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Discussion paper

# Quota Enforcement and Capital Investment in Natural Resource Industries

BY  
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# Quota Enforcement and Capital Investment in Natural Resource Industries\*

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## Abstract

We investigate the relationship between quota enforcement, compliance, and capital accumulation in ITQ regulated fisheries. Over-extraction and over-capacity represent two of the main fisheries management challenges, and we aim to model and analyze the two jointly. In a stylized resource model, quota violating and complying firms invest in capital, buy quotas, and choose their harvest. We show that in the short run, more capacity increases illegal extraction, while a well-functioning quota market partially alleviates this effect. We also show how tougher enforcement yields a double benefit by directly improving compliance, and by indirectly reducing incentives to invest in capacity, which improves future compliance. Our analysis thus contributes to the literature on market-based management of renewable resources.

**Keywords:** Compliance; Excess capacity; Enforcement; ITQs; Resource management.

**JEL Classification Codes:** Q0, Q2, Q22, Q28

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# 1 Introduction

Fisheries face two main challenges; over-extraction and over-investment in fishing capacity. Economists generally argue in favor of market-based instruments to resolve these issues. Catch share systems such as individual transferable quotas (ITQs) are becoming increasingly popular worldwide in both developing and developed countries worldwide.<sup>1</sup> Tradable quotas are popular in resource management because they assign property rights to extraction shares and correct firms' incentives to over-extract and over-invest. While this holds with perfect quota enforcement, full compliance is rarely feasible in reality. When firms violate quotas, the quota instrument only resolves the externality problem imperfectly. In this paper, we first investigate the linkages between quota enforcement, capacity, and the tradability of quotas, to better understand the limitations of individual property rights. Next, we analyze how stricter enforcement affects quota compliance and investment in production capacity.

Capital stuffing and non-compliance characterize many fisheries and other resource industries. Agnew et al. (2009) estimate that 20% of global fish catches are illegal or unreported, but with significant differences across regions, species, and over time. The quota compliance problem has been extensively analyzed in the fisheries economics literature (see, for example, the survey by Nøstbakken, 2008).<sup>2</sup> Excess capacity constitutes another major issue. The evolution of capacity in global fisheries has received considerable attention in the literature since the early 1990s,<sup>3</sup> and there are still numerous examples of fisheries with significant excess capacity (UNEP, 2010). Resource managers try to correct these issues with regulations, such as by introducing individual property rights to catch shares (see Costello et al., 2008).

We develop our results in a stylized model of firms operating in a single-species fishery

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<sup>1</sup>There is also considerable interest in group property rights, which have been applied in many fisheries. See Deacon (2012) for a recent overview.

<sup>2</sup>There is also a large related literature analyzing enforcement of emission permits (see, for example, Livernois & McKenna, 1999; Dhanda & Stranlund, 1999; Heyes, 2000; Stranlund et al., 2002).

<sup>3</sup>See for example the work by Squires and co-authors, including Segerson & Squires (1990); Squires (1987, 1992)

regulated with tradable catch quotas (ITQs). Profit maximizing firms decide how much to invest, harvest, and how much quota to buy. Their production possibilities (capacity) depend on the capital stock, which they cannot change in the short run.<sup>4</sup> A firm's capital stock, in turn, affects its short-run variable costs, and therefore, its profit maximizing production and quota level.

We first derive the relationship between quota violations and production capacity. We find that the firm's optimal level of capital depends on how costly it is for the firm to violate the quota (expected penalty). The cheaper this is, the stronger the incentive to invest in capital, and hence, build up more fishing capacity. However, with a market for quotas, the adjustment in quota price may partially alleviate this issue. Furthermore, in the short run, when the firm's level of physical capital is fixed, the decision of whether to exceed quotas and by how much depends on current capacity: more capital yields stronger incentives to violate the quota.

Stricter enforcement directly affects the decisions of violating firms, including their quota demand, but does not directly affect compliant firms. With a significant level of quota violations in the industry, the increase in quota demand raises the market price of quotas, which affects the behavior of all firms. Hence, the quota market effect causes violating firms to share the impact of tougher enforcement with compliant firms, causing all firms to reduce their catch levels. In addition, we show that in the long run, this causes all firms to invest less in capacity. Thus, tougher enforcement yields a double benefit by reducing violations and investment today, and thereby also lowering the violations tomorrow. Hence, we show the existence of a strong relationship between quota violations, enforcement, and capital development in both the short and long run.

Our results have strong policy implications. First, we present a new argument in favor of

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<sup>4</sup>Capital stock measures are often used to measure potential output, as well as capacity utilization. This duality holds when the capacity to capital stock ratio is constant (Berndt & Fuss, 1989; Kirkley et al., 2002).

tradable quotas since the quota market can partially alleviate the compliance problem in an industry characterized by excess capacity. Second, we show how stricter enforcement pays off in ways not previously considered. In addition to reducing violations in the short run, stricter enforcement weakens firms' incentives to build up excess capacity, which in turn increases quota compliance in the long run. In contrast to previous work, we are able to theoretically account for these additional effects of enforcement by considering the interaction between quota compliance and investment in production capacity.

Our paper relates to studies of regulatory enforcement and excess-capacity in natural resource industries. While these issues have been studied extensively, previous work treats each issue separately.<sup>5</sup> In contrast, we study these issues jointly. In particular, this paper closely relates to Chavez & Salgado (2005) who analyze the efficiency of property rights to manage fisheries under imperfect enforcement. Their focus is on how enforcement and compliance might challenge the performance of property rights in fisheries. Our paper extends this work by also analyzing the role of capacity, and the linkages between quota enforcement and capacity. The close relationship between quota violations and excess-capacity is particularly relevant for the fisheries case since over-extraction and excess capacity characterize this industry globally (Arnason et al., 2009). Our work also relates to Charles et al. (1999) who analyze firm-level fishing and compliance behavior under different types of regulations. However, they do not consider the case of transferable quotas.

While we use the fishery as our primary example in this study, the establishment of individual property rights to catch shares are key in resource management also beyond the case of fisheries. Tradable permits restrict extraction of resources such as emissions (or

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<sup>5</sup>Some studies in the regulatory enforcement literature allude to the linkages between enforcement and firm-level characteristics, such as excess capacity. For example, Stranlund & Dhanda (1999); Murphy & Stranlund (2007) study what type of firms regulators should target to increase enforcement effectiveness, and find that this effectiveness is independent of exogenous firm characteristics in emission trading programs. The difference between our paper and theirs is that we jointly investigate non-compliance and excess capacity, while they focus on how to reduce non-compliance given fixed firm characteristics.

the use of clean air), forestry, minerals and metals, petroleum, and water.<sup>6</sup> The cap-and-trade system is well known when managing pollution externalities. Tradable property rights are implemented in forest management for example in Canada (Burton et al., 2003). Oil producing firms in the United States operate with firm-level production quotas (see Libecap & Wiggins, 1984, on prorationing). Finally, transferable water rights are important to ensure efficient water usage (Griffin & Hsu, 1993; Rosegrant & Binswanger, 1994). However, just like in the fisheries case, such individual property rights schemes only ensure efficient resource use under perfect enforcement. In reality, perfect enforcement is rarely possible or even desirable for a regulator or enforcement agency. In this paper, we analyze the implications of non-compliance in such settings, and focus particularly on the role of the quota market. While we analyze the case of the fishery, our framework can easily be applied to other resource industries.

In the next section, we present our stylized resource extraction model. Section 3 describes the relationship between compliance and capacity in the short run, while section 4 analyzes the role of enforcement for both quota compliance and long-run capital accumulation. We present our conclusions in the last section.

## 2 A stylized resource extraction model

We develop a stylized model to illustrate the relationship between quota enforcement and capital accumulation in a resource industry. While our framework is general and applicable to many quota regulated industries, we use the fishery as an example. In quota regulated fisheries, the regulator establishes property rights to catch shares (quotas), which are allocated to firms. We start by analyzing individual firm behavior in this framework. Next, we

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<sup>6</sup>For example, Tietenberg (2003) reviews the application of tradable permits to air-pollution control, water supply, and fisheries.

analyze the relationship between quota enforcement, extraction, and capacity development, focusing on the role of the quota market.

Each firm's catch and profit depend on its production capacity and quotas.<sup>7</sup> A firm's production depends on the physical capital level ( $K$ ) and variable inputs ( $L$ ).<sup>8</sup> We assume a homogeneous and single aggregate capital stock for the firm. Hence, the production function is given by  $Y = F(K, L)$ , where we assume a constant production technology, and a constant relationship between the firm's capital stock and its fishing capacity. For simplicity, we consider a single-species fishery where each firm extracts one ITQ-regulated species. The production function  $F(K, L)$  is increasing in the two inputs ( $F_K > 0, F_L > 0$ ), but at a decreasing rate ( $F_{KK} < 0, F_{LL} < 0$ ). While both inputs are necessary for production, they can be substituted for each other. Firms are price takers in all markets, and the price of capital is  $r > 0$ , the price of variable inputs is  $w > 0$ , and the market price of quota is  $a$ .<sup>9</sup> Furthermore, we assume the industry consists of heterogeneous firms that differ only in production costs (efficiency).

While firms can quickly adjust their use of variable inputs, and thus their production level, the capital level is fixed in the short run. On this basis, we can define the short-run variable cost function,  $C(Y, k)$ , which relates the cost of variable inputs to the level of production,  $Y$ , given the fixed, short-run level of capital,  $k$ . In the long run, the firm can adjust both  $L$  and  $K$ . The general production function discussed above is concave, which implies a convex cost function in production. Furthermore, costs decline at a decreasing rate in physical capital ( $C_K < 0, C_{KK} > 0$ ), are increasing and convex in production ( $C_Y > 0$ ,

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<sup>7</sup>We consider a perfect quota market in what follows, which is equivalent to having a rental market for quotas. Because non-compliance is an issue only when the quota binds, we focus on this case only.

<sup>8</sup>This implies that a firm's production is independent of the resource stock. Furthermore, we abstract from resource dynamics, which is reasonable when the quota system ensures a stable stock size and stock availability affects all firms in the same way.

<sup>9</sup>The assumption of a fixed price of capital requires perfect capital markets. In some industries, this might be a strong assumption due to the non-malleability of capital (Clark et al., 1979). For tractability, however, we abstract from the case of non-malleable capital, but our main results would hold also in this case.

$C_{YY} > 0$ ), and the marginal cost is decreasing in capital ( $C_{YK} < 0$ ).<sup>10</sup> The cost function is concave in input prices. These characteristics satisfy the free disposal property and guarantee a well-behaved cost function. We introduce firm-level heterogeneity in costs by assuming the following firm-specific variable cost function:  $C_i(Y_i, K_i) = c_i D(Y_i, K_i)$ , where  $c_i$  is a firm-specific cost parameter that is inversely related to firm  $i$ 's productivity, while  $D(Y, K)$  is the common part of the cost function, which satisfies the same properties as  $C(Y, K)$ . To analyze aggregate market effects, we make the additional assumption that there is a unit mass of heterogenous firm, with uniformly distributed cost parameters,  $c_i$ .

We assume a perfectly competitive quota market without transaction costs and financial constraints. In such market, we know from the Coase theorem that the post-trade quota allocation is independent of the initial allocation of quotas. We therefore disregard the pre-trade quota allocation by assuming that firms purchase a given number of harvest quotas from a regulator.<sup>11</sup> The market price of quotas,  $a$ , is the price that clears the market by ensuring that the aggregate quota demand exactly equals the number of quotas available. This price is taken as given by the firms. Absent a quota market, we assume that each firm has an exogenously given quota allocation, which they can use free of charge.

When firms comply with the quota, the extraction rate  $Y$  equals the quota:  $Y = Q$ . However, perfect enforcement is often very costly, implying that regulators choose to enforce property rights imperfectly (Polinsky & Shavell, 1979).<sup>12</sup> With imperfect quota enforcement, some firms will exceed their quotas at the risk of detection and punishment, with inspection (and detection) probability  $\gamma \in [0, 1]$ . The punishment if detected is given by a continuous, twice-differentiable and convex penalty function  $P(Y, Q)$ , which satisfies the following prop-

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<sup>10</sup>Convexity of the cost function requires an output elasticity of variable inputs below one.

<sup>11</sup>In real-world ITQ fisheries, fishing firms often obtained quota free of charge based on historical catch levels. Later they can adjust their quota holdings by buying and selling quotas in the quota market. However, absent transaction costs, our results are independent of how and to whom quotas are allocated initially.

<sup>12</sup>As the expected punishment increases, the imperfect enforcement case approaches that of perfect enforcement since there is a point at which no firm finds it optimal to take the risk of detection and severe punishment.



erties for  $Y > Q$ :  $P_Y > 0$ ,  $P_Q < 0$ ,  $P_{YY} \geq 0$ ,  $P_{QQ} \geq 0$ ,  $P_{YQ} < 0$  (see e.g. Hatcher, 2005).<sup>13</sup> In addition, we assume the penalty is sufficiently high to fully deter violations when firms are inspected with certainty ( $\gamma = 1$ ). Finally, there is no penalty if a firm complies:  $P(Y, Q) = 0$  if  $Y \leq Q$ .

In appendix A.1, we analyze the special case of a penalty function that is linear in the absolute violation. This specification is commonly used in economic models of enforcement and compliance. As this analysis shows, applying a linear penalty function provides few new insights since it yields a corner solution in the ITQ case, where either all firms comply or all firms violate. Based on this, we move forward using a general, non-linear penalty function.

Given that firms are risk neutral, they seek to maximize expected profits net of fine payments. They choose capital investment, the use of variable inputs, and quota purchases to accomplish this. While capital is fixed in the short run and variable in the long run, firms can adjust their quota in both the short and the long run. This is appropriate since it typically takes longer to adjust the level of physical capital than to buy and sell (or lease) quotas in an efficient quota market. On this basis, we can specify a firm's maximization problem as follows:<sup>14</sup>

$$\max_{\{Y, K, Q\}} pY - C(Y, K) - rK - aQ - \gamma P(Y, Q), \quad (1)$$

where the output price  $p$  is constant, and the equilibrium quota price  $a$  is taken as given by the firm.<sup>15</sup> The last term is the expected punishment of violating the quota, which drops out if the firm complies.

Let us now characterize the solution to the optimization problem (1). We start out with the first-order condition for capital, which is independent of whether the firm complies with

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<sup>13</sup>If we also impose that  $\lim_{Q \rightarrow 0} P(Y, Q) \rightarrow \infty$ , no firm will produce without quota.

<sup>14</sup>Note that we suppress the firm index,  $i$ , when this is clear from the context.

<sup>15</sup>The term  $aQ$  drops out in the case of non-transferable quotas.

its quota:

$$-C_K = r. \quad (2)$$

This condition only applies in the long run, since in the short run, the firm's capital level is fixed at  $K = k$ . The optimal long-run capital level requires that the marginal reduction in variable costs from having more capital equals the unit price of capital.

The optimality condition for resource extraction ( $Y$ ) depends on whether the firm complies with its quota:

$$p - C_Y = \gamma P_Y \quad (\text{non-compliant}), \quad (3)$$

$$p - C_Y = a \quad (\text{compliant}). \quad (4)$$

Optimality condition (3) holds for quota violating firms. In this case, the optimal catch level requires that marginal extraction profit equals the marginal expected punishment. For a compliant firm, condition (4) states that the marginal extraction profit must equal the quota price. For the compliant firm, this condition also determines how much quota to buy, since compliance implies  $Y = Q$ .

For a violating firm, the following optimality condition determines how much quota to buy,  $Q$ :

$$a = -\gamma P_Q. \quad (5)$$

Hence, a violating firm should buy quotas until the marginal reduction in expected punishment from having more quota equals the quota price. Given the properties of the penalty function, equation (5) implies that the firm's quota demand is downward-sloping in the quota price  $a$ .

Let us consider the special case where the penalty depends (non-linearly) on the absolute quota violation,  $P(Y, Q) = P(Y - Q)$ , which implies that  $P_Y = -P_Q$ . If we impose this on

the first-order conditions of the violating firm (equations 3 and 5), we find that the optimal harvest level of both compliant and violating firms are given by the condition,  $P - C_Y = a$  (cf. equation 4). This does, however, not imply that compliant and violating firms choose the same harvest level. To see this, recall the firm-specific cost function,  $C_i(Y_i, K_i) = c_i D(Y_i, K_i)$ , which implies the following optimality condition for harvest:  $P - c_i D_Y = a$ . Based on this, and the properties of the cost function, it is clear that high-cost firms (high  $c_i$ ) will choose lower levels of harvest than more efficient firms (with lower  $c_i$ ). The same reasoning holds for the general penalty function.

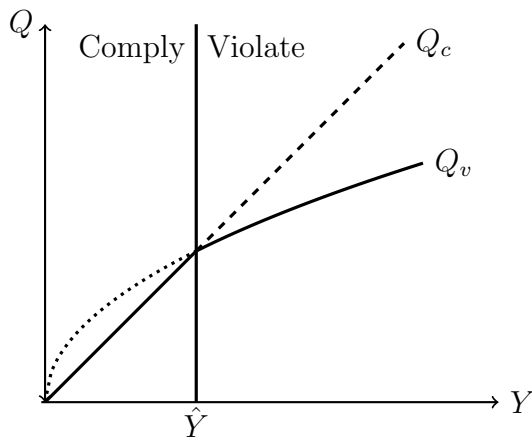


Figure 1: Comply or violate? A firm's quota level,  $Q$ , as a function of production,  $Y$ .  
*Note:  $Q_c$  and  $Q_v$  denote the optimal quota level as a function of harvest for a compliant and a violating firm, respectively.*

To summarize, firms base their production and compliance decision on maximization of expected profits, and a firm violates the quota if the payoff from doing so exceeds the (expected) costs. The more efficient the firm (low  $c_i$ ), the higher the payoff, and the more likely the firm is to violate its quota. This is illustrated in figure 1, which shows that the higher the (optimal) production level of a firm, the more likely the firm is to violate its quota. If the firm's optimal production level is  $\hat{Y}$ , it is indifferent between compliance and quota violation. Hence, the lower the cost of the firm,  $c_i$ , the higher its optimal harvest level, and the more likely the firm is to prefer quota violation to compliance.

### 3 Capacity and compliance

In this section, we analyze the *short-run relationship* between quota compliance and capital investment (capacity), focusing particularly on the role of the quota market. The quota market is key for a complete understanding of this relationship, because when quotas are tradable, a marginal change in industry-level fishing capacity might affect the quota price. Hence, we need to investigate both the direct effect of more capital on firms' production and on quota demand, and the indirect effect driven by the quota market response.

To analyze the implication of capital on production and compliance, we start out by taking the total derivative of firms' optimality conditions with respect to their fixed short-run level of capital,  $k$ . For a compliant firm, we totally differentiate condition (4), and the quota condition:  $Y = Q$ . Doing this and solving for the change in extraction and quota levels yield:<sup>16</sup>

$$\frac{dY_c}{dk} = -\frac{C_{YK}}{C_{YY}} - \frac{1}{C_{YY}} \frac{da}{dk}, \quad (6)$$

$$\frac{dQ_c}{dk} = \frac{dY_c}{dk}. \quad (7)$$

Note that the latter relationship holds because compliant firms harvest exactly their quota. We express the firm's behavior in terms of  $\frac{da}{dk}$ , since this effect, while taken as given by price taking firms, depends on the aggregate change in quota demand of all firms, compliant and violating. Let us for a moment investigate what happens absent a change in quota price ( $\frac{da}{dk} = 0$ ). Then, these equations show that a compliant firm increases its production and quota level in response to a marginal increase in the fixed, short-run capital level, since  $C_{YK} < 0$  and  $C_{YY} > 0$ . This is not surprising, as we know that more capital lowers the firm's variable extraction cost, which makes it profitable to produce more.

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<sup>16</sup>For details on the calculations, see Appendix A.2.

More short-run capital might also imply an increase in the number of violating firms because it strengthens the incentives to violate quotas. The marginally compliant firm, illustrated by the firm producing at  $Y = \hat{Y}$  in figure 1, will change its compliance behavior and become a quota violator with marginally more capital. Such firm responds to a higher capital level by increasing both its extraction and quota level. However, the effect of such firm's behavior on aggregate quota demand is negligible because of our assumption of a unit mass of firms with uniformly distributed individual cost parameters. For this reason, we ignore the effect on the marginally compliant firm in our discussion of quota market implications.

We now turn to the case of quota violators. Totally differentiating a violating firm's optimality conditions for production (3) and quota (5), and rearranging, yields:

$$\frac{dY_v}{dk} = \frac{C_{YK} - \frac{P_{YQ}}{P_{QQ}} \frac{da}{dk}}{\gamma \left( \frac{P_{YQ}^2}{P_{QQ}} - P_{YY} \right) - C_{YY}}, \quad (8)$$

$$\frac{dQ_v}{dk} = -\frac{1}{\gamma P_{QQ}} \frac{da}{dk} - \frac{P_{YQ}}{P_{QQ}} \frac{dY_v}{dk}. \quad (9)$$

Like before, we write these effects in terms of the quota market response,  $\frac{da}{dk}$ . As for the compliant firm, a violating firm's quota level depends on the production level. To understand how capital affects extraction (equation 8), note first that the denominator of this equation is negative. This follows from the assumption of a convex penalty function, and  $C_{YY} > 0$ . Next, since  $C_{YK} < 0$ , we find that without considering the effect of a quota price change, the violating firm's production level increases in  $k$ .

Equation (9) tells us that violating firms demand more quota as production increases. Hence, a higher short-run capital stock implies increased quota demand from violating firms. This result is in line with previous work on noncompliance that shows how the incentives to violate increase with the firm's payoff.

For the special case of the penalty that is a function of the absolute violation,  $P(Y - Q)$ , equations (8) and (9) reduce to:  $\frac{dY_v}{dk} = -\frac{C_{YK} + \frac{da}{dk}}{C_{YY}}$  and  $\frac{dQ_v}{dk} = -\frac{1}{\gamma P_{QQ}} \frac{da}{dk} + \frac{dY_v}{dk}$ . With a constant quota price, these equations imply that a violating firm's response to a marginal increase in the capital stock is to increase both production and quota levels by the same amount, thereby holding the absolute violation constant.<sup>17</sup> If instead  $|P_{YQ}| < |P_{QQ}|$ , which implies that the marginal penalty,  $P_Q$ , responds more to a unit reduction in illegal landing than to a unit increase in quota, the catch level of the violating firm increases more than the quota level. Hence, in this case, more capital will strictly increase these firms' absolute quota violations.

Finally, note that absent a quota market, firms are not able to obtain more quota, but more capital would nonetheless strengthen their incentives to increase production. For a compliant firm, this implies that the shadow price of the firm's quota constraint increases with its capital level, thereby making compliant firms more likely to become quota violators. Violating firms can increase production without obtain more quota, and hence, more capital will increase their violation also absent a quota market.

Without quota trade, the effects we have discussed above would be the full story. However, with a quota market, these effects only represent the first part of the story. We have established that in the short run, all firms will increase their production levels, and thus their quota demand, in response to a marginal increase in industry-level fishing capacity.<sup>18</sup> With the quota supply given, the market clearing condition implies an increase in the quota price to ensure that the aggregate quota purchase before and after the marginal change in capital remains the same. Hence, we have that  $\frac{da}{dk} \geq 0$ . This increase in quota price contributes to

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<sup>17</sup>Note that this is in line with the result of Dhanda & Stranlund (1999) for the case of tradable emissions permits.

<sup>18</sup>Note that a higher industry-level of fishing capacity might imply a lower price of capital. However, this does not affect our result since firms' short-run behavior is unaffected by the price of capital and the level of capital is fixed in the short run. In section 4, we discuss how such capital price response will affect our long-run results.

reducing the positive impact of capital on production (and quota purchase).

To see this, let us first consider compliant firms. According to equation (6), the direct effect of more capital is an increase in production. However, the effect of the quota price on production, and thus quota purchase, is negative, as captured by the last term of equation (6). Next, consider violating firms. We know that the denominator of (8) is negative. A higher quota price ( $\frac{da}{dk}$ ) thus reduces the positive effect of the capital stock on these firms' catch level. Equation (8) shows how an increase in quota price has a negative effect on the quota demand of violating firms. First, the quota price has a direct negative effect on the number of quotas that violating firms purchase. This is captured by the first term of equation (9). Second, there is an indirect effect of a higher quota price because it lowers production, thereby reducing the need for quotas, as captured by the last term of equation (9).

To summarize, our analysis shows how the quota market partially alleviates the incentives to increase production in response to a marginal increase in industry-level fishing capacity. The reason is that more capital in the short run lowers variable operating costs, which in turn yields a higher demand for quotas, and thus higher quota price. Next, more expensive quota reduces firms' incentives to produce more. Hence, the total effect on catches of more capacity at the industry level is lower with a quota market than without trade in quotas. The magnitude depends on several factors, including the sensitivity of quota demand to increased production, the exact distribution of cost parameters across firms, and current production and capital levels.

We also find that tradable quotas results in a higher share of non-compliant firms. Regardless of whether quotas are tradable, the share of non-compliant firms increases in response to a marginal increase in short-run industry-level capacity. However, with tradable quotas, the increase in quota price strengthens this effect, because low-cost firms that are more likely to violate also have a competitive advantage in the quota market. Hence, more

firms prefer violation to compliance. This result is summarized below:

**Result 1.** *The quota market response (higher quota price) counteracts the incentive to increase production in response to a marginal increase in industry-level capacity, but induces more firms to violate quotas.*

The main implication of result 1 is that property rights to quotas and well-functioning quota markets alleviate the negative effect of excess capacity on illegal production (quota violations). This is a new argument in favor of tradable quotas in resource industries such as fisheries. This is particularly relevant when enforcement and punishment levels are constrained. Note, however, that although quota trade reduces the aggregate level of illegal catches, it might also cause the number of compliant firms to fall and quota violators to account for a larger share of total extraction.

Excess capacity characterizes many fisheries and other natural resource industries. First, resource dynamics may be subject to significant natural fluctuations, which can cause fluctuations in the total quota. Consequently, fishing fleets may have excess capacity for periods of time when resource abundance and quotas are relatively low. Second, the race to fish and the history of regulations play an important role. Initially, most fisheries have few or no regulations, which leads to a race to fish and capital accumulation. By the time regulators remove the production externality, for example by introducing property rights to catch shares, there might already be large excess capacity present. When whole industries are characterized by over-capitalization, it might become difficult to sell off production capital. Hence, firms might have few incentives to disinvest and the economic lifetime of the capital determines when capital levels normalize. This implies that excess capacity caused by past regulations (or lack thereof) might affect incentives to comply with quotas for many years to come. Indeed, many fisheries are still characterized by significant over capitalization, even after decades of capacity reducing policies.



## 4 The role of enforcement

We now shift our focus from the short run to the long run. We investigate how a change in enforcement affects the long-run production, capital and compliance levels. To analyze the effect of stricter enforcement in the presence of a quota market, we must account for the quota price response and how it affects firm behavior. A change in the expected penalty for violating quotas affects behavior directly, but also indirectly through the response in the quota price, given that quota violations occur in the first place. We start out by analyzing the relationship between a firm's long-run level of capacity and quota enforcement, focusing on the impact of a marginal increase in the inspection rate,  $\gamma$ .

In the long run, firms can change their level of capital. The optimality condition for capital is the same for all firms, regardless of compliance behavior. Taking the total derivative of optimality conditions (2) with respect to  $\gamma$  yields:<sup>19</sup>

$$\frac{dK_j}{d\gamma} = -\frac{C_{YK}}{C_{KK}} \frac{dY_j}{d\gamma}, \quad j = c, v. \quad (10)$$

We see that the impact of enforcement on a firm's optimal capital stock has the same sign as the change in production. This is in line with the substitutability assumption between capital and labor, and a convex cost function.

Let us next consider how the inspection rate affects the production and quota decisions of the firms. Given that compliant firms are not constrained by the expected penalty but rather by the quota, these firms do not directly respond to a change in the inspection rate. Hence, absent a quota market, these firms are unaffected by tougher enforcement. We therefore start by analyzing the implication of tougher enforcement on a violating firm by totally differentiating its optimality conditions for production (3) and quota (5) with respect to  $\gamma$ .

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<sup>19</sup>Appendix A.2 provides a more detailed description of the calculations.

Doing this, substituting in for  $\frac{dK_v}{d\gamma}$  from equation (10), and rearranging yields:

$$\frac{dY_v}{d\gamma} = \frac{P_Y - \frac{P_{YQ}}{P_{QQ}} \left( \frac{da}{d\gamma} + P_Q \right)}{\frac{C_{YK}^2}{C_{KK}} - C_{YY} + \gamma \left( \frac{P_{YQ}^2}{P_{QQ}} - P_{YY} \right)}, \quad (11)$$

$$\frac{dQ_v}{d\gamma} = -\frac{1}{\gamma P_{QQ}} \left( \frac{da}{dk} + P_Q \right) - \frac{P_{YQ}}{P_{QQ}} \frac{dY_v}{d\gamma}. \quad (12)$$

Since the expected penalty constrains violating firms,  $\gamma$  must have a negative impact on the production level of these firms. Given the convexity of the cost and penalty functions, we know the denominator of (11) is negative. Hence, for the problem to be feasible, we impose the following assumption:

$$P_Y \geq \frac{P_{YQ}}{P_{QQ}} P_Q, \quad (13)$$

which implies that the marginal penalty of production must be equal to or exceed the marginal penalty of obtaining more quota, given that the firm increases its quota holding by a share  $-\frac{P_{YQ}}{P_{QQ}}$  of the increase in production. If assumption (13) does not hold, violating firms would increase their production as the expected penalty goes up. Note that assumption (13) holds with equality for the penalty function  $P(Y, Q) = P(Y - Q)$ .

To understand the quota market response to tougher enforcement, we analyze violating firms' quota demand. The effect of enforcement on the quota demand of a violating firm depends on two opposing factors. First, tougher enforcement induces the firm to demand more quota, all else equal, as captured by the first term of equation (12). Second, lower production reduces the firm's quota demand, as given by the last term of equation (12). Note that the latter effect requires that assumption (13) holds. If it is violated, however, and tougher enforcement increases production, both of the factors given above would positively affect violating firms' quota demand. In the following, we therefore focus on the more interesting case when assumption (13) holds.

For now, we disregard any change in the quota price ( $\frac{da}{d\gamma} = 0$ ), since what will determine

the sign of the quota price response is the sign of  $\frac{dQ_v}{d\gamma}$ . Next, to sign equation (12), we substitute in for  $\frac{dY_v}{d\gamma}$  using (11), while assuming  $\frac{da}{d\gamma} = 0$ . After some manipulation, this yields:

$$\frac{dQ_v}{d\gamma} = -\frac{P_Q}{P_{QQ}} \left[ \frac{1}{\gamma} - \frac{P_{YQ}}{B} \left( \frac{P_{YQ}}{P_{QQ}} - \frac{P_Y}{P_Q} \right) \right], \quad (14)$$

where  $B \equiv \frac{C_{YK}^2}{C_{KK}} - C_{YY} + \gamma \left( \frac{P_{YQ}^2}{P_{QQ}} - P_{YY} \right) < 0$ . Given the properties of the penalty function, equation (14) is positive if and only if the bracketed term is positive. This will be the case when assumption (13) holds. If the penalty is a function of the absolute violation,  $Y - Q$ , equation (14) reduces to:  $\frac{dQ_v}{d\gamma} = \frac{P'(Y-Q)}{\gamma P''(Y-Q)} > 0$ , which it is straightforward to sign based on the properties of the penalty function.

We have now established that violating firms demand more quota in response to tougher enforcement. However, with quota supply given, the market clearing condition implies that aggregate quota levels must be the same before and after the marginal change in enforcement. It follows that the quota price must increase to balance the quota market:  $\frac{da}{d\gamma} > 0$ . Having established this, we can now go back and reconsider the effect of enforcement on the optimal production and quota levels of the violating firm (equation 11 and 12). We see that the quota price effect dampens both the increase in quota purchase, and the reduction in catch levels.

Let us next investigate the effect on compliant firms. Taking the total derivative of optimality conditions (2), (4), and  $Y = Q$ , with respect to  $\gamma$ , and rearranging yields:

$$\frac{dY_c}{d\gamma} = \frac{\frac{da}{d\gamma}}{\frac{C_{YK}^2}{C_{KK}} - C_{YY}}, \quad (15)$$

$$\frac{dQ_c}{d\gamma} = \frac{dY_c}{d\gamma}, \quad (16)$$

in addition to (10). First, equation (15) confirms that the compliant firm is only affected by tougher enforcement indirectly through the quota price. Given that the price of quota goes

up, and the fact that the denominator of (15) is negative, we find that tougher enforcement reduces the production also of compliant firms.

Tougher enforcement might also change the compliance behavior of the marginally non-complaint firm. The direct effect of tougher enforcement will push this firm toward compliance, since violation becomes more expensive, all else equal. However, the resulting increase in the quota price will counteract this effect as it makes compliance (quota purchase) more expensive. As in section 3, however, we disregard the impact of the marginal firm on aggregate quota demand, since its impact on the market price is negligible. In the following, we focus on the vast majority of firms, who do not change their compliance behavior in response to marginally tougher enforcement.

To summarize, we find that as long as there are quota violators in the industry who change their behavior in response to tougher enforcement, the market response (quota price) will indirectly affect all firms. The quota price, unlike the inspection rate, affects the behavior of all firms, as can be seen from equations (11), (12), and (15). Thus, enforcement affects all firms through this indirect channel (quota market), which thus works as a mechanism to spread the burden of tougher enforcement from violating to compliant firms. This improves the allocative efficiency of catches in the industry. In the case of non-transferable quotas, this indirect effect of enforcement cannot occur. Compliant firms are then unaffected by changes in enforcement, unless such changes induce them to change their compliance behavior.<sup>20</sup>

Now that we have established the implication of tougher enforcement on production levels, we can analyze how enforcement affects long-run capital investment, captured by equation (10). Given the properties of the cost function, we know that  $-\frac{C_{YK}}{C_{KK}} > 0$ , and hence, the impact of enforcement on the long-run capital level is negative for both compliant and violating firms. In section 3, we showed that the capital level affects catches and compliance

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<sup>20</sup>Note that given equation (10), this must hold also in the short run when capital is fixed. However, since firms are less flexible in the short run, the industry response to tougher enforcement is stronger in the long run than in the short run.

in the short run. Hence, the effect of enforcement on capital highlights a second benefit of tougher quota enforcement. Not only does this yield lower aggregate production relative to the total quota today, it also reduces illegal fishing in the long run as capital investment falls. A lower future capital stock increases variable costs, and thus compliance in the future. We can think of this as a double benefit from stricter enforcement. This effect is generally neglected in benefit-cost analysis of quota enforcement, and in contrast to previous work, we are able to study this effect by formally analyzing the relationship between quota compliance and capital investment incentives. Result 2 summarizes our main result on enforcement.

**Result 2.** *A marginal increase in the inspection rate,  $\gamma$ , increases the quota demand of violating firms, which pushes the quota price up. Therefore, with tradable quotas, stricter enforcement reduces the production level and long-run capacity of both compliant and violating firms.*

The first part of this result, that stricter enforcement increases quota demand and the equilibrium quota price, is known from previous work on ill-enforced transferable quotas, including the work by Dhanda & Stranlund (1999) on emissions permits and Chavez & Salgado (2005) on tradable fishing quotas. The result on the relationship between enforcement and capacity development is, however, a new contribution to this literature.

Note that we have thus far ignored a possible response in the price of capital,  $r$ , to long-run changes in industry level capital. It might be argued that the market price of capital will fall in response to the reduction in capital investments we get in response to tougher enforcement. In Appendix A.2, we also account for this effect in the analysis. Our results show that such price adjustment in the market for fishing capital will dampen the effects of tougher enforcement presented above. As firms wish to reduce their long-run capital levels in response to tougher enforcement, the price of capital falls and thereby weakens the incentives to cut capital investments. A smaller fall in capital levels (smaller  $\frac{dK}{d\gamma}$ ), induces

firms to reduce production less than in the case with a constant capital price,  $r$ . However, all our results hold also when we account for such adjustment in the capital price.

Finally, our enforcement analysis reveals some distributional effects. Tougher enforcement yields a market equilibrium where compliant firms account for less of the catches and less quota. While also violating firms reduce their catches, they acquire relatively more quota under stricter quota enforcement. Hence, although tougher enforcement lowers the aggregate level of illegal catches, it also shifts (legal) production, and thus revenues, from compliant to non-compliant firms. While this might sound unattractive from a distributional point of view, it will contribute to increased efficiency for the industry as a whole, since firms that are more likely to comply are characterized by relatively higher harvesting costs. Hence, allocative efficiency improves if low-cost firms produce relatively more. The welfare implications of this are, however, beyond the scope of this study.

## 5 Concluding remarks

Fishing capacity is a main theme in recent policy debates on the status of global fisheries. For example, the World Bank report “The Sunken Billions” describes a crisis in the world’s marine fisheries and estimates that the loss from poor management of fisheries exceeds USD 50 billion per year globally (Arnason et al., 2009). They attribute the loss primarily to two factors: depleted fish stocks and fleet overcapacity. In a later study, Hannesson (2015) argues that if there is a crisis in world fisheries today, it is a crisis of waste rather than stock collapse. He is particularly concerned with the extensive rent dissipation due to overcapitalization and excessive use of labor in world fisheries, and argues that while most collapsed fisheries have eventually recovered,<sup>21</sup> overcapitalization is still a significant problem in fisheries globally. Indeed, the current capacity level in world fisheries is 1.8-2.8 times the desired level according

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<sup>21</sup>The Newfoundland northern cod fishery is a noticeable exception.

to the United Nations Environmental Program (UNEP, 2010).<sup>22</sup> Our study analyzes how overcapitalization affects both quota compliance and the quota market in ITQ fisheries. We show that fisheries managers can avoid the waste crisis described by Hannesson (2015) not only through regulations but also by stricter enforcement of regulations. Furthermore, markets for quotas can play a key role in reducing such waste.

In a stylized resource model with a market for extraction rights (ITQs), we show that in the short run, more capacity strengthens the firms' incentives to violate quotas, while stricter quota enforcement has the opposite effect. In the long run, however, stricter enforcement can alleviate both over-extraction and over-capitalization in the industry. To be more specific, our theoretical analysis shows that the lower the expected penalty of violating quotas, the stronger the firms' incentives to invest in physical capital. With a market for quotas, an increase in the expected penalty raises the quota demand of violating firms. This drives up the quota price, which in turn, affects the behavior of all firms in an ITQ fishery. Hence, the quota-market response ensures that tougher enforcement affects all firms, either directly or indirectly through the quota price. Furthermore, stricter enforcement today affects future compliance since firms invest less under stricter quota enforcement. Lower investments in fishing capacity yields lower levels of capital in the future, and hence, weaker incentives to violate quotas. Our work thus emphasizes that assigning property rights to catch shares is insufficient to ensuring efficient levels of both capital investment and production. Quota enforcement is essential, but if close-to-perfect enforcement is infeasible, we show that well-functioning markets for catch shares can partially alleviate the non-compliance problem.

Our study focuses on the situation in which the enforcement of quotas is imperfect. The cost of enforcing property rights in fisheries is high as fishing operations are difficult to control (see e.g. Arnason et al., 2000). The marginal benefits from full compliance are likely

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<sup>22</sup>While this estimate includes fisheries that are not quota regulated, capacity estimates for quota-regulated fisheries show that excess capacity is widespread also there.

lower than the marginal enforcement costs, and hence, perfect quota enforcement is unlikely. When enforcement costs are low, production quotas can generally ensure efficiency both in production and capital investment. However, as enforcement costs increase, perfect quota enforcement becomes infeasible (or impossible), and the quota instrument alone does not suffice to ensure full efficiency.

Insufficient regulations in combination with technical advances in technology are important factors behind the collapse of fish stocks and other common property resources (see e.g. Taylor, 2011; Hannesson, 2015). The number of unregulated fisheries is declining, while technological progress is an ever ongoing process. Indeed, absent proper regulations, technological progress can increase the industry's fishing capacity, and as such, exaggerate the problem (more waste), rather than contributing to more efficient fishing practices (less waste). Recent work shows how capital augmenting innovation in fishing technologies improves the fishing power of the boats, and thus increases the fleet's capacity (Squires & Vestergaard, 2013). A positive technology shock, for example the introduction of the sonar in the late 1950s, will increase profitability, and thus the short-run incentives to violate quotas. However, with a market for quota shares, our results show that the quota price will increase in response to such technology shock, and thereby dampen this effect.

Technical progress also affects enforcement. In recent years, we have seen a move toward more sophisticated monitoring, control and surveillance (MCS) technologies, including remote monitoring of catch volumes and composition using electronic cameras, or of vessel position and fishing time using satellite-based vessel monitoring systems (VMS). The introduction of such technologies reduces the cost of enforcement, and can thus increase compliance levels. In addition, as our long-run results show, a positive enforcement shock reduces the incentives to invest in (excess) capacity. Hence, technological progress plays an important role for both compliance and overcapitalization levels in fisheries.



While our study focuses on the relationship between capacity and compliance in single-species ITQ regulated fisheries, the results extend to the multi-species setting. For example, in a recent study, Hutniczak (2014) focuses on multi-species fisheries, in which some stocks are regulated with individual quotas, while other targeted stocks are unregulated. Her empirical results show that an individual quota program significantly increases pressure on unregulated species when there is excess capacity in the fleet. Applying our results to this setting implies that tougher enforcement of quota regulated species, which weakens firms' incentives to invest in capacity, might spill over on unregulated species. Consequently, tougher enforcement of ITQ regulated species in a multi-species fishery reduces the pressure also on unregulated species.

Lastly, our results have several implications for quota enforcement in the context of real-world fisheries management. First, when determining TAC and enforcement levels, fisheries managers should take into account the current level of capacity in both the industry as a whole and in different fleet segments. The level of capacity directly affects the incentives to violate quotas, and thus, total extraction and the allocation of catch shares across fleet segments. Since fisheries management objectives are typically expressed in terms of biomass and extraction levels (Anderson, 2015), it is crucial to ensure that actual catch levels meet extraction targets. Second, given that the level of capacity affects both quota violations and increases pressure on unregulated species (Hutniczak, 2014), fisheries managers should carefully consider how the TAC – both its level and the variation over time – will affect the incentives to invest in fishing capital. Third, as our analysis illustrates, the quota price does not only reflect the industry's marginal cost of harvesting, but also contains information about the marginal expected penalty, and thus, the level of quota violations. For fisheries managers this implies that, in addition to facilitating an efficient quota market, they should pay close attention to developments in the quota price, and particularly in response to announced changes in policy parameters, such as quotas and enforcement levels.

Finally, many fisheries have considerable excess capacity when the ITQ system is introduced. Capital irreversibility might leave firms with poor incentives to reduce capital stocks in the short run, implying that it may take many years from the introduction of ITQs until capital stocks adjust to their lower equilibrium levels. This represents a challenge, as higher capacity gives firms stronger incentives to violate quotas, all else equal. For fisheries managers this implies that any policy aimed at reducing fishing capacity, such as vessel decommissioning schemes or transferable quotas, will also reduce quota violations, and should therefore be evaluated in light of this. In addition, it suggests that one should introduce property rights to catch shares, or other programs that eliminates the race to fish, sooner rather than later to limit the capitalization of fishing fleets.

There are many possibilities for future work on the relationship between enforcement, capital, and quota compliance in ITQ regulated fisheries. One possibility is to investigate the role of technical progress. Capital augmenting technological improvements increase the technical efficiency of a firm, and are therefore likely to strengthen the incentives to violate quotas. As discussed above, technological progress is also likely to affect the efficiency of enforcement. Another possibility for future work is to analyze the relationship between capacity, compliance, and the quota market in a multi-species setting with both ITQ regulated and unregulated species.

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# A APPENDIX

## A.1 Linear penalty function

Many papers on compliance and enforcement assume a linear penalty function. Within the framework of our paper with transferable quotas, the linear penalty case is straightforward but offers little in terms of new insights. To see this, consider the following commonly used linear penalty function,  $P(Y, K) = \gamma f(Y - Q)$ . The marginal expected penalty is constant at  $P_Y = \gamma f$ , and a firm will comply if and only if  $a \leq \gamma f$ . Another consequence of the marginal expected penalty being constant is that we get a corner solution for quota purchases. Compliant firms buy quota according to  $Q_c = Y$ , while violating firms do not buy quota at all:  $Q_v = 0$ . Furthermore, all firms face the same marginal expected penalty regardless of production level. Hence, either all firms comply and purchase quota or all firms violate and purchase no quota. Consequently, a violating firm's quota purchase is unaffected by its level of capital, as it is always zero (given that the firm continues to violate).

Let us now consider the effect of the quota market. The lower the demand for quotas, the lower the quota price,  $a$ . Consequently, if all firms violate and no firm purchases quota, the quota price must drop until quota demand picks up again. Hence, the quota market will ensure that  $a \geq P_Y$ , which means that all firms comply in equilibrium. This makes the case of a linear penalty function uninteresting for the purpose of our study.

## A.2 Total differentiation of FOCs

In this appendix, we show how to derive the total differential equations presented in the paper.

### Short run: Effect of capital

We start out by differentiating the first-order conditions for harvest and quota with respect to the fixed level of capacity (short run). For a compliant firm, we totally differentiate condition (4), and the quota condition,  $Y = Q$ . This yields:

$$-C_{YY} \frac{dY}{dk} - C_{YK} = \frac{da}{dk}, \quad (\text{A.1})$$

$$\frac{dY}{dk} = \frac{dQ}{dk}. \quad (\text{A.2})$$

Substituting in for  $\frac{dQ}{dk}$  in equation (A.1) and rearranging yields equation 6.

For a violating firm, we totally differentiate optimality conditions (3) and (5):

$$-C_{YY} \frac{dY}{dk} - C_{YK} = \gamma \left( P_{YY} \frac{dY}{dk} + P_{YQ} \frac{dQ}{dk} \right), \quad (\text{A.3})$$

$$\frac{da}{dk} = -\gamma \left( P_{YQ} \frac{dY}{dk} + P_{QQ} \frac{dQ}{dk} \right). \quad (\text{A.4})$$

Rearranging equation (A.4) yields:

$$\frac{dQ}{dk} = -\frac{1}{\gamma P_{QQ}} \frac{da}{dk} - \frac{P_{YQ}}{P_{QQ}} \frac{dY}{dk}, \quad (\text{A.5})$$

which is identical to equation (9). Next, substitute in for  $\frac{dQ}{dk}$  in (A.3):

$$-C_{YY} \frac{dY}{dk} - C_{YK} = \gamma \left( P_{YY} \frac{dY}{dk} - P_{YQ} \left[ \frac{1}{\gamma P_{QQ}} \frac{da}{dk} + \frac{P_{YQ}}{P_{QQ}} \frac{dY}{dk} \right] \right). \quad (\text{A.6})$$



Solving equation (A.6) for  $\frac{dY}{dk}$  yields equation (8) in section 3.

### Long run: Effect of enforcement

When deriving how a change in enforcement affects the long-run levels of capital, harvest and quota, we base this on the model specified in the main part of the paper, but also take into account that the price of capital might respond to a change in the demand for capital. A higher demand for fishing capital might imply more expensive capital, and that  $r'(K) \geq 0$ .

Totally differentiating the optimality condition for capital (2) with respect to  $\gamma$  and rearranging yields:

$$C_{KK} \frac{dK}{d\gamma} - C_{YK} \frac{dY}{d\gamma} = \frac{dr}{dK} \frac{dK}{d\gamma}, \quad (\text{A.7})$$

$$\frac{dK}{d\gamma} = - \left( \frac{C_{YK}}{C_{KK} + \frac{dr}{dK}} \right) \frac{dY}{d\gamma}. \quad (\text{A.8})$$

Note that equation (A.8) reduces to equation (10) in section 4, when  $\frac{dr}{dK} = 0$ . The additional term included in (A.8) captures the effect of a possible change in the price of capital,  $\frac{dr}{dK} \geq 0$  on the response of capital to tougher enforcement. With a positive relationship between the capital level and the capital price, (A.8) shows this will dampen the marginal effect of enforcement on capital. Specifically, if tougher enforcement reduces production, this reduction will be lower if we account for the capital price change  $\frac{dr}{dK} > 0$ . This is because firms will reduce capital levels less when the price of capital falls. Below, we show that this has implications for the marginal effect of enforcement on production and quota levels.

If we differentiate the violating firm's optimality condition for quota (5) and isolate the term  $\frac{dQ}{d\gamma}$ , we obtain:

$$\frac{da}{d\gamma} = -P_Q - \gamma \left( P_{YQ} \frac{dY}{d\gamma} + P_{QQ} \frac{dQ}{d\gamma} \right), \quad (\text{A.9})$$

$$\frac{dQ}{d\gamma} = \frac{-1}{\gamma P_{QQ}} \left( \frac{da}{d\gamma} + P_Q + \gamma P_{YQ} \frac{dY}{d\gamma} \right), \quad (\text{A.10})$$

where (A.10) is equivalent to equation (12) in section 4.

Finally, differentiating the violating firm's optimality for harvest, equation (3), with respect to  $\gamma$  yields:

$$-C_{YY} \frac{dY}{d\gamma} - C_{YK} \frac{dK}{d\gamma} = P_Y + \gamma \left( P_{YY} \frac{dY}{d\gamma} + P_{YQ} \frac{dQ}{d\gamma} \right). \quad (\text{A.11})$$

Now, we can substitute in for  $\frac{dr}{d\gamma}$  and  $\frac{dQ}{d\gamma}$  in equation (A.11):

$$-C_{YY} \frac{dY}{d\gamma} + \left( \frac{C_{YK}^2}{C_{KK} + \frac{dr}{d\gamma}} \right) \frac{dY}{d\gamma} = P_Y + \gamma P_{YY} \frac{dY}{d\gamma} - \frac{P_{YQ}}{P_{QQ}} \left( \frac{da}{d\gamma} + P_Q + \gamma P_{YQ} \frac{dY}{d\gamma} \right), \quad (\text{A.12})$$

and solve for  $\frac{dY}{d\gamma}$ :

$$\frac{dY}{d\gamma} = \frac{P_Y - \frac{P_{YQ}}{P_{QQ}} \left( \frac{da}{d\gamma} + P_Q \right)}{\frac{C_{YK}^2}{C_{KK} + \frac{dr}{d\gamma}} - C_{YY} + \gamma \left( \frac{P_{YQ}^2}{P_{QQ}} - P_{YY} \right)}. \quad (\text{A.13})$$

Equation (A.13) reduces to equation (11) in section 4, when the price of capital is independent of the level of capital,  $\frac{dr}{dK} = 0$ . If a higher demand for capital raises the price of capital in the market, we have that  $\frac{dr}{dK} > 0$ . This will reduce the denominator of equation (A.13), and thus increase the marginal effect of enforcement on the violating firm's harvest, which we know is negative.<sup>23</sup> Hence, accounting for the capital price response reduces the negative effect of tougher enforcement on production.

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<sup>23</sup>We disregard the possibility that the capital price effect can change the sign of  $B_1$ .

To identify how tougher enforcement affects quota demand, we can substitute in for  $\frac{dY}{d\gamma}$  in equation (A.10), while assuming that  $\frac{da}{d\gamma} = 0$ :

$$\frac{dQ}{d\gamma} = -\frac{P_Q}{\gamma P_{QQ}} - \frac{P_{YQ}}{P_{QQ}} \left( \frac{P_Y - \frac{P_{YQ}}{P_{QQ}} P_Q}{\frac{C_{YK}^2}{C_{KK} - \frac{dr}{dK}} - C_{YY} + \gamma \left( \frac{P_{YQ}^2}{P_{QQ}} - P_{YY} \right)} \right). \quad (\text{A.14})$$

After some manipulation, this expression simplifies to:

$$\frac{dQ}{d\gamma} = -\frac{P_Q}{P_{QQ}} \left[ \frac{1}{\gamma} - \frac{P_{YQ}}{B_1} \left( \frac{P_{YQ}}{P_{QQ}} - \frac{P_Y}{P_Q} \right) \right], \quad (\text{A.15})$$

where  $B_1 \equiv \frac{C_{YK}^2}{C_{KK} + \frac{dr}{dK}} - C_{YY} + \gamma \left( \frac{P_{YQ}^2}{P_{QQ}} - P_{YY} \right)$ . In section 4 we explain that given the properties of the cost and penalty functions,  $B_1 < 0$  for  $\frac{dr}{dK} = 0$ . If we instead have that  $\frac{dr}{dK} > 0$ , this will increase  $B_1$ . Thus, if a higher demand for capital raises the capital price, this will dampen the effect of a marginal change in enforcement on both production and quota demand.

Note, finally, that the effects of the capital price response hold also for a penalty function that depends on the absolute quota violation,  $P(Y - Q)$ . This will dampen the reduction in capital and production levels, in response to a marginal change in enforcement. Although  $\frac{dr}{dK}$  drops out of equation (A.15) when we consider this particular set of penalty functions, the marginal effect on quota demand will be affected, since the change in production level affects  $P_Q$  and  $P_{QQ}$  (cf. equation A.15).

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