Working Paper No. 25/10

Quota Enforcement in Resource Industries: Self Reporting and Differentiated Inspections

by

Lars Gårn Hansen
Frank Jensen
Linda Nøstbakken

SNF Project No. 5181
The effect of political uncertainty in fisheries management:
A case study of the Northeast Arctic cod fishery

The project is financed by the Research Council of Norway

INSTITUTE FOR RESEARCH IN ECONOMICS AND BUSINESS ADMINISTRATION
BERGEN, JUNE 2010
ISSN 1503-2140

Working Paper No. 25/10

Quota Enforcement in Resource Industries: Self Reporting and Differentiated Inspections

Lars Gårn Hansen[*] Frank Jensen[†] Linda Nøstbakken[‡]

Abstract

Individual quotas are a dominant instrument in the management of common pool renewable resources like fisheries. However, there is concern about the basic effectiveness of quota regulation due to widespread non-compliance. In this paper we develop a model of enforcement in a quota regulated renewable resource industry and consider a case with significant non-compliance, and with exogenous constraints on fines and enforcement budget. We propose a reform of the enforcement system by introducing self reporting of excess extraction and (explicit) differentiation of inspection rates based on compliance history. We show that the proposed reform increases the effectiveness of quota management and allows the regulator to implement a wider range of aggregate extraction targets than under the traditional enforcement system. This is shown without violating the inspection budget constraint or the fine constraint, and while ensuring an efficient allocation of aggregate catch.

JEL Classification: D61, H0, Q20, Q22, Q28
Keywords: Non-compliance, Self reporting, Enforcement, Quota regulation, Fishery.

---

[*] Institute of Food and Resource Economics, University of Copenhagen, Denmark.
[†] Institute of Food and Resource Economics, University of Copenhagen, Denmark.
[‡] University of Alberta School of Business, Edmonton, Alberta T6G 2R6, Canada, and SNF, Norway.

1 Introduction

Much work has been devoted to exploring optimal management of common pool renewable resources like fisheries, including the optimal design of quota-based systems. There has also been an increasing focus on compliance issues. The productivity growth in production technologies has increased both the importance of ensuring effective enforcement and the incentives of firms to violate the regulations.

Currently, regulatory non-compliance is widespread in world fisheries. Recent estimates suggest that illegal and unreported catches constitute on average about 20% of reported catches in world fisheries (Agnew et al., 2009). The estimates vary both across regions, fish species, and over time, but the number is nonetheless considerable. Quotas are typically enforced by use of random inspections. Inspection rates may be higher for vessels perceived by inspectors to be more likely to violate quotas, but such differentiation in inspection rates is not a formal part of the enforcement system.[1] If violations are detected, violators are prosecuted and punished (fined). Reducing quota violations requires tougher enforcement or tougher punishment. The latter is equivalent to increasing fines under the traditional enforcement system. However, both increased enforcement efforts and higher fines may be politically infeasible due to budgetary and legal constraints.[2] This could leave resource managers in a situation with substantial problems of quota violations, but without the ability to take further actions to reduce violations.

The objective of this paper is to propose a reform of the traditional enforcement system that increases the effectiveness of quota regulation while satisfying budgetary and legal constraints. Our enforcement model contains two important extensions of the traditional quota enforcement model. The first extension is that firms may self report catches in excess of quotas. Upon doing so the firm pays a given amount per self reported unit (a reduced "fine"). This makes it legal to exceed quotas as long as the correct excess quantity is reported and paid for. The second model extension is to introduce differentiated inspections based on the firms' compliance history. Firms that are inspected and found to violate quotas, that is, exceeded their quotas without fully self reporting this, are moved into an inspection group with a higher inspection rate for a given period of time. In addition, detected violators are prosecuted and punished

---

[1] To our knowledge, differentiated inspection rates are not a formal part of the enforcement system in any fishery. However, we know that at least in some fisheries inspections are to some degree targeted on vessels that based on their compliance record are perceived to have a higher likelihood of violating regulations.

[2] Fines are typically constrained by the principle that the punishment should be proportional to the crime, which restricts the use of higher fines to combat illegal fishing. Furthermore, substantial increases in enforcement costs are often politically infeasible due to budgetary constraints.

(fined). For a given maximum fine (punishment level) we show that this enforcement system always can ensure a given aggregate catch level more efficiently than the standard enforcement system (irrespective of how inspection rates are differentiated in this system). Furthermore, the enforcement system increases enforcement effectiveness. Therefore, for a given fine level and inspection budget, the proposed system generally achieves a larger range of target aggregate catch levels than the traditional enforcement system. An example and numerical results are provided that demonstrate these improvements, as well as possible limitations of the proposed enforcement system.

Both self reporting of violations and differentiated inspections based on compliance history have been studied in the regulatory economics literature. From the strand of this literature that studies enforcement systems based on self reporting, we know that such systems are commonly used in environmental regulation (Russell, 1990) and have proven to be effective in many cases where high compliance rates are achieved even though both sanctions and inspection rates are low (Livernois & McKenna, 1999).

The self-reporting literature suggests that higher compliance rates may be the result of more efficient targeting of inspection resources, which is made possible by self reporting. A number of papers in this literature considers incorporation of self reporting into a fine-based environmental regulation system, showing that this could increase compliance and efficiency (Malik, 1993; Kaplow & Shavell, 1994; Livernois & McKenna, 1999; Innes, 1999, 2001; Macho-Stadler & Pérez-Castrillo, 2006). The main advantage is that self reporting allows the regulator to increase compliance by focusing control resources on agents that do not self report violations (Kaplow & Shavell, 1994; Malik, 1993; Innes, 1999).[3] Another advantage is that self reporting may allow regulated agents to reduce their avoidance costs (Innes, 2001). On the other hand, the enforcement system must give agents incentives to self report, for example by reducing the fine for self reported relative to unreported violations(Livernois & McKenna, 1999).

Another strand of literature suggests that high compliance rates combined with low sanction rates could be the result of what Heyes & Rickman (1999) refer to as regulatory dealing (Harrington, 1988; Greenberg, 1984; Heyes & Rickman, 1999). The basic idea is that firms are given lenient treatment in some situations where they do not comply (reduced or no sanctions) in exchange for increased compliance in others. Harrington (1988) suggests a system with two enforcement groups. Firms found to violate regulations in the current period are placed in an enforcement group with tougher sanctions next period. He shows that firms who do not have incentives to comply under undifferentiated sanctioning and inspection rates, can be induced to comply under the

---

[3] In the environmental literature, compliance is usually a binary choice (to comply with or violate regulations). Hence, if one self reports, there is no reason why such report is untruthful.

differentiated system when in the tough sanctioning group. The reason is that firms in this group have an additional incentive to comply with regulations, namely the reward of being transferred to the low sanction group next period if compliant.

Both the self reporting and regulatory dealing mechanisms for increasing compliance suggested in the literature, are based on incentives generated by the enforcement system. This makes them relevant when developing enforcement reforms that could increase compliance with fisheries regulations.[4]

Our contribution to this literature is to introduce the well-known concepts of self reporting, on the one hand, and differentiated inspections and sanctions, on the other, into the management of a quota regulated natural resource. The policy implications are that resource managers can increase the range of implementable aggregate catch targets and ensure efficient allocation without increasing enforcement costs, by making some simple modifications to the traditional quota enforcement system. In contrast to many previous models of enforcement of environmental regulations (e.g. Kaplow & Shavell, 1994; Malik, 1993; Innes, 1999), quota violations can take on a continuum of values and hence require inspections to ensure truthfulness. Furthermore, we consider the enforcement of an inefficiently allocated quota, where firms with heterogenous costs are allocated a fixed share of the total quota. In this case, an efficient allocation of catch shares is obtained if all firms exceed their quotas and self report their excess catches. Consequently, it becomes more important to focus on inducing truthful self reporting rather than obtaining full quota compliance. This contrasts recent result for enforcement of environmental regulations by Macho-Stadler & Pérez-Castrillo (2006).

In the fisheries economics literature a number of studies investigate optimal enforcement of a regulated fishery given the traditional enforcement system (Sutinen & Andersen, 1985; Milliman, 1986; Anderson & Lee, 1986), while others consider the choice of regulatory instruments in the presence of non-compliance (Charles et al., 1999; Chavez & Salgado, 2005). However, our approach of combining self reporting and inspection differentiation to increase the effectiveness of a given inspection budget is new to this literature.

---

[4] Other explanations for high compliance rates in environmental regulation when sanctions and inspection rates are low have been suggested. One explanation is the risk of repercussions over financial and output markets if violating environmental regulations, which affect firm profits (see e.g. Hamilton, 1995; Konar & Cohen, 1997; Anton et al., 2004). If consumers or investors care about the firm's environmental reputation, their reaction to disclosures of non-compliance with environmental regulations could be costly to the firm, which may explain higher compliance rates even though regulatory sanctions are small. Such effects may be important in the case of large differentiated firms that consumers and investors can identify in the market, but are presumably less important for smaller, undifferentiated firms that are not easily identified in the market, such as those operating in many fishing industries. See also Helland (1998), Sandmo (2000), and Short & Toffel (2008).

Section 2 presents the basic model of the traditional quota enforcement system. The model is specified for a fishery that is regulated with non-transferable quotas, and the case of the fishery is used as an example throughout the paper. Section 3 introduces our proposed enforcement system based on self reporting and differentiated inspection rates, and proves theoretically that the proposed system generally is more efficient and more effective than the traditional enforcement system. Section 4 provides a numerical example to illustrate the ideas. In this section functional forms are specified and numerical simulations are used to show optimal enforcement under the traditional enforcement system and under our proposed enforcement system, and to compare the two under different requirements for regulatory intensity. Section 5 provides concluding remarks.

2 The Traditional Enforcement System

In this section we develop a model of a quota regulated fishing industry consisting of n firms that harvest a fish stock. The regulator sets a total quota that is allocated in equal shares to the n firms as non-tradable quotas. [5] The regulator can only detect quota violations through costly inspections that allow him to observe firm level catches.

Ideally the objective of the regulator is to maximize sustainable aggregate industry profit net of inspection costs. Under the traditional enforcement system, the regulator has two instruments; the size of the total quota and the inspection rate. When a firm is inspected and found to violate regulations, it can be fined. However, the maximum fine is assumed exogenously given as the fine is constrained by the principle that the punishment should be proportional to the crime (legal constraint). Hence, higher fines cannot necessarily be imposed to reduce illegal fishing. Furthermore, there is a budget constraint on control efforts that limits the inspection rate. This can be explained by substantial increases in enforcement costs often being politically infeasible due to budgetary constraints.

2.1 The Firms and the Fish Stock

Total harvest is subject to a resource constraint $\Delta X_t = F(X_t) - Y_t$, which states that the change in the resource stock in period t equals the period's stock growth, $F(X_t)$, minus the total harvest, Y_t. To keep things simple we disregard transition dynamics and assume that the regulator compares sustainable states. That is, regulator considers

---

[5] In real-world fisheries, many quota systems allow for some trade in quotas, but such trade is often highly restricted.

sustainable catch level (Y) and stock (X) combinations that satisfy:

$$Y = F(X) \tag{1}$$

with the objective of maximizing aggregate sustainable profit less inspection costs.[6]

In a sustainable equilibrium without quota regulations each firm in the industry chooses the extraction level that maximizes its own profit conditional on the resource stock:

$$\pi_i = py_i - c(y_i, \alpha_i, X) \tag{2}$$

where p is the output price, y_i is firm i's harvest, and $c(\cdot)$ is a cost function that relates harvest cost to harvest quantity and the size of the fish stock X. The cost parameter α_i is firm specific, which indicates that there are cost differences between the n firms.

Let $y^*(\alpha_i, X)$ denote the optimal harvest level of a firm with cost parameter α_i at a given stock level. All differences between firms are captured in the cost parameter α_i. Hence, the industry is uniquely characterized by the distribution of cost parameters $g(\alpha)$. Aggregate harvest is the sum of all firms' catches, $Y = \sum\limits_i y_i^*$. In steady state aggregate harvest must equal stock growth in each period. This implies the following steady-state relationship between aggregate harvest and stock:

$$\sum_i y^*(\alpha_i, X) = F(X). \tag{3}$$

A large resource stock will not only generate a large equilibrium aggregate catch ($F(X)$) but also lower marginal extraction costs ($\frac{\partial^2 c}{\partial y \partial X} < 0$) and so sustainable combinations of large stock and yield are preferable. However, without regulations productive extractors with relatively low marginal extraction costs choose catch levels that result in aggregate catch levels larger than the sustainable yield associated with this stock ($Y = F(X)$). Hence, without regulations stocks are driven down and the sustainable unregulated equilibrium is typically characterized by low yield and stock levels. In certain cases, the stock can even be driven to extinction with an equilibrium yield of zero. Regulations are introduced because of this externality in resource extraction. The purpose of regulation is to reduce extraction below the uncoordinated level to reach the preferred equilibrium.

---

[6] The model and results we present in the following generalize to the dynamic setting. However, while this complicates derivations it does not as such affect results nor does it add real insights about the workings of the suggested enforcement mechanism.

2.2 The Regulator and Enforcement

Each firm is allocated a non-transferable quota q. The firm chooses whether to comply with its quota, knowing that quota violation comes at the risk of being fined if the violation is detected. The regulator can only observe the firms' harvest levels by conducting costly inspections of firms. The regulator is constrained by an inspection budget that allows for a given number of inspections per period, $m < n$. Without differentiation between firms, this results in an inspection rate of $\gamma = \frac{m}{n} < 1$ for each firm per period of time. The cost per inspection is c_m. We assume that each firm is inspected at most once per period, and that the inspection accurately reveals the actual harvest level of the firm in that period. Hence, we abstract from the possibility of firms making several fishing trips per period.

A fine up to a maximum of f can be imposed per unit harvested in excess of the quota. The maximum fine is stipulated by exogenously given legislation and statutes, and is assumed to be high enough to fully deter quota violations if applied with certainty. If a firm is inspected during a time period, we assume that all illegal landings are observed (no inspection error). The regulator knows the cost function and the distribution of cost parameters in the industry $g(\alpha)$, but does not know the individual firm's cost parameter α_i. All n firms are allocated the same resource quota $q = \frac{Q}{n}$, where Q is the total allowable harvest.[7] Under this system, firms choose harvest quantities to maximize profits net of expected fine payments (cf. equation 2), i.e.:

$$y_i^*(\alpha_i, q, \gamma, X) = \arg\max_{y_i} \left[\pi\left(y_i, \alpha_i, X\right) - \gamma f\left(\max(0, y_i - q_i)\right)\right] \tag{4}$$

A welfare maximizing regulator would seek to maximize total sustainable industry profit net of enforcement costs. Assuming that the fine is set to its maximum value, f, the problem of the regulator can be stated as follows:

$$\begin{aligned} \max_{\gamma,q} \quad & \left(n \int_{\alpha} \pi\left(y_i^*, \alpha_i, X\right) dg(\alpha) - c_m \gamma n\right) \\ \text{s.t.} \quad & y_i^* = \arg\max_{y_i} \left[\pi\left(y_i, \alpha_i, X\right) - \gamma f\left(\max\left(0, y_i - q\right)\right)\right] \ , \forall i \\ & n \int_{\alpha} y_i^*\left(\alpha_i, q, \gamma, X\right) dg(\alpha) = F(X) \\ & 0 \leq \gamma \leq \tfrac{m}{n} \end{aligned} \tag{5}$$

The first line of equation (5) is the sum of industry extraction profit, which is given

---

[7] Note that regulators typically differentiate quotas according to e.g. the type and size of the firm. This is not our focus and to keep the analysis tractable we abstract from this. Extending the model accordingly is easy.

as the number of firms n multiplied by the average extraction profit over all firms, minus inspection cost ($c_m\gamma n$). Industry profit depends on the distribution of the cost parameter α. The problem is to choose the quota and inspection rate that maximize extraction profits subject to three constraints: (i) that firms choose profit maximizing harvest quantities (second line), (ii) that aggregate harvest equals stock growth in equilibrium (third line), and (iii) that the inspection rate does not cause a violation of the inspection budget (fourth line). If aggregate catch must be regulated the solution to this problem is to set quotas so tight that all firms are induced to catch illegally and hence are constrained by the expected fine on illegal catches rather than by the quota. The regulator then sets inspection rates (γ) so that the optimal catch level is achieved. This ensures an efficient allocation of the aggregate catch target since all firms are constrained by the same expected fine.[8]

In practice regulators do not do this. Rather, the standard regulatory approach is to take the enforcement system and its costs as given (i.e. fix inspection costs at the allowed maximum) and use the resource quota q as the only policy instrument.[9] Hence, γ is fixed at its maximum level, $\bar{\gamma} = \frac{m}{n}$, and the problem becomes:

$$\begin{aligned} &\max_{q} \quad \left(n \int_{\alpha} \pi\left(y_i^*, \alpha_i, X\right) dg(\alpha) - c_m \bar{\gamma} n \right) \\ &\text{s.t.} \quad y_i^* = \arg\max_{y_i} \left[\pi\left(y_i, \alpha_i, X\right) - \bar{\gamma} f\left(\max\left(0, y_i - q\right)\right) \right] \ , \forall i \\ &\qquad\ \ n \int_{\alpha} y_i^*\left(\alpha, q, \bar{\gamma}, X\right) dg(\alpha) = F(X) \end{aligned} \tag{6}$$

For large q no firms are constrained in their harvest. All firms face a zero marginal shadow price on the harvest quota. As q is reduced, there is a point at which some firms become constrained, and from this point onward, reducing q further reduces aggregate harvest. As q falls, more firms become constrained, and firms that are already constrained become more constrained and consequently face a larger marginal shadow price of their quota. At some point the most efficient firms begin to find it profitable to harvest illegally (when the marginal shadow cost of their catch quota exceeds the expected fine). From this point onward, these firms do not reduce their catches when the quota is reduced. They are constrained by the expected fine generated by the enforcement system, not by the quota system. At some point q is at a level where all firms harvest illegally and no further reductions in aggregate harvest occur when the quota

---

[8] In contrast, if firms were constrained by the uniform catch quota or by different expected fines instead of by the same expected fine, aggregate catch would be allocated inefficiently because the firms would not face the same marginal shadow price of catches.

[9] This means that the entire inspection budget is spent, which implies a maximization of the inspection rate γ.

is reduced. Thus beyond this point the quota instrument is not effective. Reductions in aggregate catch beyond this point are not possible under the traditional inspection system since fines and inspection costs are at their maximum constraints. Between these two points the quota instrument is effective in the sense that aggregate harvest is affected when the quota is adjusted.[10] On the other hand, the quota instrument is clearly not efficient since heterogeneous firms face different marginal shadow prices of catches when constrained by a uniform catch quota. The standard recommendation in this situation is to make quotas tradable, which would allow for an equalization of shadow prices of catches across firms.

However, in many fisheries there are substantial non-compliance problems and one may in fact be close to or at the point where all firms violate quotas. In such cases, (almost) all firms are exceeding their catch quotas and are thus constrained by the expected fine on illegal catches. When all fishing firms face (and perceive) the same inspection probability, their perceived shadow price of catches become identical. Consequently, low cost firms (low α) will harvest more than high cost firms (high α), resulting in higher cost efficiency than if all firms harvested the same quantity regardless of cost differences. Hence, if one is at or close to the point where all firms fish illegally, the gain from tradability is limited and non-tradable quotas may be (nearly) as efficient as tradable quotas. In this situation it may also be efficient to set the probability of inspection equal to the maximum constraint $\gamma = \bar{\gamma}$ (spending the entire inspection budget) as regulators typically do.

The main problem that regulators face in this situation is that further reductions in aggregate harvest beyond the point where no firm complies with quotas cannot be achieved by further reductions in quotas. This is because all firms are violating their quotas, which means that their catch levels are not constrained by their quota but by the size of the expected punishment induced by the enforcement system. Hence, it may be well founded when resource regulators seem more concerned with the lack of effectiveness of quotas than with quotas being tradable. If a fishery manager is in this situation and is constrained by an upper limit on enforcement resources and fines, it seems reasonable to try to increase the effectiveness of enforcement by differentiating inspection probabilities between fishing firms. As noted in the introduction, although such differentiation typically is not part of the formal enforcement system, this may

---

[10] Note that aggregate harvest is not generally equal to the aggregate quota. Initially, the aggregate harvest is lower than the aggregate quota because many fishing firms do not fully utilize a lax quota. As the quota is tightened vessels become constrained and illegal fishing becomes an option. Hence, at some point aggregate catch exceeds the aggregate quota. As long as at least some firms are constrained by the quota, tightening of the quota affects these vessels and quotas are thus effective in reducing aggregate catch.

be what fisheries control agencies in some cases are trying to do when they target vessels that have been less compliant than others in the past. To the extent that this results in targeting of vessels that are more sensitive to changes in expected fines, effectiveness is increased. However, the observation that a vessel is less compliant than others does not necessarily mean that the vessel is more sensitive to increases in the expected fine.[11] Furthermore, regardless of whether this type of inspection differentiation increases or decreases effectiveness, the fishing firms will face different expected fines, and, consequently, the allocation of aggregate catch will become less efficient.

Alternative enforcement schemes must be considered if fisheries managers are to achieve further reductions in aggregate harvest while ensuring that they are efficiently allocated. The self-report based enforcement system proposed next aims at doing just that.

3 The Self-Report Based Enforcement System

In this section we propose an alternative to the traditional quota enforcement system based on self reporting and differential inspection rates. Although illegal fishing is a considerable problem worldwide (Sumaila et al., 2006; Agnew et al., 2009), neither self reporting nor differentiated inspections have been formally analyzed in the context of fisheries, nor have they been applied in fisheries regulation.[12]

Our proposed alternative enforcement system is presented within the same framework as the traditional enforcement system introduced above. There are, however, some important differences. Instead of inspecting all firms with the same probability, firms are assigned to one of two enforcement groups with different inspection probabilities; group 1 with low probability of inspection, and group 2 with high probability of inspection. In the first group, firms are allowed to self report harvest quantities in excess of quota, in which case there is a rebate on the fine paid. If inspected firms are found to have self reported all excess catches they remain in the first group. If they have not, they must pay the full fine and are moved to the second inspection group. The threat of being moved to the second group, the so-called "control hell"

---

[11] That is, compliance, $y_i^*(\alpha_i, q, \gamma, X) - q$, may be positively, negatively or uncorrelated with the sensitivity to changes in expected punishment, $\frac{\partial y_i^*(\alpha_i, q, \gamma, X)}{\partial \gamma}$

[12] Some regulatory systems have elements that resemble self reporting. In many regions, such as Australia, Canada, the European Union, Iceland, Norway, and the United States, fishing vessels are required to keep logbooks with information about their catches and harvest activities. However, the key element of a self report enforcement system, namely that firms are given incentives to self report violations, is to our knowledge not an element in current fisheries regulation systems.

with high inspection rates, is an effective deterrent that makes it possible to increase firms' perceived punishment relative to the traditional enforcement system, without increasing inspection costs.[13] In addition, the self-reporting scheme allows the regulator to use the self report rebate, that is, the reduction in fine when a firm self reports excess catches, as an additional control variable. This makes it possible to increase the allocation efficiency of the system, as will be shown below.

The idea of using the threat of "control hell" to strengthen the incentives to comply without increasing fines or inspection costs was originally suggested by Greenberg (1984). We use it here in basically the same form but for a different purpose; to induce self reporting of violations rather than compliance. Self reporting of violations in the environmental enforcement literature is often seen as a way to increase efficiency by reallocating inspection resources to firms that do not self report violations (Kaplow & Shavell, 1994; Malik, 1993; Innes, 1999). This is because violations in these models can take on only one value and a self reported violation by a rational agent therefore must be truthful. In our setting quota violations can take on a continuum of values and therefore require inspection to ensure truthfulness. This type of violations are considered by Macho-Stadler & Pérez-Castrillo (2006), but in their model they find that allocation of resources should be focused on inducing compliance rather than truthful self reporting. In our case we are enforcing an inefficient allocation of quotas and it is therefore better to allow firms to exceed their quotas and instead induce truthful self reporting of excess catches, which improves the allocative efficiency.

3.1 The Regulator and Enforcement

The inspection probability depends on whether the firm is in group 1 or group 2 and is denoted $\gamma_j \in [0,1]$, where $j = 1,2$ refers to the group. A firm in group 1 that self reports harvest in excess of quota, must pay a fine rf per unit, where $r \in (0,1)$ is a factor indicating the fine rebate for self reporting. In group 2, self reporting gives no rebate, hence, a firm that self reports must pay the full fine f per unit. Furthermore, a firm in group 1 that is inspected and found to have underreported its quota violation must pay the full fine and is moved to group 2. Once in group 2, the firm stays there until found to have self reported correctly during u consecutive inspections after which the firm is moved back into group 1.

The inspection probabilities in table 1 are determined by the regulator and are constrained by the inspection budget. As under the traditional enforcement system,

---

[13] To make "control hell' even crueler to strengthen its deterrence effect, there are several possibilities, such as to introduce quota reductions for firms while in "hell."

Table 1: Punishment Scheme

	Group 1		Group 2	
	Self report	Violate	Self report	Violate
Not inspected	$rf(y_i - q)$	0	$f(y_i - q)$	0
Inspected	$rf(y_i - q)$	$f(y_i - q)$	$f(y_i - q)$	$f(y_i - q)$
Inspection prob.	γ_1 *Violate: move to group 2*		$\gamma_2 > \gamma_1$ *Full self reporting u times: move to group 1*	

the regulator can perform a given number of inspections per year, denoted m, which determines the inspection probability. If all firms are equally likely to be inspected (all firms are in group 1), the inspection probability is $\gamma_1 \leq \frac{m}{n}$.[14]. The inspection rate is higher in group 2 than in group 1. Hence, the more firms there are in inspection group 2, the lower the inspection rate can be in group 1.[15] The maximum fine is assumed to be exogenously given and high enough to fully deter quota violations if applied with certainty.

As under the traditional enforcement system, the regulator seeks to maximize total industry profit net of enforcement costs $n \int\limits_{\alpha} \pi \left(y^*, \alpha, X\right) dg(\alpha) - c\gamma n$, where γ in this case refers to the average inspection rate over both inspection groups (weighted average). However, now the set of policy instruments available to the regulator includes two inspection rates (γ_1 and γ_2) and the period of time a firm must be in "control hell" (group 2) following the detection of a violation, before it can be moved back into group 1.

To ensure an efficient allocation of aggregate catch across firms, the regulator sets the total quota sufficiently low for the individual quota to be binding for all firms and inducing them to exceed the quota.

3.2 The Firms

Under the self report based enforcement system, the firm has four main options. It can (i) comply with its quota, (ii) report the entire illegal extraction, (iii) report some of the illegal extraction, or (iv) not report any extraction in excess of the quota. With a fine structure that is linear in illegal quantity and detection probabilities being constant,

---

[14] The inspection probability is assumed to be positive and strictly below one.

[15] In general, the following must hold: $1 \geq \gamma_2 > \gamma_1 > 0$. In addition, the inspection budget cannot be exceeded, which implies that $\gamma_1 \leq \frac{m - \gamma_2 n_2}{n - n_2}$, where n_2 is the number of firms in inspection group 2.

it is easily shown that the firm either reports all or does not self report any excess extraction. Thus, the relevant options for a firm are reduced from four to three, as option (iii), where one exceeds the quota and reports only part of the excess quantity, is never chosen.

On this basis, there are three distinct behavioral strategies a profit maximizing firm can use and the firm chooses the strategy that yields the highest sum of discounted future profits.

- Strategy A: Stay in group 1. To ensure that the firm is never moved into group 2, the firm must always act in compliance with regulations. Consequently, the firm must self report any excess extraction (options i or ii). Since the quota is set sufficiently low for no firm to find option (i) optimal, only option (ii) remains. In a sustainable equilibrium, optimal harvest is the same in all periods. Hence, $y_i^a = \underset{y_i}{\arg\max} \left[\pi\left(y_i, \alpha_i, X\right) - rf\left(y_i - q\right)\right]$, which gives a net expected profit of $\Pi_i^a = \pi\left(y_i^a, \alpha_i, X\right) - rf\left(y_i^a - q\right)$. Letting EV_i^a denote the present value of future profits for firm i when following strategy A we have that:

$$EV_i^a = \sum_{t=0}^{\infty} \beta^t \Pi_i^a, \tag{7}$$

  where β is the discount factor ($\beta = 1$ implies no discounting while $\beta = 0$ implies that future periods are completely disregarded).

- Strategy B: Alternate between groups. To alternate between groups, the firm must be willing to violate regulations while in group 1, and comply with regulations while in group 2. Thus, the behavior of a firm that follows strategy B depends on the inspection group the firm is currently in. In inspection group 1, the firm chooses to violate quotas (option iv), while in group 2, the firm self reports all excess extraction (option ii). Formally, when in group 1, the firm sets $y_i^{b1} = \underset{y_i}{\arg\max} \left[\pi\left(y_i, \alpha_i, X\right) - \gamma_1 f\left(y_i - q\right)\right]$, which gives net expected profit of $\Pi_i^{b1} = \pi\left(y_i^{b1}, \alpha_i, X\right) - \gamma_1 f\left(y_i^{b1} - q\right)$. In group 2, the firm sets $y_i^{b2} = \underset{y_i}{\arg\max} \left[\pi\left(y_i, \alpha_i, X\right) - f\left(y_i - q\right)\right]$, which gives net expected profit of $\Pi_i^{b2} = \pi\left(y_i^{b2}, \alpha_i, X\right) - f\left(y_i^{b2} - q\right)$. In the first period under this strategy, the firm is in group 1 and expected profit is Π_i^{b1}. The inspection rate γ is the probability of being moved to group 2 in the next period, and hence, expected profit in the next period is $(1-\gamma)\Pi_i^{b1} + \gamma\Pi_i^{b2}$. In every future period t the firm perceives some probability $0 \leq \nu_i(t) \leq 1$ of being in group 2 (where $\nu_i(0) = 0$, $\nu_i(1) = \gamma$, etc.). Hence, the expected profit in period t is $\left(1 - \nu_i(t)\right)\Pi_i^{b1} + \nu_i(t)\Pi_i^{b2}$. Thus, the present value of future profits under strategy B becomes:

$$EV_i^b = \sum_{t=0}^{\infty} \beta^t \left[(1 - \nu_i(t))\, \Pi_i^{b1} + \nu_i(t) \Pi_i^{b2} \right], \tag{8}$$

where $0 \leq \nu_i(t) \leq 1$ for all t.

- Strategy C: Stay in group 2. To always be in group 2, the firm must never comply with its quota nor self report excess extraction. Thus, the firm's only option is to always violate the quota (option iv). This yields a catch quantity of $y_{it}^c = \arg\max_{y_{it}} \left[\pi\left(y_{it}, \alpha_i, X_t\right) - \gamma_2 f\left(y_{it} - q_t\right) \right]$, with corresponding net expected profit of $\Pi_{it}^c = \pi\left(y_{it}^c, \alpha_i, X_t\right) - \gamma_2 f\left(y_{it}^c - q_t\right)$. The present value of future profits for a firm following strategy C is:

$$EV_i^c = \sum_{t=0}^{\infty} \beta^t \Pi_i^c. \tag{9}$$

Since the maximum fine (f) is assumed to be sufficiently high to fully deter violations if applied with certainty, strategy C is always dominated by self reporting in group 2, that is, by strategy B when $\gamma_2 = 1$. Thus, firms will choose either strategy A or strategy B.

3.3 Welfare implications

Compared to the traditional enforcement system, there are several more policy instruments available under the self-report based system. It is clear that introducing more enforcement policy variables as part of the regulators set of control variables cannot reduce welfare if policy variables are set optimally, since the traditional enforcement system is a possible specification. In the following we prove two propositions showing that there generally is a welfare gain when shifting to the self report based enforcement system. The first proposition considers the situation where quotas under the traditional enforcement system have been tightened so much that all firms violate. In this situation all firms are constrained by the expected fine (none are quota constrained), hence, further quota reductions have no effect on aggregate harvest. The first proposition states that a self-report based enforcement system allows the regulator to implement further (welfare increasing) reductions in aggregate harvest and that it ensures an efficient distribution of these reductions across firms. The second proposition considers the situation where quotas under the traditional enforcement system are still effective (i.e., some firms are quota constrained) and states that in such case the aggregate harvest target can be implemented more efficiently under a self-report based enforcement system.

Proposition 1. *When all firms under traditional enforcement violate quotas, so that aggregate harvest cannot be reduced further under this enforcement system, there generally exists an enforcement system with self reporting and differential inspections that reduces aggregate harvest and allocates this reduction efficiently among firms without increasing the inspection budget of the enforcement agency.*

Proof. The proof of proposition 1 begins by considering a differentiated inspection system where the inspection rates are $\gamma_1 = \gamma$ and $\gamma_2 = 1$, and where the fine rebate factor when self reporting is $r = \gamma$. Noting that quotas are exceeded by all firms when the expected fine is γf, we have that $y_i^a = \arg\max_{y_i} \left[\pi\left(y_i, \alpha_i, X\right) - rf\left(y_i - q\right)\right]$, $y_i^{b1} = \arg\max_{y_i} \left[\pi\left(y_i, \alpha_i, X\right) - \gamma f\left(y_i - q\right)\right]$, and $y_i^{b2} = \arg\max_{y_i} \left[\pi\left(y_i, \alpha_i, X\right) - f\left(y_i - q\right)\right]$. Consequently, the net expected profits associated with the harvest levels of the different strategies are so that $\Pi^a = \Pi^{b1} > \Pi^{b2}$.

This implies that $\beta^t \Pi_i^a \geq \beta^t \left[\left(1 - \nu_i(t)\right) \Pi_i^{b1} + \nu_i(t) \Pi_i^{b2}\right]$ for all t when $0 \leq \nu_i(t) \leq 1$. Hence, by equations (7) and (8) we have that

$$EV_i^a = \sum_{t=0}^{\infty} \beta^t \Pi_i^a \geq \sum_{t=0}^{\infty} \beta^t \left[\left(1 - \nu_i(t)\right) \Pi_i^{b1} + \nu_i(t) \Pi_i^{b2}\right] = EV_i^b.$$

Furthermore, from $\nu_i(1) = \gamma$, the second element of the right-hand side sum is $(1 - \gamma)\Pi_i^{b1} + \gamma \Pi_i^{b2}$, which is strictly smaller than the second element of the left-hand side sum $\beta \Pi_i^a$ if $\beta > 0$. Thus, the expected present value of strategy A is strictly larger than that of strategy B if $\beta > 0$, while $EV_i^a = EV_i^b$ only in the case of $\beta = 0$, that is, if the firm completely disregards the future. It follows that for $\beta > 0$, where EV_i^a is strictly greater than EV_i^b, there exists a value of $r = \gamma + \epsilon$, where ϵ is a small positive constant, for which strategy A dominates for all firms. Thus, with self reporting and differentiated inspection rates it is possible to reduce illegal catches slightly, without exceeding the exogenous constraint on the imposed fine or the inspection budget. Since all firms choose strategy A, no firms enter group 2, and hence total inspection costs equals $c\gamma n$. Furthermore, since all firms self report all quantities in excess of quotas and pay rf per unit, firms' optimal harvest quantities ensure that all firms face the same marginal shadow cost of harvesting in equilibrium. Consequently, the aggregate harvest reduction is allocated efficiently across firms. $\square$

Corollary 1. *In the situation specified in proposition 1, an enforcement system with self reporting and differential inspections allocates a reduction in aggregate harvest* *more efficiently than what is possible with a differentiation of inspection rates under the traditional enforcement system.*

Corollary 2. *In the situation specified in proposition 1, an enforcement system with self reporting and differential inspections allocates a reduction in aggregate harvest more efficiently than differentiated inspection rates under the traditional enforcement system* ($\beta = 0$)*.*

Proof. From proposition 1 it follows that the self-report based enforcement system with differentiated inspections allocates the reduction efficiently. Hence, no other enforcement system can allocate a reduction more efficiently. Furthermore, any reduction in aggregate catch resulting from a differentiation of inspection rates under the traditional enforcement system implies a corresponding differentiation of expected fines. Since any differentiation of expected fines results in an inefficient allocation of aggregate catch, such allocation must be strictly less efficient than the allocation implemented by the enforcement system with self reporting and differentiated inspections. ☐

Proposition 2. *When some firms under the traditional enforcement system do not violate quotas, there generally exists an enforcement system based on self reporting and differentiated inspection rates that implements the same aggregate harvest target more efficiently without increasing the inspection budget of the enforcement agency.*

Proof. Consider the same differentiated inspection system as above, with inspection rates $\gamma_1 = \gamma$ and $\gamma_2 = 1$ and with a self-report rebate factor of $r = \gamma$. From the proof of proposition 1 it is clear that $EV_i^a > EV_i^b$ for all firms that violate their quotas when $\beta > 0$. If the self-report rebate factor r is increased slightly, this will also be the case for $\beta = 0$. Thus, all firms that violate their quota will choose strategy A and self report their violations. Now, consider a quota reduction to the point where all firms choose to exceed their quotas. This results in aggregate harvest below the target. Next, reduce inspection rates in group 1 and increase the self-report rebate factor proportionally (reduce γ and r proportionally) until aggregate harvest again reaches the target level. The proportional reduction in γ and r will ensure the dominance of strategy A over strategy B so that all firms continue to follow strategy A. Since all firms exceed their quota and fully self report (i.e., remain in group 1), they all face the same marginal shadow cost of catch in equilibrium. Thus, the aggregate catch target under self-report based enforcement is implemented efficiently. By assumption, some firms are constrained by quotas and not fines under the traditional enforcement system. Hence, the aggregate harvest target under traditional enforcement is implemented inefficiently. Since all firms under the self-report based enforcement system choose strategy A, no firms enter group 2, and inspection rates in group 1 are reduced so that total inspection costs are reduced relative to the traditional enforcement system: $c\gamma n \leq C$. Thus, under the self-report based enforcement system, it is possible to reach the same aggregate production target more efficiently then under the traditional enforcement system and without exceeding the exogenous constraint on the fine with lower inspection costs. $\square$

It follows that irrespectively of how intensive quota regulation is under the traditional enforcement system (with uniform inspection rates), a shift to the proposed self-report based enforcement system will generally allow the regulator to increase welfare. Our focus is the situation where traditional quota regulation is no longer effective (covered by proposition 1 and its two corollaries). The advantages of the proposed enforcement system in this situation arise from the combination of differentiated inspection rates and the possibility to self report excess harvest. First, with two inspection groups, the risk of being moved to "control hell" increases expected punishment relative to the traditional compliance system without increasing inspection costs. Second, self reporting in effect allows the regulator to use the self-report rebate factor rather than the harvest quota as the control variable when implementing the aggregate harvest target, which ensures efficient allocation of total harvest quantity across heterogenous firms. This is why reducing aggregate catch by shifting to an enforcement system with self reporting and differential inspections results in a strictly greater welfare increase then would result from any possible differentiation of inspection rates within the traditional enforcement system.

4 An Example

In the previous sections we showed that the proposed enforcement system based on self reporting and differentiated inspections generally is better than the traditional enforcement system. We now illustrate this by looking at an example and numerically simulate equilibrium effects under different combinations of key parameters characterizing the enforcement problem. The key parameter that we vary in the following is the growth rate of the fish stock, which has implications for the productivity of the fishing industry and thereby the required intensity of regulation.[16]

---

[16] The higher the growth rate, all else equal, the stronger the need for regulation and enforcement in order to maintain a certain stock level since the stock regenerates more slowly, while the incentives of the individual fishermen to harvest are unchanged.

4.1 Model specification

As above, there are n firms in the industry and the per-period extraction profit of firm i is given by the following quadratic functional form:

$$\pi(y_i, \alpha_i, X) = py_i - \frac{\alpha_i y_i^2}{2X}. \tag{10}$$

We assume the firm specific cost parameter α is uniformly distributed: $g(\alpha) = \frac{1}{\bar{\alpha}-\underline{\alpha}}$ for $\bar{\alpha} \geq \alpha \geq \underline{\alpha}$. A firm's revenue is given as the product of the fixed output price p and the quantity produced y_i. The cost function in (10) is increasing and convex in harvest quantity, and decreasing in the size of the fish stock X. Any price or cost differences between fish extracted legally and illegally are disregarded.[17]

Industry production is subject to the resource constraint:

$$\Delta X = F(X) - Y = hX\left(1 - \frac{X}{K}\right) - Y \tag{11}$$

where h and K, respectively, denote the intrinsic growth rate and the carrying capacity of the resource stock.

The objective is to compare different enforcement systems. To facilitate comparison we assume that the goal of the fishery manager always is to maximize sustainable yield. This means that discounting and costs are disregarded when determining the optimal catch and stock levels, and, consequently, the target equilibrium level is generally not economically optimal. We analyze implementation of the maximum sustainable yield (MSY) target under the traditional quota enforcement system and the proposed self-report based system, which are presented in what follows.[18]

Under *traditional enforcement*, the regulator chooses the quota Q and the inspection probability γ so as to achieve the aggregate catch target, which is enforced by imposing a given fine f through undifferentiated inspection ($n\gamma$ inspections). The inspection rate is constrained upward by the inspection budget. Firm profits depend on whether the firm complies with or violates the quota. A compliant firm's profit is given by (10)

---

[17] The analysis easily generalizes to the case of price and/or cost differences between legal and illegal extraction.

[18] We focus on steady states and do not analyze the dynamic trajectory toward steady state. However, the results presented in what follows generalize beyond the steady state and to other policy objectives than the MSY target, including that of maximizing economic yield (MEY). The MSY target was chosen for two reasons. First, it is the same for all modifications of the enforcement system and therefore facilitates comparison across systems. Second, it is easier to calculate than the MEY target and therefore allows us to focus more attention on the more important question of whether and to what degree the target is reached under different modifications of the enforcement system.

with $y_i \leq q$. If the firm violates the quota, the expected profits are reduced by the expected fine (cf. equation 4). The firms' profit maximizing harvest levels are easily derived by solving the profit maximizing problem for each value of α_i.[19] Aggregate harvest can then be calculated as the sum over all n firms.

Under *self-report based enforcement* we assume the regulator sets the quota q low enough so that it constrains all firms. This implies the quota constraint $q < \bar{q} \equiv \frac{pX}{\bar{\alpha}}$, where a quota below $\bar{q}$ induces all firms to exceed their quota. The question then is whether firms choose to self report. This depends on the size of the self-report rebate factor (r), the inspection probabilities (γ_1 and γ_2) and the time period the firm must remain in group 2 if inspected and found to have exceeded the quota without truthfully self reporting (u).

The fine f is exogenous. Let the inspection rate in group 2 be $\gamma_2 = 1$ and assume the inspection rate in group 1 is set so that the inspection budget is met. When all firms choose strategy A, this implies that γ_1 is equal to the number of inspections available under the budget constraint divided by the total number of firms. If some firms choose strategy B, the inspection rate in group 1 must be reduced not to exceed the inspection budget because of the higher intensity of inspections in group 2. No firm chooses strategy C. Hence, the problem of the regulator is to set the self-report rebate factor r to reach the aggregate catch target.

For ease of exposition, we assume the parameter u always can be set sufficiently high for no firm to prefer strategy B to strategy A.[20] Hence, u is chosen so that the following inequality holds: $\alpha_0 < \underline{\alpha}$, where α_0 is the value of α a firm is indifferent between strategies A and B. Hence, u is set high enough to ensure that all firms choose strategy A. Based on the reaction function of strategy A firms we can derive the aggregate catch response function (details are given in appendix A.2):

$$Y = \frac{nX\left(p - rf\right)}{\bar{\alpha} - \underline{\alpha}} \ln\left(\frac{\bar{\alpha}}{\underline{\alpha}}\right). \tag{12}$$

In steady state the aggregate catch must equal the natural growth of the fish stock (cf. equation 3). Setting $Y = F(X)$ and solving for the self-report rebate factor r yields:

$$r_o = \frac{1}{f}\left[p - \frac{h\left(1 - \frac{X}{K}\right)\left(\bar{\alpha} - \underline{\alpha}\right)}{n \ln\left(\frac{\bar{\alpha}}{\underline{\alpha}}\right)}\right]. \tag{13}$$

---

[19] For details, see appendix A.1.

[20] The derivation of aggregate catch as a function of policy parameters when strategy B cannot be excluded is shown in appendix A.2

Equation (13) gives the value of the rebate factor r that ensures an equilibrium aggregate catch level of $F(X) = Y$.[21] The optimal fine rebate factor r_o is seen to be increasing in the steady-state stock level (X), decreasing in the size of the fine (f), increasing in the output price (p), decreasing in the growth rate of the stock (h), and increasing in the degree of cost heterogeneity measured by the difference between the upper and lower bounds on the uniformly distributed cost parameter ($\bar{\alpha}$ and $\underline{\alpha}$). Recall that the lower the value of r the higher the value of the per unit rebate obtained by self reporting ones excess catches. To find the self-report rebate factor r that ensures that aggregate steady-state catches equal MSY, we can substitute for the maximum sustainable yield stock level, X_{msy}, in equation (13).

4.2 Enforcement system equilibria

We now specify parameter values to numerically analyze the equilibria of the two enforcement systems. Parameter values are given in table 2.

Table 2: Parameter values

Parameter	Value	Description
p	0.5	Price (per unit)
f	1	Fine (per unit)
$[\underline{\alpha}, \bar{\alpha}]$	$[75, 125]$	Interval, cost parameter α
n	100	Number of fishing firms
m	20	Total number of inspections given by budget
h	$[0, 1.0217]$	Interval, intrinsic growth rate of resource stock
K	500	Carrying capacity of fish stock

We consider a vector of different values of h, the intrinsic growth rate of the stock. We define required regulatory intensity (RRI) as an indicator of the level of enforcement required to maintain the stock at the target level (MSY). The required regulatory intensity is a function of the growth rate of the stock. The higher the growth rate, *ceteris paribus*, the less enforcement is needed to maintain a certain stock level since the stock replenishes itself faster thereby allowing for larger aggregate catches. Furthermore, we normalize the regulatory intensity to lie between zero and one. When the growth rate of the stock is at its highest ($h = 1.0217$), RRI is zero. As the growth rate

---

[21] Note that parameter values exist for which $r_o < 0$ or $r_o > 1$. However, assuming a profitable industry ensures $r_o > 0$. The constraint $r_o \leq 1$ can be violated at a high output price p or a large number of firms n, which implies a lower inspection rate for a given inspection budget. For the parameter values used in this example, the optimal rebate factor r_o is always feasible (i.e., $0 \leq r_o \leq 1$).

is gradually reduced from this point toward $h = 0$, the regulatory intensity gradually increases toward one. Formally, the required regulatory intensity is defined as follows:

$$RRI = 1 - \frac{h - \underline{h}}{\bar{h} - \underline{h}},$$

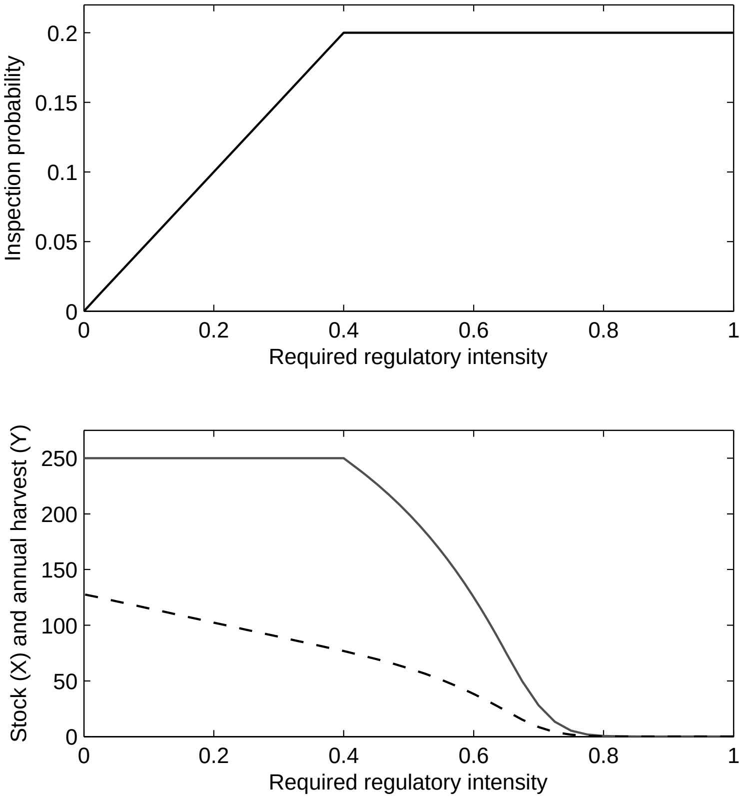
where $\bar{h}$ and $\underline{h}$ are the upper and lower values considered of the intrinsic growth rate. The upper value $\bar{h} = 1.0217$ is chosen as the value that yields equilibrium aggregate catch equal to MSY under open access (no enforcement). In that particular case MSY is 124.515 units of fish ($MSY = \frac{hK}{4}$). The lower the intrinsic growth rate relative to this point, the lower the MSY and the higher the RRI. Notice that the MSY stock level is independent of the growth rate of the stock and therefore equal to $X_{msy} = \frac{K}{2} = 250$ for all h.

We start out analyzing *traditional enforcement*. With a given inspection budget and a fixed cost per inspection, the regulator can perform a total of $m = 20$ inspections per period. Without differentiation in inspections across firms, this gives a probability of inspection of $\gamma = \frac{m}{n} = 0.20$ for each firm. With fines given exogenously, the regulator has two instruments that can be used to reach the MSY target; namely the size of the quota and the inspection rate, with the latter constrained to $\gamma \in [0, 0.20]$. To minimize enforcement costs, the regulator always chooses the lowest possible inspection rate γ in cases where there is a trade-off between setting a lower quota and a higher inspection rate.

The steady-state equilibrium under traditional enforcement as a function of RRI is shown in figure 1. As the RRI increases from zero (where MSY is reached without regulations), a steady increase in the inspection rate γ is required to maintain the equilibrium at the MSY level. The problem under traditional enforcement is that the inspection rate cannot exceed $\gamma = 0.20$, due to the inspection budget constraint. Therefore, as the RRI exceeds 0.40 (or for growth rates $h < 0.61$), it is not possible to reach the target steady state of MSY. For fisheries with lower growth rates the regulator cannot reach the target stock and aggregate catch levels without violating the budget constraint. This is evident in the lower panel of figure 1. As the RRI approaches one (i.e., stock growth rate decreases toward zero), the equilibrium stock and aggregate catch approach zero because the inspection rate is too low.

Under *self-report based enforcement* the regulator has several additional instruments to control aggregate harvest. The number of periods a firm must be in control hell upon being apprehended for illegal fishing (u) is held constant in this example, but could have been used to affect aggregate harvest. In addition, the regulator can vary the self-report rebate factor r, the quota Q, and the inspection probabilities γ_1 and γ_2. Since

Figure 1: Equilibrium under traditional enforcement system as a function of RRI. *Inspection rate in upper panel, equilibrium stock (dashed line) and aggregate harvest in lower panel.*



we already assumed u was set sufficiently high to deter all firms from choosing strategy B, no firm will be in enforcement group 2 (control hell), and hence, no inspections are necessary in group 2. This leaves the regulator with the inspection rate $\gamma_1 = \gamma \leq 0.2$ in group 1, in addition to the quota and the self-report rebate factor, as the relevant policy instruments.

Recall that the total quota is set low enough for the quotas to binding for all firms. The threshold level for when the quota binds is $\bar{q} = \frac{hK(\bar{\alpha}-\underline{\alpha})}{4\bar{\alpha}n(\ln\bar{\alpha}-\ln\underline{\alpha})}$, which depends on, among other factors, the growth rate h. In the numerical analysis we set the quota to 80% of $\bar{q} \times n$, which means that we let the total quota increase with the growth rate h. Furthermore, we only consider self-report rebate factors r below 0.5, which is a requirement for firms to choose to self-report their excess catches.[22]

The regulator can calculate the optimal self-reporting rebate factor according to equation (13). The resulting r_o increases linearly with the RRI toward the upper limit

---

[22] From the optimality condition of strategy A firms, it is clear that unless $p > rf$, no firm would choose to self report.

of 0.5. The self-report based enforcement system is never constrained, and hence, the regulator can reach the objective of MSY regardless of the RRI. A condition for this to hold is that the regulator can in fact set u high enough to deter all firms from exceeding quotas without self reporting (strategy B). The more firms must pay per self reported unit, the higher u must be for this to hold, all else equal. If u is constrained, the self-report based enforcement system could reach a limit beyond which it is not possible to reach the steady-state target catch level. Nonetheless, the flexibility of the self-report based enforcement system is always greater than that of the traditional system.

Comparison of enforcement systems

Having characterized and analyzed the equilibria of the two enforcement systems over a range of RRIs, we turn to a comparison of the effectiveness and efficiency of the systems. We do this by calculating equilibrium welfare net of inspection costs for each enforcement system.[23] We consider two specification of the traditional enforcement system; the standard specification where everyone faces the same inspection rate and a scenario where the control agency has the ability to perfectly differentiate inspection rates across firms based on their cost efficiency.[24]

Results are summarized in table 3. The self-report based system is fully efficient and represents the first-best solution. Traditional enforcement with a uniform inspection rate is efficient when a relatively little enforcement is necessary to maintain the fish stock at target (MSY) levels (low RRI). As the RRI increases beyond 0.40, the traditional system becomes less and less efficient relative to the self-report based system. The inspection budget constraint has been reached and the enforcement effort cannot be increased any further. As a result the equilibrium stock level is lower than the target, which reduces welfare. In contrast, the more flexible self-report based system is efficient over the full range of RRIs and generates considerably higher profits over

---

[23] Inspection costs are disregarded. This is because under self-report based enforcement, there is a trade-off between the inspection rate γ_1, and hence the inspection cost, and the number of periods a detected non-compliant firm must be in inspection group 2 u. Consequently, inspection costs under unconstrained self-report based enforcement can almost be fully eliminated if only u is increased sufficiently and the inspection rate is (marginally) larger than zero. This is not an option under traditional enforcement, where deterrence depends critically on the inspection rate and the fine payment if detected. Hence, by not deducting inspection costs from welfare, we underestimate the advantage of the self-report based system relative to traditional enforcement.

[24] Hence, we assume that the regulator can observe each firm's cost parameter α_i and that the firms know their respective inspection rates.

a large interval of RRIs (0.41-0.6).[25] For an RRI of 0.5, the traditional system only achieves 89.5% of the potential welfare while the equilibrium aggregate catch is 4.1% below the optimal (target) level. As the RRI increases, the gap between the outcomes under the traditional system and the self-report based system increases. For high values of RRI, that is, for slow growing species, traditional enforcement cannot prevent extinction.

As long as the RRI is low, it is optimal to let the inspection rate be the same for all firms in order to promote efficient allocation of aggregate catch. However, when the objective of MSY can no longer be achieved with an undifferentiated inspection rate ($\gamma_i = 0.2,\ \forall i$), illegal fishing can be reduced by increasing the inspection rates of the most cost efficient firms, while reducing the inspection rates facing the least efficient firms. We explore this possibility by introducing perfect differentiation of inspection rates under the traditional system.[26]

The numerical analysis shows that with perfectly differentiated inspection rates, the MSY catch target can be achieved for RRIs below 0.47, compared to 0.41 with a uniform inspection rate. By targeting those firms that have the highest sensitivity to changes in expected punishment (i.e., the most cost efficient firms), the regulator can reach the catch target for a wider range of RRIs. However, this reduces the cost efficiency of the fleet because it causes inefficient allocation of catches across firms. This results in a loss of welfare even if aggregate catch levels are close to or at the target level. Hence, under perfect differentiation of inspection rates the loss in welfare comes from two sources; lower yields and inefficient allocation of catches across firms. This is illustrated in table 3, where aggregate catch levels under traditional enforcement for RRIs of 0.4 and 0.5 are higher when inspection rates are perfectly differentiated, while welfare levels are considerably lower. For an RRI of 0.5, the regulator almost achieves the catch target using perfect differentiation of inspection rates (99.4%). However, the inefficient allocation of catches causes a significant reduction in welfare (33.7% reduction compared to first-best solution).

Thus far, we have shown that self-report based enforcement is always at least as efficient as the traditional system. The the RRI is relatively low little is gained from introducing the self report based system. If, on the other hand, the need for enforcement is high relative to the available enforcement resources, the potential gains from intro-

---

[25] If we also account for inspection costs, the self-report based system is superior to the traditional system over whole interval of RRIs, since the inspection rate under self-reporting can always be reduced slightly compared to the traditional system, by increasing u.

[26] This represents the best possible outcome in terms of achieving the MSY target by use of differentiated inspection rates. In real industries, regulators do not have perfect information on firm-level costs and must settle with imperfect differentiation of inspection rates.

Table 3: Equilibrium welfare and yield for different RRIs by enforcement system. *Outcomes relative to first best solution (100 = optimal).*

RRI	0.40		0.50		0.60		0.74	
	Welfare	Yield	Welfare	Yield	Welfare	Yield	Welfare	Yield
First best solution	26.83	76.66	23.96	63.88	20.44	51.11	14.45	33.22
Outcome by scenario								
Trad., uniform insp.	100	100	89.5	95.9	65.7	75.1	5.8	7.3
Trad., diff. insp.	100	100	66.3	99.4	55.2	88.3	0	0
Self reporting	100	100	100	100	100	100	100	100

ducing the self-report based system are considerable. The above analysis was based on the assumption that u, the number of periods a detected violator must spend in group 2 (control hell), can be chosen freely. In real-world resource management, u is likely to be constrained. We therefore conclude this section by investigating the implications of imposing an upper limit on the enforcement parameter u.

When u is constrained, it is no longer necessarily the case that all firms choose strategy A (self reporting). As long as some firms choose strategy B, these firms will be moved back and forth between inspection groups 1 and 2, depending on whether their quota violations are detected and the time period they must spend in group 2 once detected, u. If u is constraint to 1, 2 or 3 years, respectively, a strategy B firm spends 83.33%, 71.43% and 62.50% of the time in group 1 in the long run. Assuming that the number of firms is sufficiently large, we can interpret these numbers as the shares of strategy B firms in groups 1 in equilibrium. This is used to calculate aggregate catches under the constrained self-report based enforcement system.

Our numerical results show that self-report based enforcement is considerably less flexible when u is constrained. The lower the upper limit on u, the smaller is the interval of RRIs over which the enforcement system is capable of reaching the target harvest level. The constrained self-report based enforcement system can maintain the target equilibrium level for RRIs above 0.41 ($u = 3$), 0.42 ($u = 2$) or 0.43 ($u = 1$).[27] The RRI at which the constrained enforcement system no longer can achieve the harvest target is basically the same as the point where the traditional system fails to achieve the target. Hence, if the degree of punishment in "control hell" is constrained, the flexibility of the

---

[27] To improve the performance of a constrained self-report based system we can introduce quota reductions for firms in group 2. In the current analysis we have assumed no quota reductions in group 2. In general, any strategy can be used that makes "control hell" more hellish and thereby further deters firms from choosing strategy B.

self-report based enforcement system is considerably reduced. However, as we proved in the theoretical analysis, the self-report based system is at least as efficient as the traditional system when the latter is limited by the inspection budget constraint.

5 Concluding Remarks

In this paper, we present an alternative enforcement system for quota regulated resource industries. The system is based on self reports of catches in excess of quotas and differentiated inspection rates based on firms' compliance records. We show how the proposed enforcement system can increase both the efficiency and the effectiveness of quota enforcement compared to the traditional enforcement system without self reports or (explicit) differentiation in inspection rates. The efficiency is increased as the proposed system ensures an efficient allocation of aggregate catch across firms and can reduce the inspection costs compared to the traditional enforcement system. The effectiveness is increased as the self-report based system can reach a wider range of target aggregate catch levels than the traditional system.

The regulatory situation we address is one where there are significant problems of non-compliance with quotas. In addition, the punishment for quota violations as well as the inspection budget are constrained. Under the traditional enforcement system, once the constraints are binding further quota reductions are ineffective, as they cannot be enforced (all or most firms violate their quotas). In some fisheries, the enforcement agencies may try to address this issue by targeting inspections on vessels with poorer compliance histories. However, whether this increases or decreases enforcement effectiveness depends on the cost structure of the regulated fishing industry, but the allocative efficiency will in any event be reduced.

Instead we suggest an explicit and well-defined differentiation of inspection rates contingent on correct self reporting of quota violations. Rather than targeting inspections on firms that the control agency perceives as more reactive to expected fines (i.e., more likely to violate quotas), our proposed differentiation system introduces the threat of a “control hell” to all firms. Any firm that is detected violating its quota without having correctly reported this will face higher inspection rates than other firms for a given period of time. This threat strengthens the violation deterrence. Furthermore, by relying on self selection through the self-reporting component, our system can increase the effectiveness of inspections without prior information about individual firms' responsiveness to incentives.

The analysis of our reformed quota enforcement system implies a shift in focus away from inducing quota compliance *per se*, toward inducing correct self reports of catches in excess of quotas. Correct self reporting increases the allocative efficiency compared to quota compliance. This is why the increase in effectiveness under our reform of the enforcement system can be achieved without reducing the allocative efficiency.

Under the self-report based enforcement system, firms that exceed their quotas and self report pay a fixed fee per unit excess catches. Hence, the self-report based system resembles a management system with a combination of catch quotas and landing fees. Furthermore, even though the initial allocation of quotas is not so that the most efficient firms are allocated more, as long as the firms choose to exceed their quota and correctly self report, the firms will choose their catch levels so that they all face the same marginal shadow price of catches. Hence, the aggregate catch will be allocated efficiently across firms regardless of the initial distribution of quota units.

We presented a numerical example that demonstrates these improvements, as well as possible limitations of the proposed enforcement system. The main limitation of the self-report based system is that its ability to increase the range of steady-state aggregate production targets depends on political constraints, such as the time period violating firms can be sentenced to spend in the high inspection group.

The focus on ensuring correct self reporting of violations implies a number of other advantages not captured by our analysis. First, as pointed out by Innes (2001), once regulated firms correctly self report, they no longer have an incentive to avoid inspections. In many fisheries there may be significant avoidance opportunities and consequently the costs of avoidance and combating avoidance may be substantial (Anderson & Lee, 1986; Milliman, 1986). The welfare effect of not incurring such costs may be substantial, which further increases the relative efficiency of the proposed enforcement system. A second advantage is in terms of reduced risk for firms. As noted by Kaplow & Shavell (1994), risk-bearing costs are eliminated under self reporting, which is relevant if fishing firms are risk averse. A third advantage is the possibility of increased precision in catch and stock estimates when firms report their actual catches. The value of decreased measurement error depends on the characteristics of the resource, but can be significant. Hence, in addition to the advantages we have focused on in the paper, the proposed self-report based enforcement system have several other advantages compared to the traditional enforcement system that further increase the potential welfare gain.

References

Agnew, D., Pearce, J., Pramod, G., Peatman, T., Watson, R., Beddington, J., & Pitcher, T. (2009). Estimating the worldwide extent of illegal fishing. *PLoS ONE*, 4(2), e4570.

Anderson, L. & Lee, D. (1986). Optimal governing instrument, operation level, and enforcement in natural resource regulation: the case of the fishery. *American Journal of Agricultural Economics*, 68(3), 678–690.

Anton, W., Deltas, G., & Khanna, M. (2004). Incentives for environmental self-regulation and implications for environmental performance. *Journal of Environmental Economics and Management*, 48(1), 632–654.

Charles, A. T., Mazany, R. L., & Cross, M. L. (1999). The economics of illegal fishing: A behavioural model. *Marine Resource Ecnomics*, 14, 95–110.

Chavez, C. & Salgado, H. (2005). Individual transferable quota markets under illegal fishing. *Environmental and Resource Economics*, 31, 303–324.

Greenberg, J. (1984). Avoiding tax avoidance: A(repeated) game-theoretic approach. *Journal of Economic Theory*, 32(1), 1–13.

Hamilton, J. T. (1995). Pollution as news: Media and stock market reactions to the toxics release inventory data. *Journal of Environmental Economics and Management*, 28(1), 98–113.

Harrington, W. (1988). Enforcement leverage when penalties are restricted. *Journal of Public Economics*, 37, 29–53.

Helland, E. (1998). The enforcement of pollution control laws: Inspections, violations, and self-reporting. *Review of Economics and Statistics*, 80(1), 141–153.

Heyes, A. & Rickman, N. (1999). Regulatory dealing – revisiting the [h]arrington paradox. *Journal of Public Economics*, 72(3), 361–378.

Innes, R. (1999). Remediation and self-reporting in optimal law enforcement. *Journal of Public Economics*, 72(3), 379–393.

Innes, R. (2001). Violator avoidance activities and self-reporting in optimal law enforcement. *Journal of Law, Economics, and Organization*, 17(1), 239.

Kaplow, L. & Shavell, S. (1994). Optimal law enforcement with self-reporting of behavior. *The Journal of Political Economy*, 102(3), 583–606.

Konar, S. & Cohen, M. (1997). Information as regulation: The effect of community right to know laws on toxic emissions. *Journal of Environmental Economics and Management*, 32(1), 109–124.

Livernois, J. & McKenna, C. (1999). Truth or consequences-enforcing pollution standards with self-reporting. *Journal of Public Economics*, 71(3), 415–440.

Macho-Stadler, I. & Pérez-Castrillo, D. (2006). Optimal enforcement policy and firms' emissions and compliance with environmental taxes. *Journal of Environmental Economics and Management*, 51(1), 110–131.

Malik, A. (1993). Self-reporting and the design of policies for regulating stochastic pollution. *Journal of Environmental Economics and Management*, 24(3), 241–257.

Milliman, S. (1986). Optimal fishery management in the presence of illegal activity. *Journal of Environmental Economics and Management*, 13(4), 363–381.

Russell, C. (1990). Monitoring and enforcement. In P. Portney (Ed.), *Public policies for environmental protection* (pp. 243–274). Washington DC.

Sandmo, A. (2000). *The public economics of the environment*. Oxford: Oxford University Press.

Short, J. & Toffel, M. (2008). Coerced confessions: Self-policing in the shadow of the regulator. *Journal of Law, Economics, and Organization*, 24(1), 45–71.

Sumaila, U. R., Alder, J., & Keith, H. (2006). Global scope and economics of illegal fishing. *Marine Policy*, 30, 696–703.

Sutinen, J. G. & Andersen, P. (1985). The economics of fisheries law enforcement. *Land Economics*, 61(4), 387–397.

APPENDIX

A Deriving aggregate catch levels

A.1 Traditional enforcement system

Profits for compliant and non-compliant firms are given by equations (10) and (4). By solving the profit maximization problem of the firm for any value of α_i, it can be shown that firm level harvests are:

$$y_i^* = \begin{cases} \min\left(\frac{pX}{\alpha_i}, q\right) & \text{for } \alpha_i \geq \hat{\alpha} \\ \frac{X}{\alpha_i}(p - \gamma f) & \text{for } \alpha_i < \hat{\alpha}, \end{cases} \tag{A.1}$$

where $\hat{\alpha}$ is the value of the firm specific cost parameter α for which a firm would be indifferent between compliance and non-compliance.

A.2 Self-report based enforcement system

To calculate aggregate harvest as a function of the self-reporting rebate when firms choose strategies A and B, we start out by analyzing optimal firm-level behavior. We calculate optimal individual catches based on the assumption that firms seek to maximize profits. From the profit function specified above, optimal catches are as follows:

$$y_a^* = \frac{X}{\alpha}(p - rf) \tag{A.2}$$

$$y_{b1}^* = \frac{X}{\alpha}(p - \gamma_1 f) \tag{A.3}$$

$$y_{b2}^* = q, \tag{A.4}$$

where subscripts a, $b1$, and $b2$ denote a firm choosing strategy A (in group 1), a firm choosing strategy B currently in group 1, and a firm choosing strategy B currently in group 2, respectively. By substituting catch response functions from equations (A.2-A.4) into equation 3 and adjusting for the long-run shares of strategy B firms that are in groups 1 and 2, an expression for aggregate catch can be found.

We can now calculate the value of α for which a firm is indifferent between strategies A and B, which we denote α_0. Strategy B is relatively more attractive to more productive firms (low α_i) because their gains from not self reporting excess catches in group 1 are greater than for less productive firms (with high α_i). Thus, if some firms prefer strategy B to strategy A it must be firms with low values of α_i.

We now derive the value of α that makes a firm indifferent between strategies A and B, which we denote α_0. The present value of all future payoffs for a firm following strategy A is:

$$EV_a = \sum_{t=0}^{\infty} \beta^t \pi_a^* \left(\alpha_i, X\right), \tag{A.5}$$

which can be rewritten:

$$EV_a = \frac{\pi_a^* \left(\alpha_i, X\right)}{1-\beta}. \tag{A.6}$$

Correspondingly, the expected present value of all future payoffs for a firm following strategy B is:

$$EV_b = \sum_{t=0}^{\infty} \beta^t \pi_b^* \left(\alpha_i, X\right). \tag{A.7}$$

This can be rewritten as follows:[28]

$$\begin{aligned} EV_b &= \pi_{b1}^* \left(\alpha_i, X\right) + (1-\gamma_1)\beta EV_b + \gamma_1 \left(\sum_{t=0}^{u} \beta^t \pi_{b2}^* \left(\alpha_i, X\right) + \beta^{u+1} EV_b \right) \\ EV_b &= \frac{\pi_{b1}^* \left(\alpha_i, X\right) + \gamma_1 \left(\sum\limits_{t=0}^{u} \beta^t \pi_{b2}^* \left(\alpha_i, X\right) \right)}{1-(1-\gamma_1)\beta - \gamma_1 \beta^{u+1}}. \end{aligned} \tag{A.8}$$

The value of α_i that separates firms choosing strategy A from firms choosing strategy B can be identified by equating the present values of the two strategies ($EV_a = EV_b$) and is denoted α_0. We substitute in for the maximized profit functions, $\pi_a^* = \frac{X}{2\alpha}\left(p - rf\right)^2 + rfq$ and $\pi_{b1}^* = \frac{X}{2\alpha}\left(p - \gamma_1 f\right)^2 + \gamma_1 fq$, and obtain:

$$\frac{\frac{X}{2\alpha_0}\left(p - rf\right)^2 + rfq}{1-\beta} = \frac{\frac{X}{2\alpha_0}\left(p - \gamma_1 f\right)^2 + \gamma_1 fq + \gamma_1 \sum\limits_{t=0}^{u} \beta^t \left(pq - \frac{\alpha_0 q^2}{2X}\right)}{1-(1-\gamma_1)\beta - \gamma \beta^{u+1}}$$

Rearranging the expression yields the following second order equation in α_0:

$$\begin{aligned} &\alpha_0^2(1-\beta)\gamma_1 \sum_{t=0}^{u} \left(\frac{\beta^t q^2}{X}\right) - 2\alpha_0 \left[\gamma_1(1-\beta)\left(fq + \sum_{t=0}^{\infty} \beta^t pq\right) - rfq\left(1-(1-\gamma_1)\beta - \gamma_1\beta^{u+1}\right)\right] \\ &+X\left(p - rf\right)^2\left(1-(1-\gamma_1)\beta - \gamma_1\beta^{u+1}\right) - X\left(p - \gamma_1 f\right)^2(1-\beta) = 0 \end{aligned} \tag{A.9}$$

---

[28] We assume that firms take the current level of the stock, as well as all policy variables, as given when considering future operations and profits.

Solving equation (A.9) gives the following:

$$\alpha_0 = \frac{-B + \sqrt{B^2 - 4AD}}{2A}, \tag{A.10}$$

where A , B and D are defined as follows:

$$\begin{aligned} A &= (1-\beta)\gamma_1 \sum_{t=0}^{u} \left(\frac{\beta^t q^2}{X} \right), \\ B &= 2 \left[rfq \left(1 - (1-\gamma_1)\beta - \gamma_1 \beta^{u+1}\right) - \gamma_1 (1-\beta) \left(fq + \sum_{t=0}^{\infty} \beta^t pq \right) \right], \\ D &= X \left(p - rf\right)^2 \left(1 - (1-\gamma_1)\beta - \gamma_1 \beta^{u+1}\right) - X \left(p - \gamma_1 f\right)^2 (1-\beta). \end{aligned}$$

Finally, under the assumption that u can be set high enough to ensure that all firms chose strategy A, we can calculate aggregate catch response function. We use the reaction function of strategy A firms from equation (A.2). In addition we know the probability density function of the uniformly distributed variable α, which is $\frac{1}{\bar{\alpha}-\underline{\alpha}}$ (for $\underline{\alpha} \leq \alpha \leq \hat{\alpha}$). Given that there is a continuum of firms, total catches can be expressed as:

$$Y = nX \left(p - rf\right) \frac{1}{\bar{\alpha} - \underline{\alpha}} \int_{\underline{\alpha}}^{\bar{\alpha}} \frac{1}{\alpha} d\alpha \tag{A.11}$$

By solving the integral and rearranging, the aggregate catch response function becomes:

$$Y = \frac{nX \left(p - rf\right)}{\bar{\alpha} - \underline{\alpha}} \ln \left(\frac{\bar{\alpha}}{\underline{\alpha}} \right). \tag{A.12}$$