tax so setting a total quota is identical to imposing a tax on a representative fisherman.

2.1.The fisherman's problem

We assume that the representative fisherman maximizes the total industry profit for each time period separately[26] (the fisherman is myopic) with the harvest as the control variable. A single-species assumption is adopted[27] and illegal behavior, such as tax avoidance and/or non-compliance with quotas,[28] is disregarded. Furthermore, the fisherman disregards the resource restriction and this generates a stock externality. Finally, the fisherman potentially faces a marginal tax and a quota and must take the value of these instruments into account when making decisions on harvest levels.

Thus, the fisherman's maximization problem is:[29]

$$\max_{h_t}[(p-\tau_t-s_t)h_t-c(h_t,x_t)] \tag{1}$$

s.t.

$$h_t \le Q_t \tag{2}$$

In (1) and (2), a time index (*t*) is included in all relevant variables and parameters, which implies that we interpret all equations for a given time period below. In (1) and (2) p is the output price,[30] h_t is the total harvest, x_t is the stock size, τ_t is the tax rate, Q_t is the quota, s_t is a constant, marginal opportunity cost of holding quotas and $c(h_t,x_t)$ is the cost function.[31] We assume that $c_{h_t}>0$ and

[26] This assumption is common in fisheries economics (e.g. Clark, 1990).
[27] Multi-species models are considered by Anderson (1975).
[28] See Becker (1968) for a discussion of non-compliance with quantity regulations and Allingham and Sandmo (1972) for a discussion of tax avoidance.
[29] See e.g. Clark (1990) for justified for this maximization problem.
[30] We assume that the price does not change over time, which implies that the time index is excluded as a subscript on the price. However, it is straightforward to generalize the result of the analysis to the case where the price changes over time.
[31] We assume that the cost function is unchanged over time and, therefore, we exclude a time index on the cost function. However, the results in the paper easily generalize to the case where the cost function changes over time.

$c_{h_t h_t} = k > 0$, where the subscripts denote partial derivatives and *k* is a constant. Thus, the cost function is assumed to be quadratic in harvest[32] which implies that the marginal cost of harvest is positive and increasing. Furthermore, we assume that a larger fish stock implies lower costs ($c_{x_t} < 0$), which means that we analyze a search fishery (see Neher, 1990).

Two points worth discussing in relation to (1) and (2). First, the term $s_t h_t$ in (1) represents the opportunity cost of harvest in an ITQ system.[33] This captures that, when harvesting one unit of a fish, one quota unit is used. This quota unit could, alternatively, have been sold on the ITQ market, which would generate revenue on s_t leading to the conclusion that $s_t h_t$ is the opportunity cost of harvest. However, we assume that s_t is exogenous for the fisherman which corresponds to an assumption about perfect competition on the ITQ market.[34] Second, based on the value of τ_t found below, it is easy to show that the marginal tax depends on the harvest level. Despite this fact, we assume that the fisherman takes the marginal tax as given when maximizing profits. A similar assumption is adopted in standard economic theory on perfect competition on an output market (e.g.Varian, 1992). Here an individual producer takes the output price as given while, at the same time, the market supply curve has a positive slope.

Since the problem in (1) and (2) is an optimization problem subject to an inequality constraint, we can find a solution to the problem with a set of Kuhn-Tucker conditions. To reach these conditions, we set-up a Lagrange-function:

$$L = (p - \tau_t - s_t)h_t - c(h_t, x_t) + \beta_t(Q_t - h_t), \tag{3}$$

where β_t is a Lagrange-multiplier or shadow price representing the net profit gain of obtaining one quota unit more. Thus, β_t is the marginal cost of the quota restriction.

[32] A quadratic cost function is consistent with the literature on price versus quantity regulation. Here the cost function is assumed to be either locally quadratic (e.g. Weitzman, 1974) or globally quadratic (e.g. Adar and Griffin, 1976).
[33] See e.g. Clark (1990) for a justification for including the opportunity cost of holding quotas in the fisherman´s objective function.
[34] It can be argued that $s_t h_t$ should be excluded in the objective function because the opportunity cost is a constant in the fisherman´s optimality condition. However, we chose to include the opportunity cost of harvest to be consistent with traditional fisheries economic literature represented by Arnason (2009) and Clark (1990).

With h_t as the fisherman's control variable, we obtain the following Kuhn-Tucker conditions:[35]

$$\pi_h = p - \tau_t - s_t - c_{h_t} - \beta_t = 0,\ \beta_t \geq 0,\ Q_t \geq h_t \text{ and } \beta_t(Q_t - h_t) = 0. \qquad (4)$$

According to the first component of (4) optimality requires that the marginal revenue, p, is equal to the net private marginal costs. The net private marginal costs are defined as the sum of the marginal costs of harvest, c_{h_t}, the marginal costs of the quota restriction, β_t, the marginal tax costs, τ_t and the marginal opportunity cost of holding ITQs, s_t. The second component of (4) demands that the marginal cost of the quota restriction is non-negative ($\beta_t \geq 0$), while the third component states that the actual harvest must be less than or equal to the quota ($Q_t \geq h_t$). Finally, the last component of (4) states that the excess quota multiplied by the marginal cost of the quota restriction must be zero. Thus, from the last three conditions in (4), we can identify three possible cases: A) The quota is binding, while the marginal cost of the quota restriction is positive; B) The quota is non-binding, while the marginal cost of the quota restriction is zero, and; C) The quota is binding and the marginal cost of the quota restriction is zero.

In the rest of this paper, we follow traditional fisheries economics and assume that the sum of all net private marginal costs is low enough to make the quota restriction binding ($Q_t = h_t$).[36] This assumption implies that (4) can be written as:

$$\pi_h = p - \tau_t - s_t - \beta_t - c_{h_t} = 0,\ \beta_t \geq 0,\ Q_t = h_t. \qquad (5)$$

The conditions in (5) characterize a private optimum for the harvest as selected by the representative fisherman.

[35] Note that normally a non-negativity restriction on the control variable is a part of the Kuhn-Tucker conditions, which implies that the first-order condition in (4) holds as an inequality (e.g. Sysæter et al., 2008). However, for our purpose, zero harvest is uninteresting so we assume that the first-order condition in (4) holds with an equality. In other words, we assume an interior solution for the harvest.

[36] Since we discuss whether two instruments should be used simultaneously, the situation in which the quota is non-binding is uninteresting. Here only one instrument in form of the marginal tax can be used and to reach the optimal marginal tax, the cost of the stock externality and the tax revenue must be reflected in the tax.

2.2. The regulator's problem

Our solution of the regulator's problem differs from existing fisheries economic literature in three important ways. First, to find the optimal values for the instruments, it is common to derive a first-order condition for the social optimal harvest and equate this with the fisherman's optimality condition (e.g. Clark, 1980). However, in this paper, we follow Xepapadeas (1997) and impose the fisherman´s optimality condition as a restriction on the regulator´s maximization problem. Second, in the literature on price versus quantity regulation, it is common to use the harvest as the control variable so the optimal values of the instruments are found indirectly from the optimality conditions for the harvest (see e.g.Koenig, 1984a; Jensen and Vestergaard, 2003; Hansen, 2008). However, in actual fisheries policy, the regulator selects the values of the instruments directly and only indirectly controls the harvest.[37] Therefore, we follow Xepapadeas (1997) and use the tax and the quota (the regulatory instruments) as control variables. Third, we include a double-dividend arising from taxation of harvest when correcting a stock externality.[38] Specifically, we let $0 < \varepsilon < 1$[39] denote a constant marginal cost of public funds and, therefore, the term $(1-\varepsilon)\tau_t Q_t$ represents the social value of the tax revenue. This value is included in the regulator's objective function.

As in traditional fisheries economics we construct a dynamic model for the regulator[40]and this has three implications. First, we follow the tradition which has its roots in Clark and Munro (1975) and assume that the regulator maximizes the present value of current and future welfare, implying that discounting is included. Second, we introduce adjustments towards a steady-state equilibrium, implying that a dynamic resource restriction is incorporated (e.g. Conrad and Clark, 1987). Lastly, we assume continuous time and an infinite horizon so that the problem can be solved with standard dynamic optimization techniques represented by optimal control theory (e.g. Barro and Sala-i-Martin, 1995).

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[37] An example of actual fisheries can justify this model set-up. In Denmark, a total allowable catch determined by the EU is allocated to fishermen as ITQs and this represents the choice of regulatory instrument. Now fishermen can trade with quotas and quota trading is identical to selection of harvest.

[38] In the literature on fisheries regulation, the tax revenue is normally considered as a pure transfer. However, in modern incentive theory, it is common to include a double-dividend arising from taxation to correct externalities (Bovenberg, 1999).

[39] Note that ε is assumed to be identical for all time periods but the results in the paper generalize straightforward to time dependent ε .

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

By using Q_t and τ_t as the control variables (and x_t as the state variable), we can set-up the following maximization problem:[41]

$$\max_{\tau_t, Q_t} \int_{t=0}^{\infty} (pQ_t - c(Q_t, x_t) + (1-\varepsilon)\tau_t Q_t)e^{-rt}\,\mathrm{dt} \tag{6}$$

s.t.

$$\dot{x}_t = G(x_t) - Q_t \tag{7}$$

$$\pi_h = p - \tau_t - s_t - \beta_t - c_{h_t} = 0,\ \beta_t \geq 0,\ Q_t = h_t \tag{8}$$

In the objective function ((6)), we have not included the opportunity cost of ITQs represented by $s_t h_t$ which is consistent with traditional fisheries economics (Arnason, 2009). To explain this tradition, let the regulator's welfare function be defined for a given number of fishermen. Now the opportunity cost of holding ITQs for some fishermen is equal to the "opportunity revenue" obtained from selling ITQs for other fishermen. This implies that $s_t h_t$ represents a pure transfer between the fishermen, which must be excluded in a welfare function (e.g. Freeman, 1979).

In (7), $G(x_t)$ is a natural growth function and we assume that $G'(x_t) > 0$ for $x_t < x_{msy}$ and $G'(x_t) < 0$ for $x_t > x_{msy}$, where x_{msy} is the stock size associated with the maximum sustainable yield.[42] Furthermore, we assume that $G''(x_t) < 0$.[43] With this definition of $G(x_t)$, the restriction in (7) captures that the change in the stock size between time periods must equal the natural growth minus the harvest. This restriction was labeled a dynamic resource restriction above.

Condition (8) is the Kuhn-Tucker conditions from the fisherman´s problem when the quota restriction is binding. As can be seen from the objective function in (6), the regulator is interested in setting τ_t as high as possible given that the quota is binding. Therefore, τ_t is set such that $\beta_t = 0$

[41] When maximizing (6) subject to (7) and (8), the two restrictions are assumed to hold for every time period separately.
[42] Note that we use subscript to denote partial derivatives when a function depends on several variables, while primes are used when a function only depends on one variable.
[43] The restrictions on the derivatives of the growth function are fulfilled by a standard logistic specification.

so a corner solution for β_t is reached in our model.[44] From this observation it follows that the marginal tax must be set so that all quota rents are exhausted. This result is reached because a double-dividend is included in the regulator´s welfare function. Thus, the restriction in (8) reduces to:

$$p - \tau_t - s_t - c_{Q_t} = 0. \tag{9}$$

Note two facts in relation to (9). First, (9) is derived from the fisherman´s Kuhn-Ticker conditions so the restriction captures the fact that when selecting Q_t and τ_t the regulator must accept the fisherman´s choice of the harvest. Second, from (9) (or (5)) a relationship between Q_t and τ_t exists. Specifically, we can totally differentiate (9) with respect to Q_t and τ_t to obtain $\frac{d\tau_t}{dQ_t} = -c_{Q_tQ_t} = -k$. Thus, given (9) we have an implicit, negative and linear relationship between the marginal tax and the quota. Therefore, for each value of the marginal tax there exists a unique value of the quota and, consequently, we refer to (9) as the marginal tax-quota relation below.[45]

Based on the problem in (6), (7) and (9), the following current-value Hamiltonian may be set-up:[46]

$$H = pQ_t - c(Q_t, x_t) + (1-\varepsilon)\tau_t Q_t + \delta_t(G(x_t) - Q_t - \dot{x}_t) + \lambda_t(p - \tau_t - s_t - c_{Q_t}), \tag{10}$$

where $\delta_t > 0$ and $\lambda_t > 0$ are adjoint variables. δ_t is the shadow price of the resource restriction, while λ_t is the marginal value of the fisherman´s profit from the regulator´s point of view.

When discussing regulation, it is well-known that we can focus on the optimality conditions for the control variables and disregard the conditions for the state variable x_t and the adjoint variables (δ_t and λ_t).[47] Thus, the optimality conditions are:

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[44] Since we have that $\beta_t = 0$ and $Q_t = h_t$ at only one point this solution seems to be unstable. However, in the model in this section we have full certainty so this problem is assumed away. Furthermore, in the model for cost uncertainty in section 3 the corner solution can be understood as a tendency towards which the fishery is moving.

[45] In the literature on price versus quantity regulation, (9) is normally labelled the fisherman´s response function (e.g. Weitzman, 1974). However, because we consider combining taxes and ITQs, this term is misleading so instead we refer to (9) as the marginal tax-quota relation.

[46] See, e.g. Barro and Sala-i-Martin (1995).

[47] See e.g. Jensen et al (2016).

$$\frac{\partial H}{\partial Q_t} = p - c_{Q_t} + (1-\varepsilon)\tau_t - \delta_t - \lambda_t c_{Q_t Q_t} = 0 \quad (11)$$

$$\frac{\partial H}{\partial \tau_t} = (1-\varepsilon)Q_t - \lambda_t = 0 \quad (12)$$

Now let us interpret the two optimality conditions in (11) and (12). The term $Q_t(1-\varepsilon)$ in (12) is the effect of a marginal change in the tax rate τ_t on tax revenue (valued in terms of reductions in other distortionary taxes), while λ_t is the marginal value of the fisherman's profit (from the regulator's point of view). Thus, the first-order condition for the tax requires that the marginal value of the tax revenue shall be equal to the marginal value of the fisherman's profit. According to (11) the first-order condition for the quota shall take into account the marginal profit, $p - c_Q$, the marginal cost of the resource restriction, δ_t, the marginal value of the tax revenue, $(1-\varepsilon)\tau_t$ and the effect on the fisherman's marginal profit, $\lambda_t c_{QQ}$. Thus, in total, the regulator must take all the marginal relations included in (11) and (12) into account.

By comparing (11) and (5), we see that δ_t is included in the former equation, but not in the latter. This difference arises because the fisherman does not take the resource restriction into account, while the regulator includes this constraint. Thus, the fisherman does not incorporate the effect of their harvest on the stock size and, thereby, the future harvest possibilities. This is exactly the definition of the stock externality, which means that δ_t can be defined as the marginal cost of the stock externality (Anderson, 1977).

There are three other points worth mentioning in relation to (11) and (12).[48] First, the optimality conditions must hold for all time periods and the relevant variables may change over time on an adjustment path towards a steady-state equilibrium.[49] Second, in (11) and (12), we only derive the optimality conditions for τ_t and Q_t and, therefore, optimality for the marginal tax and the quota is conditional on the optimal selection of the regulatory instruments in all future time periods. Third,

[48] See, e.g. Jensen et al. (2016) for a discussion of these three points.
[49] This argument requires that a unique steady-state equilibrium exists. Even though the conditions for this can be strict (Conrad and Clark, 1987) we assume that a unique equilibrium exists.

we have not included optimality conditions for x_t, λ_t and δ_t and, therefore, optimality in (11) and (12) is conditional on the optimality of the stock and adjoint variables.

By comparing (11) and (5), we see that the fisherman´s choice of harvest will differ from the regulator´s choice of harvest for three reasons. First, the marginal cost of the stock externality, δ_t, tends to make the fisherman´s choice of harvest larger than the regulator´s choice of harvest, which is well documented in the fisheries economic literature (Anderson, 1977). Second, the double-dividend captured by $(1-\varepsilon)\tau_t$ tends to make the regulator´s choice of harvest larger than the fisherman´s choice of harvest; an effect which, to our knowledge, has not previously been documented in the fisheries economic literature. Third, the value of the fisherman´s profit, $\lambda_t c_{Q_t Q_t}$, tends to make the regulator´s choice of harvest smaller than the fisherman´s choice of harvest. Including this effect is also a novel contribution to the fisheries economic literature.[50] Thus, including a double-dividend and incorporating the fisherman´s decisions as a restriction on the regulator´s problem has an ambiguous effect on the difference between the regulator´s and the fisherman´s choice of harvest. However, due to the three effects, the regulation of fisheries is necessary because the private and social optimal harvest levels differ.

2.3. Optimal regulation

Now we can derive the optimal marginal tax and the optimal quota. By solving (11) for τ_t and (12) for Q_t we get:[51]

$$\tau_t = \frac{\delta_t + \lambda_t c_{Q_t Q_t} - (p - c_{Q_t})}{1-\varepsilon} \tag{13}$$

$$Q_t = \frac{\lambda_t}{1-\varepsilon}. \tag{14}$$

Note, first, that to find the optimal τ_t and Q_t we should, in principle, solve (13) (or (10)), (14) (or (11)), (5), (7) and an optimality condition for the stock size as five differential equations with five

[50] The second and third effects are linked together because of the marginal tax-quota relation.
[51] Note that since the regulator knows all variables and functions, (13) and (14) are identical to uniform regulation. We return to a discussion of this point below.

unknowns (x_t , Q_t , τ_t , λ_t and δ_t).[52] Alternatively, we can interpret the solutions for τ_t and Q_t for one time period, which implies that we can investigate (13) and (14) directly. The latter procedure is applied in our paper.

From (14), we see that the optimal quota is equal to the marginal value of the fisherman's profit divided by $1-\varepsilon$, which is the social value of a unit of tax revenue (what is left of one unit of tax revenue after the marginal cost of public funds has been covered). Furthermore, the optimal tax in (13) reflects the effect on the fisherman´s profit, $\lambda_t c_{Q_t Q_t}$, the marginal cost of the stock externality, δ_t , the marginal profit, $p-c_{Q_t}$, and the social value of a unit of tax revenue, $1-\varepsilon$. Since δ_t is included in (13), τ_t corrects the stock externality and because $1-\varepsilon$ and $p-c_{Q_t}$ are incorporated, the marginal tax also generates an optimal tax revenue.

Let us also discuss the implications of including a double-dividend in the regulator´s objective function for the size of the marginal tax. From (13), we see that $p-c_{Q_t}$ tends to reduce the marginal tax, while 1 - ε tends to increase the marginal tax. Thus, incorporating a double-dividend in a welfare function has ambiguous effects on the size of the optimal marginal tax as for the harvest levels (see section 2.2. above).

Last, let us relate the optimal marginal tax and quota in (13) and (14) to the theory on a first-best and a second-best optimum. From the regulator's objective function in (6), the tax revenue must be as large as possible due to the double-dividend. Furthermore, from (9) we have a negative, linear relation between τ_t and Q_t as a restriction on the regulator´s problem. This implies that we only need to impose a marginal tax on harvest to reach a first-best optimum while a quota is unnecessary.[53] Thus, even though we have two objectives represented by correcting a stock externality and raising public funds, we only need one instrument (a marginal tax on the harvest) to reach a first-best optimum. The explanation for this result is that both objectives can be related to the same regulatory variable (harvest), which means we can adjust the marginal tax to reach a first-

[52] The fact that the change in stock size is included in the resource restriction makes this constraint a differential equation so the other equations must also be converted into differential equations to reach optimal time parts for the variables (Conrad and Clark, 1987).
[53] This conclusion can also be seen directly from (13) since the stock externality problem and the problem with generating public funds are addressed by the marginal tax. Thus, the quota is not necessary for achieving these two policy objectives.

best optimum. Thus, we reach a modified version of the first-best and second-best rule in Boadway and Bruce (1984), which states that the number of objectives must correspond to the number of instruments defined by independent regulatory variables. In other words, we have shown that a single instrument may achieve several objectives as long as the instrument can be related to the same regulatory variable.

3. A dynamic model with cost uncertainty

We now introduce cost uncertainty so the following three objectives with regulation is taken into account: A) Correct a stock externality; B) Raise public funds, and; C) Solve problems with cost uncertainty. We discuss whether two instruments (a marginal tax and a quota) must be combined to reach a first-best optimum and to do this we derive an optimal marginal tax and an optimal quota.

In the literature, it is common to capture cost uncertainty by adding a random variable to the cost function (additive uncertainty). This is done explicitly in the literature on price versus quantity regulation for both pollution[54] and fisheries[55] by either using a local second-order approximation of a general function or a globally quadratic function and implicitly in the literature on price and quantity regulation.[56] However, we follow Hoel and Karp (2001) and assume multiplicative uncertainty so that the cost function becomes:

$$c(h_t, x_t, \mu_t) = \mu_t c(h_t, x_t), \tag{15}$$

where μ_t is a non-negative random variable with an expected value of one ($E(\mu_t)=1$). Now $\mu_0, \mu_1, ..., \mu_\infty$ represents a sequence of random variables for $t = 0,1,...,\infty$ and in our dynamic model, two assumptions about this sequence of random variables are imposed. First, we assume that the random variables are uncorrelated over time so that the value of μ_t cannot be used to predict the

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[54] See Weitzman (1974), Adar and Griffin (1976), Yohe (1978), Newell and Pizer (2003) and Hoel and Karp (2002).
[55] See Koenig (1984a) and (1984b), Jensen and Vestergaard (2003) and Hansen (2008).
[56] A random variable with an expected value of zero is included in a general cost function in Kwerel (1977), Roberst and Spence (1976) and Weitzman (1978).

value of μ_{t+1}.[57] Second, we assume that the regulator is unable to update the information about the random variables so that we investigate an open-loop solution as in Newell and Pizer (2003).[58]

In line with the literature, we assume that μ_t is observable to the fisherman when making harvest decisions, whereas the random variable is unobservable to the regulator when selecting the values of the instruments (e.g. Weitzman, 1974; Hoel and Karp, 2001). Specifically, we assume that the regulator only knows the distribution of μ_t including the true expected value when announcing the marginal tax and/or the quota (the ex-ante problem). However, in contrast to the existing literature, we assume that the actual value of μ_t can be observed by the regulator at the end of a regulatory period (the ex-post problem).[59] In the literature on price versus quantity regulation, this information structure is normally referred to as uncertainty[60], although asymmetric information is a more appropriate term. Specifically, we assume hidden information since an exogenous parameter is unknown to the regulator, which corresponds to an adverse selection problem (Laffont and Tirole, 1993).

3.1. The fisherman's problem

Since the fisherman knows the value of μ_t when making harvest decisions, the only difference compared to full certainty is that the marginal cost is multiplied by μ_t. Thus, under the assumption that the quota restriction is binding, we obtain the following Kuhn-Tucker conditions:

$$\pi_h = p - \tau_t - s_t - \beta_t - \mu_t c_{h_t} = 0,\ \beta_t \geq 0,\ Q_t = h_t \tag{16}$$

By comparing (16) and (5), we see that the only difference between certainty and cost uncertainty is that c_{h_t} is multiplied by μ_t in (16).

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[57] The model can be extended to include correlated random variables over time (Hoel and Karp, 2002). However, to keep the analysis as simple as possible, we assume that the random variables are uncorrelated.

[58] Hoel and Karp (2002) incorporate updating of information about the random variable by investigating a feed-back solution.

[59] It can be discussed whether μ_t can be measured by the regulator ex-post. One example where this is possible arises when the temperature in the water in a sea is affected by climate change and the temperature affects the harvest. The temperature cannot be measured ex-ante but the variable is ex-post observable. Now the marginal tax in (22) below can be used since the temperature in the water can be captured by μ_t.

[60] A tradition that started with Weitzman (1974).

3.2. The regulator's problem

In the ex-ante problem, we must now maximize the expected discounted value of the current and future welfare because the regulator does not know the value of μ_t when setting the regulatory rules. Therefore, the regulator's problem becomes:

$$\max_{\tau,Q} \int_{t=0}^{\infty} E[(pQ_t - \mu_t c(Q_t, x_t) + (1-\varepsilon)\tau_t Q_t)]e^{-rt}\,\mathrm{dt} \tag{17}$$

s.t.

$$\dot{x}_t = G(x_t) - Q_t \tag{18}$$

$$p - \tau_t - s_t - \mu_t c_{Q_t} = 0 \tag{19}$$

In (17) an expectation operator (*E[]*) is introduced because μ_t is included in the problem, while the resource restriction in (18) is the same as under full certainty. The marginal tax-quota relation in (19) now includes the random variable and in reaching (19) we have used that $\beta_t = 0$, which implies that all the quota rents are exhausted. By totally differentiating (19) (or (16)) with respect to Q_t and τ_t we get $\frac{d\tau_t}{dQ_t} = -\mu_t c_{Q_t Q_t} = -\mu_t k$ and since μ_t is a constant within each time period, we obtain a negative, linear relationship between the marginal tax and the quota as under full certainty.

We can solve the problem in(17), (18) and (19) by using an expected current-value Hamiltonian. Because $E[\mu_t] = 1$ the first-order conditions with respect to Q_t and τ_t are:

$$p - c_{Q_t} + (1-\varepsilon)\tau_t - \delta_t - \lambda_t \mu_t c_{Q_t Q_t} = 0 \tag{20}$$

$$(1-\varepsilon)Q_t - \lambda_t = 0 \tag{21}$$

By comparing (20) with (11) and (21) with (12), we see that the only difference in the two sets of equations is that μ_t enters in (20). μ_t is included in the first-order condition for the quota in (20) because the regulator cannot measure the value of the random variable ex-ante, while μ_t can be measured ex-post. Thus, the regulator can increase the expected welfare by including μ_t in the first-order conditions for Q_t. As under full certainty the two first-order conditions must hold in all time periods, Q_t and τ_t may change over time on an adjustment path towards a steady-state equilibrium and the optimality of Q_t and τ_t is conditional on the optimality of the state and adjoint variables in all time periods. By comparing the private optimal solution with the social optimal solution, we see that the only difference from full certainty is that μ_t is included in the term that captures the value of the fisherman´s profit ($\mu_t \lambda_t c_{Q_t Q_t}$).

3.3.Optimal regulation

Now we may find the expected optimal marginal tax and the quota. By solving (20) for τ_t and (21) for Q_t, we get the following results:[61]

$$\tau_t = \frac{\delta_t + \lambda_t \mu_t c_{Q_t Q_t} - (p - c_{Q_t})}{1-\varepsilon} \tag{22}$$

$$Q_t = \frac{\lambda_t}{1-\varepsilon}. \tag{23}$$

As under full certainty, we must, in principle, solve five differential equations with five unknowns (x_t, Q_t, λ_t, τ_t and δ_t) to find the optimal value of the regulatory rules for each time period, but instead we choose to interpret (22) and (23) directly. The only difference between the solutions under certainty ((13) and(14)) and cost uncertainty ((22) and (23)) is that the random variable is included in the term that represents the value of the fisherman´s marginal profit in (22) ($\lambda_t \mu_t c_{Q_t Q_t}$). This result can be explained with the information structure in the model. Unlike the fisherman, the regulator does not know the realization of μ_t ex-ante while the variable is observable ex-post. Thus, the regulator can secure an expected optimum by including μ_t in the term that reflects the expected value of the fisherman´s profit.

Let us also compare the size of the marginal tax under certainty and cost uncertainty. From (22), the expected marginal tax under cost uncertainty will decrease compared to full certainty if $\mu_t < 1$, while

[61] Because μ_t is unknown for the regulator ex-ante, (22) represents a non-linear tax. We discuss this issue below.

$\mu_t > 1$ imply that the expected marginal tax will increase compared to full certainty. This result can be explained by the fact that μ_t enters in the term that captures the expected value of the fisherman´s profit.

Let us again relate the optimal instruments in (22) and (23) to the theory on a first-best and a second-best optimum. As above, the tax revenue is included in the regulator´s objective function, (17), and we have a negative, linear relationship between τ_t and Q_t, (19). Therefore, an expected marginal tax on the harvest can achieve a first-best optimum and we do not need to use the quota in (23). To understand this result, it is important to note that all three objectives can be related to the same regulatory variable (harvest) and, therefore, a marginal tax on harvest can be adjusted to reach an expected first-best optimum. Thus, we get the same modified version of the first-best and second-best rule in Boadway and Bruce (1984) as in section 2, stating that the number of objectives must be equal to the number of instruments measured by independent regulatory variables.

4.Discussion

In this section, we discuss ten issues related to the analysis and results in this paper. First, a discussion of uniform versus non-linear taxes is useful. In relation to this issue, we obtain different results under certainty and cost uncertainty. Under certainty, the regulator knows all the relevant parameters, variables and functions ex-ante so (13) can be reduced to a uniform marginal tax. In contrast, under cost uncertainty, the regulator does not know the value of μ_t ex-ante so (22) becomes a non-linear/non-uniform marginal tax. However, under cost uncertainty, the literature on the second-best choice between a tax and a quota (the price versus quantity regulation literature) departing from Weitzman (1974) considers a uniform marginal tax. It is obvious that non-linear marginal taxes are more difficult to understand and implement than uniform taxes. However, in the principal-agent literature, it is commonly argued that non-linear marginal taxes can be implemented in practice even under asymmetric information, which provides a justification for our regulatory solution (e.g. Laffont and Tirole, 1993; Jensen and Vestergaard, 2001).

Second, in the introduction, we mentioned the literature on price versus quantity regulation and price and quantity regulation. In the literature on price versus quantity regulation, the second-best issue of choosing between a uniform tax and a quota under uncertainty is investigated, while the literature on price and quantity regulation discusses combining instruments (a uniform tax or a quota) to reach a first-best optimum under uncertainty. Our regulatory suggestion can be seen as an attempt to unify these two traditions since we suggest using a properly designed non-linear marginal tax to achieve a first-best optimum (given multiple objectives with the regulation including solving problems with uncertainty). In other words, we depart from the literature on price and quantity regulation, but instead of introducing several instruments, we suggest using a non-linear tax.

Third, the information requirements when using non-linear marginal taxes may be huge (e.g. Cabe and Herriges, 1992). Specifically, the marginal taxes in (13) and (22) require information at the fisherman level, which can be difficult to collect. Due to the information requirements raised by taxes, Arnason (1990) propose a variant of an ITQ system to minimize the need for fishermen specific information. However, we believe that another solution to the problem with huge information requirements exists. Under this solution we collect the fishermen in groups with homogeneous cost function parameters (including μ_t). Now the tax is differentiated between groups of fishermen but uniform within groups. However, this system requires collection of cost information for the various groups of fishermen and normally fishermen can have an incentive to hide this information. A solution to this problem is to use inputs as an approximation for costs and according to Dupont (1991) vessel tonnage is closely correlated with costs.

Fourth, another issue related to information requirements is that we have considered a representative fisherman that maximizes the industry profit. However, our representative fisherman problem captures a fishing industry which is assumed to consist of a given number of fishermen. Incorporating several fishermen in the model may cause information problems. To illustrate this, assume the fishermen are heterogeneous with respect to the value of μ_t under cost uncertainty. Now for determining the marginal tax in (22) the regulator must have information about each fisherman´s value of the random variable ex-post. Therefore, the regulation must be differentiated with respect to the value of this variable.

Fifth, in the economic literature, it is often argued that the marginal cost of public funds is so large that a double-dividend does not exist (e.g. Brendemoen and Vennemo, 1996). Let us, therefore, discuss the implications of excluding the tax revenue from the regulator´s objective function for both the way the model is solved and the regulatory recommendations. Regarding the way the model is solved, we cannot use the tax function as a control variable in the regulator´s problem without a double-dividend because then τ_t does not enter into the maximization problem. Thus, we recommend using the traditional method where optimality conditions for the fisherman and the regulator are compared to find the value of the regulatory instruments.[62] Concerning the regulatory recommendations, under full certainty both a marginal tax and a quota generate a first-best optimum without a double-dividend. This equivalence between the tax and the quota exists because the tax revenue is no longer a part of the regulator´s welfare function. Despite this result, our modification of the first-best and second-best rule in Boadway and Bruce (1984) still holds, but now the regulator may choose between two instruments (a tax and a quota) to reach a first-best optimum. Under cost uncertainty, only a marginal tax will work since the quota must be announced ex-ante and does not depend on μ_t . However, a correctly designed marginal tax will ensure that all objectives are fulfilled and, thereby, our modification of the first-best and second-best rule in Boadway and Bruce (1984) also holds under cost uncertainty.

Sixth, we have assumed that the opportunity cost of holding quotas is constant and following Clark (1990) this is identical to an assumption about perfect competition on the quota market. However, in actual ITQ regulated fisheries,[63] imperfect competition on quota markets is often a problem, but solving problems with imperfect competition on quota markets can also be related to the harvest. Thus, following our modification of the first-best and second-best rule in Boadway and Bruce (1984), (22) can be adjusted to take imperfect completion into account. A similar result is reached in the literature on the taxation of flow externalities for monopolies (Barnett, 1980).

Seventh, another objective with fisheries regulation could be to take equity considerations into account. Within our model, distributional objectives can take the form of ensuring that the rent generated from fishing activities is shared fairly between the regulator and the fisherman. Now the existence of a double-dividend is critical. When including a double-dividend, we have from (9) that

[62] An alternative is to only use the quota as control variable in the problem in (17), (18) and (19). From the optimal quota derived from this problem, we can find the marginal tax by substituting the quota into the fisherman´s optimality condition. However, this method and the traditional method generate exactly the same result.
[63] See e.g. Arnason (2009)

all quota rents to fishermen are exhausted. Thus, if a double-dividend is included, all rents are per definition distributed to the regulator. However, if a double-dividend is excluded in the regulator´s objective function, either a tax or a quota can ensure an optimal solution to a stock externality problem under certainty. Furthermore, as argued by Clark (1980), a tax implies that the regulator obtains the whole rent, while the fisherman receives the entire rent with ITQs. Thus, equity considerations may be an argument for combining taxes and ITQs since this can ensure any desired sharing of the rents between the fisherman and the regulator. However, this result is also consistent with our modification of the first-best and second-best rule in Boadway and Bruce (1984) since the stock externality is defined in harvest units, while equity considerations are defined in monetary units. Thus, we still obtain the result that the number of objectives has to correspond to the number of instruments defined by the independent regulatory variables.

Eight, in our model, the marginal tax is preferred to ITQs because the total quota is grandfathered away to fishermen. However, auctions is another mechanism that can be used to distribute a total quota to fishermen (e.g. Hanley et al., 2013). Now taxes and ITQs generate the same public funds and, therefore, the two instruments have the same properties under full certainty. However, with auctions as allocation rule, our modified first-best and second-best rule from Boadway and Bruce (1984) still holds, but now the regulator can choose between using two instruments (either a tax or ITQs).

Ninth, we have assumed multiplicative uncertainty, but additive uncertainty is a more common assumption in the literature on price versus quantity regulation and price and quantity regulation under uncertainty. However, our results generalize straightforwardly to additive uncertainty. To see this, consider both a first-order and a second-order local Taylor approximation of a general cost function. With a first-order approximation, the random variable will enter additively in (22), while a second-order approximation implies that the variance of the random variable must enter in the marginal tax. However, both approximations are simple extensions of our basic marginal tax rule so the results in (22) do not depend on the assumption about the nature of the cost uncertainty.

Last, we have assumed that the regulator can measure the value of μ_t ex-post and, therefore, the marginal tax in (22) can be made conditional on the random variable. Naturally enough, this is not the case for all kinds of uncertainty. However, often an unobservable variable can be approximated by using an observable variable. Furthermore, even if it is not possible to construct a measure the random variable, the results in this paper generalize to a stochastic μ_t ex-post in the sense that an expected first-best optimum can be reached with a non-linear tax provided the random variable is measured in an unbiased way.

5.Conclusion

In this paper, we have investigated whether taxes and quotas should be combined in fisheries regulation. The investigation is based on a dynamic model where both discounting and adjustments towards a steady-state equilibrium are included. The regulator maximizes the present value of current and future welfare subject to a resource restriction and a constraint reflecting the fishermen's optimality conditions for maximizing profit. In contrast, the fisherman disregards the effect of his harvest on the fish stock and, thereby, the future harvest possibilities (a stock externality arise). The regulator is uncertain about the fisherman's costs and the collected tax revenue from correcting the stock externality generates a double-dividend (the tax revenue can be used to reduce other distortionary taxes). Apart from correcting a stock externality, including a double-dividend and solving problems with cost uncertainty represents additional objectives with fisheries regulation. Thus, three objectives regulation exist and, according to theory on a first-best and a second-best optimum represented by Boadway and Bruce (1984), this implies that three instruments must be used. To investigate the theory on a first-best and second-best optimum, we have identified an optimal marginal tax and an optimal quota under the three objectives mentioned above. Contrary to the first-best and second-best rule in Boadway and Bruce (1984), we argue that one instrument (a marginal tax rule) is enough to address the problems with correcting a stock externality, collecting public funds and solving problems with uncertainty. The explanation for this result is that all three objectives can be defined by using the same regulatory variable (harvest) and, therefore, a one instrument (non-linear marginal tax on harvest) can be adjusted to incorporate all three objectives.

Our analysis contributes to at least four strands of economic literature on regulation. First, by showing that a non-linear tax may secure a first-best optimum, we contribute to the existing fisheries economic literature undertaking analysis of regulation of multiple externalities. Second, by considering non-linear marginal taxes, we extend the literature on price versus quantity regulation under uncertainty. Third, we contribute to the literature on price and quantity regulation by only recommending the use of one regulatory instrument. Last, by studying optimal regulation under the assumption of truthful revelation of private information, we extend the existing literature that applies a principal-agent approach to regulation.

By using a fisheries model, we have illustrated a modified version of the first-best and second-best rule in Boadway and Bruce (1984), stating that the number of objectives with fisheries regulation must correspond to the number of instruments defined by independent variables. However, we believe that this modification generalizes to almost all policy areas. To see this, consider, for example, unemployment polices. In Denmark, a large number of objectives exist and a huge number of instruments are used to influence the extent of the unemployment among various groups of people. However, by using our results, it is easier to use one instrument to achieve an overall objective for the extent of the unemployment. In this way, our modification of the first-best and second-best rule in Boadway and Bruce (1984) becomes an argument for deregulation since the number of instruments in actual regulation can be reduced considerably.

A limitation in this paper is that our treatment of cost uncertainty departs from very simple assumptions about the information structure. Specifically, we assume that a random variable is observable for the fisherman and relaxing this simplifying assumption by allowing for fisherman uncertainty ex-ante is an important area for future research.

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