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Capacity and Compliance in Quota Regulated Industries

by

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Capacity and Compliance in Quota Regulated Industries

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Abstract

Production quotas can restore efficiency in industries characterized by production externalities, such as resource industries and industries with environmental regulations. However, with imperfect quota enforcement, firms may have incentives to build up excess capacity relative to their quotas. Firms with more excess capacity may, in turn, have stronger incentives to violate quotas. We consider regulation with non-transferable and transferable quotas and investigate the relationship between enforcement, compliance and capital levels in the short and long run. In the short run, excess capacity leads to increased illegal production but a well-functioning quota market may alleviate the problem. In the long run, the possibility to exceed quotas gives firms incentives to build up excess capacity relative to their quotas. Furthermore, we show that the tougher the enforcement, the lower the firms' production capacity. With non-transferable quotas, only violating firms are affected by tougher enforcement. When quotas are transferable, however, tougher enforcement causes violating firms to demand more quotas, which yields an increase in the quota price that affects all firms. The higher the quota price, the lower the production level. Hence, with tradable quotas, the quota price strengthens the effect of tougher (or weaker) enforcement. At the aggregate level, our results have strong policy implications because production quotas do not fully internalize the production externality when enforcement is imperfect. In such situations, additional management instruments are required to correct the firms' incentives to build up excess capacity, which exacerbates the non-compliance problem.

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1 Introduction

Economists generally argue in favor of market-based management instruments in industries characterized by production externalities, such as resource industries. A widely used instrument is tradable production quotas, which align the incentives of profit maximizing firms with the interests of society at large. Two well-known examples are tradable emission quotas (cap-and-trade) and individual transferable quotas (ITQs) to restrict catches in fisheries. While non-tradable quotas ensure that total production is at a desirable level, tradability ensures an efficient allocation of total production across firms. Hence, with a well-functioning tradable quota system and no other externalities, there is no need to regulate other parts of the production process. Tradable quotas give profit maximizing firms the correct incentives to make socially optimal (efficient) choices. However, if quota enforcement is imperfect and firms have the opportunity to exceed their quotas (at the risk of being detected and punished), the use of individual quotas may not yield efficient outcomes. The production externality is only dealt with imperfectly. Within such framework we investigate the link between enforcement, production capacity and quota compliance.

Transferable quotas have been implement in several industries to restrict the use of resources such as emissions (or the use of clean air), fisheries, forestry, minerals and metals, petroleum and water. The cap and trade system is frequently used to internalize pollution externalities. In fisheries, there are many examples of ITQ systems worldwide, although certain restrictions on transferability are often imposed (see e.g. Costello et al., 2008). Tradable property rights are implemented in forest management, e.g. in Canada (Burton et al., 2003). In the United States, oil producing firms operate with firm-level quotas (see Libecap & Wiggins, 1984, on prorationing). Griffin & Hsu (1993) and Rosegrant & Binswanger (1994) highlight the importance of transferability of water property rights to achieve efficient use.

Non-compliance with quotas is an important issue in many industries. In fisheries, non-compliance along with excess capacity constitute the two main issues. Estimates suggest that both problems are large and economically significant. According to Agnew et al. (2009) 20% of global fish catches are illegal or unreported, but with significant differences across regions and species, and over time. For example, the share of illegal catches in the Southwest Atlantic increased from 15% in 1980 to 32% in 2000, while the corresponding numbers for the Northwest and Southeast Atlantic show a considerable decrease. Excess capacity constitutes another major issue in fisheries. The evolution of capacity in global fisheries has received considerable attention in the literature since the early 1990s, and there are numerous examples of fishing fleets with significant excess capacity. See e.g. the work by Squires and co-authors (e.g. Squires, 1987, 1992; Segerson & Squires, 1990, and EU capacity studies).

Although both compliance and excess-capacity problems have been studied extensively, the existing work treats the two issues separately, despite the close linkages between them. In this paper, we look at the issues jointly. We develop a stylized model of a firm operating in an industry regulated with a production quotas. We find that the firm's optimal level of physical capacity (capital) depends on whether it is possible to exceed the output quota and how costly this is (expected punishment). The easier it is to violate ones quota, the stronger the incentive to expand the level of capacity. However, if there is a market for quotas, the adjustment in quota price reduces this issue. Furthermore, in the short run when the firm's level of physical capacity is fixed, the decisions of whether to exceed quotas and by how much depend on the current capacity of the firm relative to its quota. The larger the capital stock (physical capacity), the stronger the firm's incentives to violate its quota. Hence, there is a strong relationship between quota violations, enforcement and capacity both in the short and long run. Consequently, with imperfect quota enforcement the quota instrument is not sufficient to provide firms with the correct incentives to produce at a socially desirable level.

We start out by theoretically analyzing the relationship between production capacity and quota violations in a model with firm-level production quotas. We show that in the short run, excess capacity leads to increased illegal production, and in the long run, the possibility to exceed quotas (imperfect enforcement) gives firms incentives to build up excess capacity relative to what is needed to produce the quantity specified by the quota. Finally, we analyze the market responses to changes in enforcement and excess capacity through chances in the equilibrium quota price. At the aggregate level, our results have strong policy implications because production quotas do not fully deal with the production externality. Unless there is perfect enforcement of quotas, additional management instruments are required to correct the firms' incentives to build up excess capacity, which in turn exacerbates the non-compliance problem. However, transferability of quotas alleviates this problem, and thus, represents a new argument for transferable quotas.

2 The model

We start out by developing a stylized model of a resource industry regulated by production quotas. The purpose is to illustrate the relationship between non-compliance with quotas and capacity. We do this by analyzing firm behavior in a quota regulated industry in which the quota is binding. As non-compliance is not an issue in cases with non-binding quotas, we do not consider this possibility. We analyze the cases of non-transferable and transferable quotas. In the latter case, we assume a perfect quota market, in which case quota tradability is equivalent to having a rental market for quotas.

Under perfect enforcement, a firm cannot exceed its quota, and hence, the production level Y is given by the quota: $Y = Q$. Under imperfect enforcement, a firm has the possibility to exceed its quota at the risk of detection and punishment. 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.

We let the inspection probability be $\gamma \in [0,1]$ and the punishment be a fine f per unit of relative quota violation. Hence, the expected punishment is $\gamma f\left(F(K,L) - Q\right)/Q$. The fine is sufficiently high for no firm to violate quotas at $\gamma = 1$. The output price p is constant.

A firm's production level is a function of capital (K) and variable inputs (L): $Y = F(K,L)$, where $F(K,L)$ is increasing in both inputs ($F'_K > 0, F'_L > 0$) but at a decreasing rate ($F''_{KK} < 0, F''_{LL} < 0$). Both inputs are necessary in production, and hence, $F(0,L) = F(K,0) = 0$. Furthermore, there is a certain degree of substitutability between the two inputs. The rental price of capital is $r > 0$ and the price of variable inputs is $w > 0$.[1] Firms are price takers in all relevant markets. Furthermore, we assume firms are risk neutral and that they seek to maximize expected profits net of fine payments.

We analyze the relationship between capacity and quota compliance in the short run and the long run for the cases of perfect and imperfect enforcement. Under perfect enforcement the firm cannot violate its quota and the maximization problem can be stated as:

$$\begin{aligned} \max_{\{K,L\}} \quad & pF(K,L) - rK - wL - aQ \\ \text{s.t.} \quad & F(K,L) = Q, \end{aligned} \tag{1}$$

where a is the quota rental price and the term aQ disappears if we consider the case of non-transferable quotas.

This is a standard constrained optimization problem and the first-order conditions of the problem include:

$$F'_K = \frac{r}{p-\lambda} \tag{2}$$

$$F'_L = \frac{w}{p-\lambda}, \tag{3}$$

[1]The assumption of a fixed rental price of capital requires perfect capital markets where one can easily buy and sell a unit of capital at a given price. In many industries, this is not necessarily the case due to among other factors non-malleability of production capital.

where λ is the shadow price of the quota constraint. If quotas are transferable, the firm's quota purchase is determined by $Q = F(K, L)$. However, if $\lambda < a$ both production level and quota purchase are zero. The optimal use of inputs is determined by the following condition:

$$\frac{F'_L}{F'_K} = \frac{w}{r}. \tag{4}$$

In the short run, the level of capital is fixed at $K = k_0$ and the firm simply chooses variable inputs L to fully utilize its quota. The optimal level of the variable input L and the shadow price of the quota constraint are given by (3) and $F(L, k_0) = Q$. For the case of tradable quotas, we have the additional condition $\lambda = a$, which determines the optimal number of quotas to acquire.

If we open up for the possibility of quota violations, the firm's maximization problem becomes:

$$\max_{\{K,L\}} pF(K, L) - rK - wL - aQ - \gamma f \frac{F(K, L) - Q}{Q}, \tag{5}$$

where, again, the term aQ disappears if we consider the case of non-transferable quotas.

The first-order conditions of problem (5) are:

$$F'_K = \frac{r}{p - \frac{\gamma f}{Q}} \tag{6}$$

$$F'_L = \frac{w}{p - \frac{\gamma f}{Q}} \tag{7}$$

$$Q = \sqrt{\frac{\gamma f}{a} F(K, L)}, \tag{8}$$

which must hold if it is optimal for the firm to violate its quota. Optimal use of the two inputs must satisfy equation (4).

With transferable quotas, the firm complies if $a \leq \frac{\gamma f}{F(K_n, L_n)}$, i.e., if the shadow price of the quota constraint (the quota price) is lower than the expected marginal punishment of violating the quota. A compliant firm's quota purchase is generally given by $Q = F(K, L)$ but if $a > \lambda$ the firm chooses not to produce and $Q = F(K, L) = 0$. Condition (8) only applies to the case of transferable quotas and states that the higher the quota price a, the lower the share of total production the firm covers by quota. The lower the quota price, the more likely the firm is to comply.

In the short run, the level of capital is fixed and we can derive the variable input use L of a non-compliant firm from equation (7) with $K = k_0$. In the long run the firm can adjust both its use of capital and variable inputs, and the optimal input combination is found by solving equations (6) and (7) for K and L. In the case of transferable quotas, equation (8), which determines quota purchases, must hold both in the short run and the long run.[2]

On this basis, the optimality conditions of a profit maximizing firm can be summarized as follows:

$$F'_K = \frac{r}{p - \phi} \tag{9}$$

$$F'_L = \frac{w}{p - \phi}, \tag{10}$$

where $\phi = \phi_c = \lambda$ if the firm complies and $\phi = \phi_n = \frac{\gamma f}{Q_n}$ if the firm violates its quota. When quotas are not tradable, the firm complies if $\lambda \leq \frac{\gamma f}{Q_n}$. With transferable quotas, the firm's quota purchase is determined by (8) if the firm violates quota regulation, that is, if $a > \frac{\gamma f}{F(K,L)}$. Finally, in the short run, condition (9) is replaced by $K = k_0$.

Both under perfect (problem 1) and imperfect enforcement (problem 5), the optimal combination of production factors requires that marginal revenues equal marginal costs, where the latter is determined by the respective input prices. However, marginal effects depend on whether the firm complies with its quota and whether we consider perfect or

[2]Hence, Q is variable both in the short run and long run. This is appropriate since it typically takes much longer to change the level of physical capital than to buy or sell (or rent) quotas in an efficient quota market.

imperfect enforcement. For a non-compliant firm (imperfect enforcement), the marginal effect depends on the expected fine payment $\frac{\gamma f}{Q}$ of an additional unit produced and we therefore adjusted by this factor. For a compliant firm, the marginal benefit is adjusted by the shadow price of the quota constraint, which is an absolute constraint when enforcement is perfect.

Having characterized the firm's optimization problem in the short and long run both under imperfect and perfect enforcement, we analyze the relationship between compliance, enforcement and capital use in equilibrium. We start out by looking at the short-run relationship between capacity and compliance. First, we focus on the behavior of individual firms that have no market power in any of the relevant markets (inputs, outputs or quota). Later, in section 5, we extend this analysis by investigating market responses to changes in short-run industry capacity and enforcement parameters.

3 Capacity and compliance in the short run

In the short run, the level of capital is fixed and the firm can only adjust production by changing its use of the variable input L. We have established that the equilibrium use of the variable input is determined by equation (10). We summarize the relationship between the short-run level of capacity and firms' incentives to violate quotas in propositions 1 and 2.

Proposition 1. *A compliant firm's incentives to violate its production quota increase with the firm's level of physical capacity.*

Proof. We first consider the case of non-transferable quota. The optimality condition for a firm that complies with its quota is given by (10) with $\phi = \lambda$. Since inputs are substitutes, the marginal product of the variable input L is increasing in the level of capital (physical capacity). Hence, the left hand side (LHS) of condition (10) is increasing in the fixed capital level k_0. We know the firm complies if and only if $\lambda \leq \frac{\gamma f}{Q}$. We can re-write the shadow price of the quota constraint in terms of capital from equation (10):

$$\lambda = p - \frac{w}{F'_L(k_0)}. \tag{11}$$

The derivative of the shadow price of the quota constraint with respect to capital describes the relationship between capital increases and tighter shadow prices:

$$\frac{\partial \lambda}{\partial k_0} = \frac{w \frac{\partial F'_L(k_0)}{\partial k_0}}{\left(F'_L(k_0)\right)^2}. \tag{12}$$

We know that $\frac{\partial F'_L(k_0)}{\partial k_0} > 0$, which implies $\frac{\partial \lambda}{\partial k_0} > 0$. This completes the proof for the case of non-transferable quotas.

Next, we consider the case of transferable quotas. We have established that in this case the firm complies if $a \leq \frac{\gamma f}{F(k_0, L)}$. Hence, for a given quota price a, the firm is more likely to violate its quota as k_0 increases if

$$\frac{\partial}{\partial k_0} \left\{ \frac{\gamma f}{F(k_0, L(k_0))} \right\} < 0. \tag{13}$$

Because of input substitutability, we know that $\frac{\partial L}{\partial k_0} > 0$. In addition, the production function is increasing in both K and L. Hence, an increase in k_0 causes $F(k_0, L)$ to increase, which implies that the inequality (13) holds. This proves that the higher the short-run capital level of a compliant firm, the stronger the incentives of the firm to violate its quota. □

The next result focuses on the production level of non-compliant firms.

Proposition 2. *The illegal production of a non-compliant firm increases with the firm's level of physical capacity.*

Proof. Consider a non-compliant firm. In this case $\phi = \frac{\gamma f}{Q}$ in equation (10). We can analyze the implications of increased capital levels on illegal production by considering the following partial derivative:

$$\frac{\partial \left[F(k_0, L(k_0)) - Q \right]}{\partial k_0} = F'_K(k_0) + F'_L(k_0)\frac{\partial L}{\partial k_0} - \frac{\partial Q}{\partial k_0}, \tag{14}$$

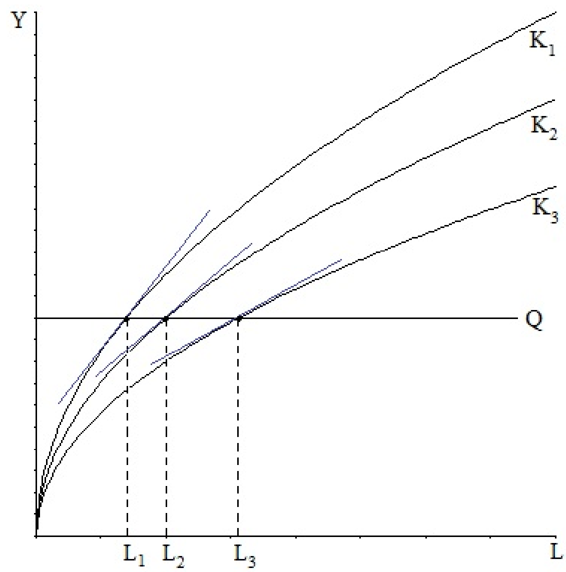
where the term $\frac{\partial Q}{\partial k_0} = 0$ if quotas are non-transferable. We know that the marginal productivity is positive both for K and L. In addition, because of input substitutability the optimal levels of K and L move in the same direction for changes in production level, and we have that $\frac{\partial L(k_0)}{\partial k_0} > 0$. It follows that for the case of non-transferable quotas $\frac{\partial [F(k_0, L(k_0)) - Q]}{\partial k_0} > 0$.

To evaluate the sign of the partial derivative in (14) for the transferable quota case, we must take into account the effect of changes in quota holdings when the level of capital increases. From equation (8) we have that $\frac{\partial Q}{\partial k_0} = \sqrt{\frac{\gamma f}{aF(k_0)}} \left(F'_K(k_0) + F'_L(k_0)\frac{\partial L}{\partial k_0} \right)$. It follows that the sign of the partial derivative (14) is positive if and only if:

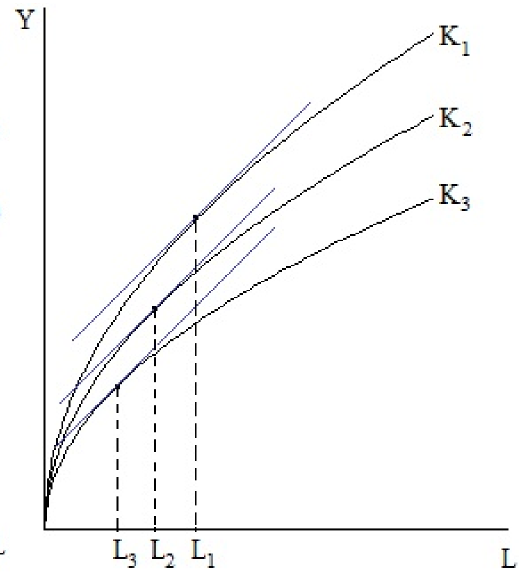
$$\left(1 - \sqrt{\frac{\gamma f}{aF(k_0)}} \right) \left(F'_K(k_0) + F'_L(k_0)\frac{\partial L}{\partial k_0} \right) > 0. \tag{15}$$

We have already established that the term in the second parentheses is positive. Hence, the inequality holds if the term in the first parentheses is positive. We know that a firm chooses non-compliance only if $\frac{\gamma f}{aF(k_0)} < 1$. Consequently, inequality (15) always holds for a non-compliant firm. This implies that $\frac{\partial [F(k_0, L(k_0)) - Q]}{\partial k_0} > 0$ regardless of whether quotas are transferable. □

The basics of propositions 1 and 2 are illustrated in figure 1 for the case of non-transferable quotas. Figure 1a shows how the marginal product of the variable input MP_L increases with the fixed level of capital. This is evident by comparing the slopes of the tangents to the production curves between the points where the firm's production equals its quota Q. The higher the level of capital, the steeper the tangent and the higher the marginal product of



(a) Compliant firm



(b) Non-compliant firm

Figure 1: The short-run relationship between capital, the variable input and production (with $K_1 > K_2 > K_3$).

the variable input. As a consequence, the shadow price of the quota constraint increases, which strengthens the firm's incentives to violate its quota.

Figure 1b illustrates why a non-compliant firm's production level increases with the fixed level of capital. The optimal input use and production level are found as the point on the production curve at which the slope of the production curve equals the right-hand side (RHS) of the optimality condition (7), which is independent of the level of capital. Hence, the three tangents shown in figure 1b have the exact same slope, but differ in the use of the variable input L and in output level Y.

Propositions 1 and 2 state that quota violations are more likely in an industry currently characterized by excess capacity. There are many possible reasons for excess capacity to be present. First, if the capital was already there by the time the resource was privatized, it may take a long period of time before capital levels normalize due to irreversibility of investments; the capital investment may be a sunk cost. The economic lifetime of the capital then determines when the situation is normalized and until that point is reached, there is excess capacity in the industry. Second, the dynamics of renewable resources may show natural fluctuations, which affects quotas. Hence, in some periods there may be excess capacity because quotas are lower than usually. Any of these situations make quota holders more likely to exceed their quotas in the short run. Note that if many firms are affected by these factors and there is a market for quotas, then we must also take into account the quota price response and how this affects individual behavior. This is the focus of section 5. First, we turn to the analysis of long-run implications.

4 Capacity and compliance in the long run

We now consider the relationship between capacity and compliance in the long run, when all inputs are variable. The main result on the long-run relationship between physical capacity and compliance is summarized in proposition 3.

Proposition 3. *The firm's long-run level of physical capacity (capital) is higher under imperfect than perfect enforcement.*

Proof. The proof of proposition 3 follows from the long-run optimality conditions of the firm. If the firm complies both under perfect and imperfect enforcement, the firm's optimal capital level is unaffected. However, if the firm violates its quota under imperfect enforcement, this will affect the long-run capital level. We know that the left-hand side of the optimality condition for capital (9), F'_K, is decreasing in capital since the marginal product of capital is decreasing. Hence, the proposition holds if the right-hand side of (9) is larger under perfect enforcement than under imperfect enforcement, given that the firm complies under perfect enforcement but violates its quota when enforcement is imperfect.

For the case of non-transferable quotas this implies that the following inequality must hold:

$$\frac{r}{p-\lambda} \geq \frac{r}{p-\frac{\gamma f}{Q}}, \tag{16}$$

where Q is constant. For a non-compliant firm $\frac{\gamma f}{Q} < \lambda$, and hence, the inequality (16) holds.

When quotas are transferable, Q is a variable and we must take into account the effect of enforcement on the firm's quota purchase. We substitute the optimal quota purchase from equation (8) into the optimality conditions for capital (9) under perfect and imperfect enforcement, assuming that the firm violates its quota in the latter case. Using the same reasoning as for the case of non-transferable quotas, we know that the capital level is higher under imperfect than perfect enforcement if the following inequality holds:

$$\frac{r}{p-a} \geq \frac{r}{p-\sqrt{\frac{\gamma f}{F(K,L)}}}, \tag{17}$$

since this implies that F'_K is higher for the firm under perfect enforcement than imperfect enforcement. From the optimality conditions, we have established that the firm chooses non-compliance only if $a > \sqrt{\frac{\gamma f}{F(K,L)}}$. Hence, the inequality (17) must hold for a firm that violates its quota when enforcement is imperfect. □

Corollary 1. *With non-transferable quotas, the long-run capital level of a non-compliant firm is decreasing in the expected punishment.*

Proof. From proposition 3 we know that a firm's optimal levels of capital and the variable input are higher if the firm violates than if it complies with its quota. Furthermore, we have established that the two inputs adjust in the same direction to changes in production level. Optimal long-run input use is determined by equations (9) and (10), with $\phi = \frac{\gamma f}{Q}$. The RHS of both conditions is decreasing in the expected punishment, $\frac{\gamma f}{Q}$. Hence, a lower marginal product (from the LHS of the equations) is equivalent to a higher use of both inputs due to their decreasing marginal products. It follows that the use of both inputs, as well as the production level, is decreasing in the expected punishment. □

Note that corollary 1 only applies to the case when quotas are non-transferable. To analyze the implications of tougher enforcement on capacity development when quotas are transferable, we must take into account the market response to enforcement change. Since a change of γ applies to all firms in the industry, this change is likely to affect the firms' quota demand, and therefore, the quota price. A complete analysis therefore requires that we account for the market response. We return to this below in section 5.

The above propositions and corollary have important implications for industry-level compliance and production capacity. First, in an industry where non-compliance with quotas cannot be ruled out (imperfect enforcement), the aggregate capacity level is higher than what is optimal for the production level given by the aggregate quota. This does not necessarily mean that aggregate capacity is too high. If quota violations is a problem in an industry, it is likely that the regulator takes expected illegal production into account when determining the aggregate quota, which is then reduced correspondingly. Hence, the optimal capacity level may be higher then the optimal level associated with full quota compliance (perfect enforcement).

Another implication of our results is that industry-level capacity depends on both the punishment level and the exerted enforcement effort in the industry. Increased enforcement or more severe punishment do not only reduce aggregate production, but also the long-run level of physical capacity. From our analysis of capacity and compliance in the short run, we know that a lower level of capital reduces firms' short run incentives to violate quotas. Hence, increased enforcement today has the indirect effect of reducing firms' incentives to violate quotas tomorrow through the reduction in long-run production capital.

Next, we extend this analysis to the case of transferable quotas by accounting for changes in quota price as a response to higher enforcement or industry level current capacity.

5 Accounting for market response to enforcement

Thus far we have focused on the cases of perfect versus imperfect enforcement and the differences between compliant and non-compliant behavior. We have not considered the implications of changing the expected punishment under transferable quotas, nor the effects of industry-level excess capacity in this situation. These cases are particularly interesting as a change of enforcement or current industry-level capacity affect the market price of quotas, which in turn affects behavior. Hence, behavior is affected both directly as e.g. the expected punishment of violating the quota changes, and indirectly through the change in quota price.

We assume an industry with heterogenous firms differing only in their production efficiency. In particular, we assume that firm i's production is determined by:

$$F(K_i, L_i) = \alpha_i G(K_i, L_i), \tag{18}$$

where $\alpha_i > 0$ is a constant efficiency parameter and the production function $G(\cdot)$ is the same for all firms. From the optimality conditions we know that a firm chooses to comply if $a \leq \frac{\gamma f}{F(K,L)}$. By substituting in for $F(K, L)$ using equation (18), we find that the compliance condition can be expressed as:

$$\alpha_i \leq \frac{\gamma f}{aG(K_i, L_i)}. \tag{19}$$

The higher the productivity of the firm, the more likely the firm is to violate quota regulation. We define $\bar{\alpha}$ as the value of α that makes a firm indifferent between compliance and quota violation. That is, it is the value of α_i for which (19) holds with equality.

Firms choose one of the following options: (i) no production and no quota purchase, $Y = Q = 0$, (ii) produce in compliance with quotas, $Y = Q > 0$, or (iii) produce in violation with quotas, $Y > Q > 0$. Since the expected punishment approaches infinity for an active firm as $Q \to 0$, no firm chooses to produce without quota (cf. equation 5). In addition, we know that the production of any given profit maximizing firm is higher if the firm chooses non-compliance than if the firm complies.

5.1 The effects of increased enforcement

We start out by analyzing the implications of tougher enforcement on physical capital ($\Delta\gamma > 0$).[3] The quota price is the price that clears the quota market: $\sum_i Q_i(a) = \bar{Q}/N$, where $\bar{Q}$ is the total quota. Aggregate quota demand depends on enforcement, and hence, the quota price is a function of enforcement level: $a = a(\gamma)$.

We start out by investigating the partial effect of increased enforcement on firm-level quota demand. There are three main effects to consider: change in quota demand for compliant firms, change in quota demand for non-compliant firms, and the effect on demand as some non-compliant firms become compliant. First, the quota demand of a compliant firm is determined by its production level: $Q = F(K_c, L_c)$. We know from the first order conditions of the firm's optimization problem that increased enforcement does not directly affect input use (cf. equations 9 and 10, with $\phi = a$) nor production level. Hence, quota demand is not directly affected by a change in enforcement: $\frac{\partial Q_c}{\partial \gamma} = 0$. Compliant firms may still be affected by a change of enforcement, but only indirectly if the quota price changes as the rest of the industry responds to tougher enforcement.

The quota demand and production level of non-compliant firms are affected by enforcement. Before we continue with the analysis, we want to establish an important relationship between the production level and input use of non-compliant firms, and enforcement. We know that, all else equal, illegal production approaches zero as γ approaches 1. Hence, the production level of a non-compliant firm is decreasing in the inspection rate; $\frac{\partial Y_n}{\partial \gamma} < 0$.

[3] This is equivalent to analyzing an increase in the fine f or in the expected punishment per unit relative violation, γf.

Furthermore, because of the input substitutability assumption, this implies that the use of capital and the variable inputs decrease as γ increases.

Next, we investigate the impact of increased enforcement on quota demand. Taking the partial derivative of non-compliant firms' quota demand (cf. equation 8) with respect to γ yields:

$$\frac{\partial Q_n}{\partial \gamma} = \frac{1}{2}\left[\frac{F\left(K_n, L_n\right) f}{\gamma a}\right]^{\frac{1}{2}} + \frac{1}{2}\left[\frac{\gamma f}{aF\left(K_n, L_n\right)}\right]^{\frac{1}{2}} \left(F'_K \frac{\partial K}{\partial \gamma} + F'_L \frac{\partial L}{\partial \gamma}\right) > 0. \tag{20}$$

We already established that input use is decreasing in γ. Hence, all terms in (20) are positive and so is the partial derivative. Not surprisingly, we find that violating firms want to buy more quota as the expected punishment of quota violations increase, all else equal.

Finally, we must consider the effect of increased enforcement on firms' decision of whether to comply. We investigate this by taking the partial derivative of $\bar{\alpha}$, the productivity parameter that makes a firm indifferent between compliance and non-compliance, with respect to γ:

$$\frac{\partial \bar{\alpha}}{\partial \gamma} = \frac{f}{aG(K,L)} - \frac{\gamma f}{aG(K,L)^2}\left(G'_K \frac{\partial K}{\partial \gamma} + G'_L \frac{\partial L}{\partial \gamma}\right) > 0. \tag{21}$$

We have established that the use of inputs is decreasing in the level of enforcement ($\frac{\partial K}{\partial \gamma} < 0$ and $\frac{\partial L}{\partial \gamma} < 0$). We also know that the marginal productivity of inputs is positive ($G'_K > 0$ and $G'_L > 0$). It follows that the partial derivative in (21) is positive.

The higher the level of enforcement, the more productive a firm must be to find it optimal to violate its quota.[4] Hence, the number of compliant firms is increasing in the enforcement level, all else equal. The quota demand effect of this shift in compliance behavior depends on whether the firms that become compliant when γ increases demand more or less quotas than they did before. There are two effects to consider. First, firms produce less when

[4]Note that the level of $G(K,L)$ depends on α. However, since the optimal production level (and input use) is increasing in α, this does not cause any problems and we can conclude as we did.

complying with quotas than when violating quotas. This follows from the fact that ϕ in optimality conditions (9) and (10) must increase when the firm chooses to become compliant as a consequence of the increase in γ. Second, firms' quota coverage increases as they become compliant, that is, the share of production for which the firm has quota increases. All else constant, the first effect reduces the quota demand, while the second effect increases the quota demand.

The effects of tougher enforcement (increase in γ) on firm behavior are illustrated in figure 2. Tougher enforcement increases the value of ϕ in the optimality conditions of non-compliant firms, denoted ϕ_n in the figure. The shadow price of compliant firms is unchanged (ϕ_c). This changes the intercept between the two ϕ values, which identifies the productivity level of a firm that is indifferent between compliance and non-compliance ($\bar{\alpha}$). Hence, with tougher enforcement firms must be more productive for quota violations to pay off. The upward shift in ϕ_n also implies that non-compliant firms produce less than they did before. Finally, the thicker segments of the ϕ_n^0 and ϕ_c curves indicate the shift for firms that were marginally non-compliant and become compliant when enforcement is tougher. For these firms the relevant ϕ value increases (cf. optimality conditions 9 and 10), indicating a reduction in these firms' production levels.

The total effect on quota demand can be stated as:

$$\Delta Q = \Delta Q_{cc} + \Delta Q_{nn} + \Delta Q_{nc}, \tag{22}$$

where the notation ΔQ_{nc} refers to change in demand from firms that change between **n**on-compliance and **c**ompliance, while Q_{cc} and Q_{nn}, respectively, refer to the demand of firms that either comply or violate both before and after the increase in γ. We know that the quota price a increases if the demand increases, since the quota supply is constant at $\bar{Q}$. Hence, we are interested in the sign of (22).

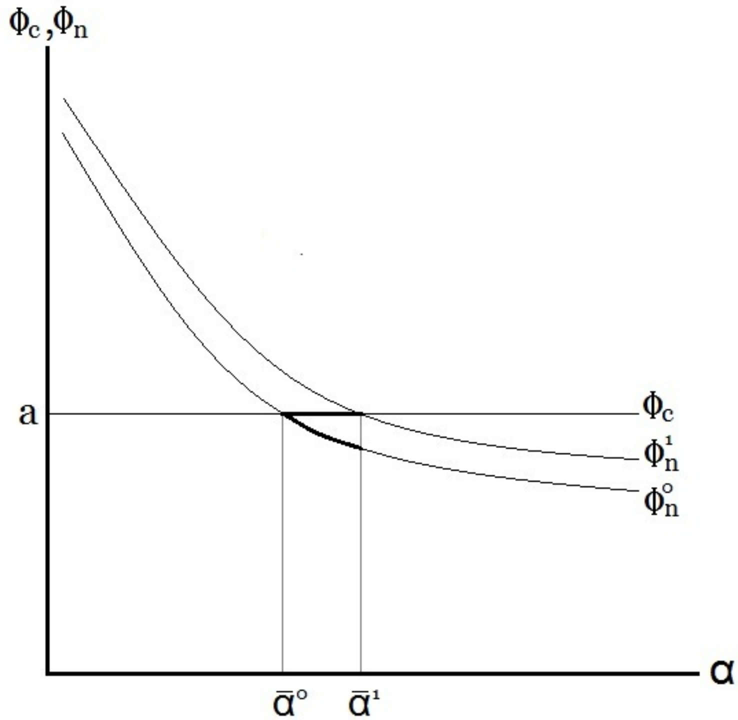


Figure 2: The effect of an increase in the inspection rate, γ, on ϕ and firm behavior, by firm-specific productivity parameter α. (*Subscript* (c, n) *denote compliant and non-compliant firm, respectively, while superscript* $(0, 1)$ *denote before and after the change in* γ*.*)

We have established that $\Delta Q_{cc} = 0$ and $\Delta Q_{nn} > 0$. Hence, the total demand effect depends on the last term, ΔQ_{nc}. Consider first the case $\Delta Q_{nc} < 0$, that is, where the marginal firms' quota demand goes down when they become compliant. If the reduction in these firms' quota demand is larger than the increase in quota demand from non-compliant firms, the total effect is a decrease in quota demand, which implies a decrease in the quota price a. This case seems unlikely since it requires that the change in production level is relatively large for firms that change compliance behavior, in addition to these firms representing a significant share of the market relative to the non-compliant firms (ΔQ_{nn}).

It can be shown that $\Delta Q_{nc} > 0$ if the relative reduction in production of each of the firms that change compliance behavior satisfies:

$$c > \sqrt{\frac{\gamma_0 f}{a Y_0}}, \tag{23}$$

where $c \equiv \frac{Y_1}{Y_0}$ and where subscript 0 denotes value before increase in γ and subscript 1 denotes value after increase. Hence, a low initial expected punishment ($\gamma_0 f$) or high initial production level and quota price increase the likelihood of this to hold. Note that we are analyzing the effects of a marginal increase in enforcement. This can only lead to a small decrease in the relevant ϕ value of these marginal firms, and hence, in their production levels. This implies that c in (23) is close to one.

The requirements for the inequality to not hold is that the expected punishment is high, which implies a relatively low level of production. Furthermore, a high value of γ means that the number of violating firms is low, which increases the likelihood that a decrease in Q_{nc} outweighs the increase in Q_{nn}. On this basis, we can derive the upper limit on γ, which we denote $\bar{\gamma}$, above which increased enforcement does not yield an increase in aggregate quota demand or the equilibrium quota price. On the contrary, increasing the level of enforcement beyond $\bar{\gamma}$ reduces total quota demand and causes a decrease in quota price.[5] As γ is a probability, it cannot exceed 1. Hence, unless $\bar{\gamma} < 1$, this case will never occur.

We focus the remainder of the analysis on the case $\gamma < \bar{\gamma}$ so that $\Delta Q_{nn} + \Delta Q_{nc} > 0$, in which case the increase in enforcement effort leads to a positive shift in the demand for quotas, which in turn causes the quota price to increase for the quota market to be in equilibrium. That is, for quota demand to equal quota supply. The increase in quota price affects compliant and non-compliant firms, as well as $\bar{\alpha}$, the firm-specific productivity parameter of a firm that is indifferent between compliance and non-compliance.

[5] $\bar{\gamma}$ cannot be calculated from the general model, as it depends on *inter alia* the distribution of individual productivity parameters α_i.

First, both compliant and non-compliant firms use less of the inputs and produce less as the quota price increases.[6] This follows from the fact that the right hand side of the optimality conditions for K and L are increasing in a in both cases (cf. equations 9 and 10 with $\phi = a$ for compliant firms and $\phi = \sqrt{\frac{a\gamma f}{F(K,L)}}$ for non-compliant firms). Hence, input use must decrease as we increase a, which causes the level of production to go down: $\Delta_a Y_{cc} < 0$ and $\Delta_a Y_{nn} < 0$, where subscript a indicates that we refer to the change in production for an increase in a.

Second, the increase in quota price reduces $\bar{\alpha}$, and hence, reduces the number of firms that choose to comply. Formally, we have that:

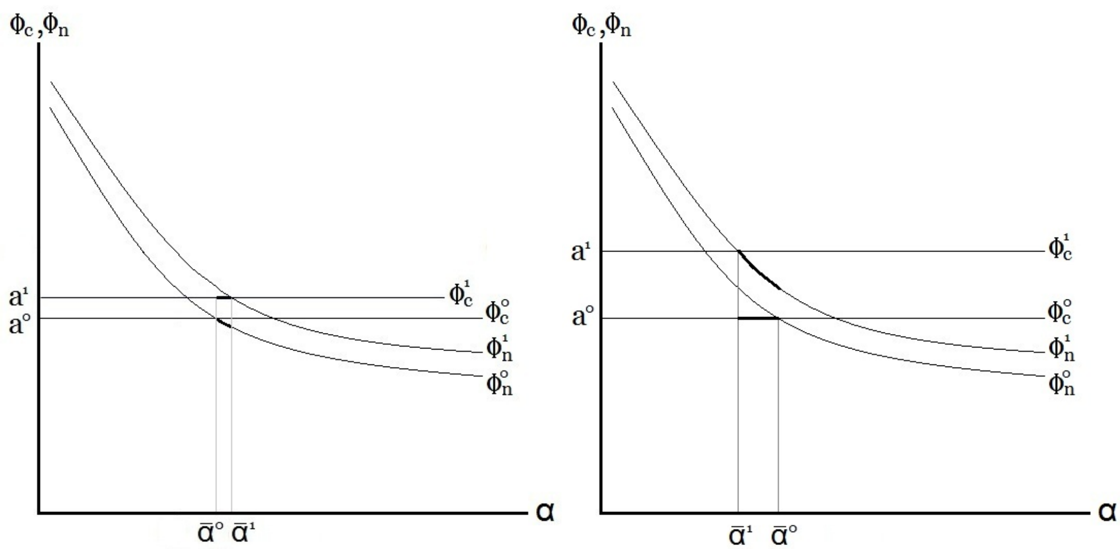
$$\frac{\partial \bar{\alpha}}{\partial a} = -\frac{\gamma f}{a^2 G(K,L)} - \frac{\gamma f}{a G(K,L)^2}\left(G'_K \frac{\partial K}{\partial a} + G'_L \frac{\partial L}{\partial a}\right). \tag{24}$$

While the first term in (24) is negative, the second term is positive. This follows from the fact that $(G'_K, G'_L) > 0$ and $\left(\frac{\partial K}{\partial a}, \frac{\partial L}{\partial a}\right) < 0$. Hence, the increase in quota price can shift the threshold value of the individual productivity parameter $\bar{\alpha}$ up or down, depending on the current production level and how much input use is affected by a change in the quota price. If current production is relatively low, the marginal productivity of inputs is relatively high and an increase in the quota price is likely to increase $\bar{\alpha}$. Also, the bigger the effect of the quota price on input use (and production), the more likely it is that an increase in quota price causes $\bar{\alpha}$ to shift upward.

The effect on these marginal firms' production and input use is the same, regardless of whether firms go from violating to complying or *vice versa*. In both cases the relevant ϕ value these firms face increases when the quota price a increases. This is because both $\phi_c = a$ and $\phi_n = \frac{\gamma f}{Q(a)}$ are increasing in a. In the case where $\bar{\alpha}$ decreases following the increase in

[6] The least productive firms may in fact choose not to produce at all (that is, firms with low α_i values, cf. equation 18). This may happen if the new equilibrium quota price is higher than the firm's shadow value of producing λ.)

quota price, the marginal firms shift from non-compliance to compliance. Then the following holds for these firms: $a_0 < \frac{\gamma f}{Q(a_1)} < a_1$, where a_0 and a_1 denote quota price before and after the increase, respectively. Similarly, if $\bar{\alpha}$ decreases following the increase in quota price, the marginal firms shift from compliance to non-compliance. For these firm we have that $a_0 < \frac{\gamma f}{Q(a_0)} < \frac{\gamma f}{Q(a_1)}$. Hence, regardless of whether an increase in quota price causes more firms to comply or more firms to violate, ϕ in optimality conditions (9) and (10) has increased for these firms. This implies an increase in the marginal products F'_K and F'_L, which requires a reduction in the use of the two inputs as well as in total production. Hence, we have that $\Delta_a Y_{nc} < 0$.



(a) More firms comply (b) More firms violate

Figure 3: The effect of an increase in the quota price (a) on ϕ and firm behavior, by firm-specific productivity parameter α. An increase in quota price can shift $\bar{\alpha}$ (a) up or (b) down. (*Subscript* (c, n) *denote compliant and non-compliant firm, respectively, while superscript* $(0, 1)$ *denote before and after the increase in* a.)

The effects of an increase in the quota price a on firm behavior are illustrated in figure 3. An increase in the quota price increases the value of ϕ both in the optimality conditions of non-compliant and compliant firms, which is why these firms produce less the higher the quota price. The intercept between the ϕ_c and ϕ_n curves identifies when a firm is indifferent between compliance and non-compliance ($\bar{\alpha}$). This intercept can shift left or right, depending on the situation. An increase (decrease) in $\bar{\alpha}$ indicates a possible increase (decrease) in the number of firms that violates quotas. The thicker segments of the ϕ curves indicate how the relevant ϕ value increases for firms that change compliance behavior following the increase in quota price, regardless of whether they shift from compliance to non-compliance or *vice versa*.

We can conclude that the effect of tougher enforcement (γ) is an initial increase in the demand for quotas (the direct effect). However, since the supply of quotas is constant, this leads to an increase in the quota price until the quota market clears. The higher quota price affects the behavior of firms; an indirect effect of tougher enforcement. We summarize the direct and indirect effects of increased enforcement effort on production, input use and quota demand in table 1.

Table 1: Partial effects of increased enforcement (γ) on firms by compliance behavior. *Notation: Compliant firms (C), non-compliant firms (N) and firms that shift between compliance and non-compliance (N↔C). Positive (+), negative (−) and no (0) effect.*

	Input use (K, L)			Production (Y)			Quota (Q)		
	C	N	N↔C	C	N	N↔C	C	N	N↔C
1) Tougher enforcem. ($\gamma\uparrow$)	0	−	−	0	−	−	0	+	+(−)
2) Higher quota price ($a\uparrow$)	−	−	−	−	−	−	−	−	+(−)
Total effect		−			−			0	

While an increase in the inspection rate γ initially only affect non-compliant firms, the indirect effect working through the quota price also affects compliant firms. Hence, tougher enforcement reduces production levels and input use for all firms, regardless of whether they are currently violating their quotas. The total effect of tougher enforcement on the quota market is an increase in the quota price. Furthermore, notice that the total effect on the quota demand of compliant firms is a reduction, which means that non-compliant firms and firms that are marginally compliant/non-compliant increases their share of total quotas. Hence, increased enforcement has a negative effect both on the quota share and the profitability of compliant firms.[7]

Let us now briefly return to the case where γ is currently so high that increased enforcement leads to a decrease in total quota demand, and hence, the equilibrium quota price. In this case the signs associated with the change in quota price, as well as the direction of this price change, shown in table 1 would be reversed. Hence, the total effect on production and input use of tougher enforcement is ambiguous as the market response cancels out the intended effect of tougher enforcement. The outcome depends on which of the two effects is stronger.

We can now return to the relationship between capital and compliance, particularly how this is affected by the level of enforcement (γ). We summarize the main long-run result in proposition 4.

Proposition 4. *For inspection rates* $0 \leq \gamma \leq \min(\bar{\gamma}, 1)$*, where* $\bar{\gamma}$ *is as defined above, the firm's long-run level of physical capacity (capital) is decreasing in* γ *independently of whether the firm currently violates its quotas.*

Proof. The proof is given by table 1 and the underlying analysis, which show that the input use (K and L) decreases for all firms, regardless of compliance behavior before and after the increase in γ. □

Proposition 4 emphasizes the possible role of quota enforcement in reducing excess capacity. If quotas are non-transferable, a change of inspection rate (or equivalently, fine levels) affects firms that currently violate quotas as well as firms that marginally prefer compliance. Other firms are not affected. When quotas are transferable, however, there is an indirect

[7] Note that this may in fact increase the efficiency of the industry as a whole, since firms that always comply are characterized by relatively low productivity. Hence, the allocative efficiency may increase if firms that are relatively more productive produce more while these low-productivity firms produce less. This is, however, beyond the scope of the current work.

effect, namely the quota market response in terms of a change of quota price. Hence, all firms are affected through this indirect channel, which works as a multiplier of the initial effect of the change of the inspection rate (cf. table 1).

5.2 Excess capacity and illegal production

Next we investigate the implications of higher production capacity on illegal production in the short run. In propositions 1 and 2, we showed that the higher the current production capacity of a firm, the stronger the firm's incentives to violate quotas (compliant firms) or the higher the illegal production (non-compliant firms). The analysis was at the firm level and the assumption was that one firm cannot affect the quota price. We did not investigate the implication of higher industry level capacity on the level of production.

In the case of non-transferable quotas, the result of higher industry level capacity is parallel to that of higher firm level capacity (cf. section 3), and we can interpret the firm as the representative firm. However, when quotas are transferable, the level of excess capacity in the industry affects how much firms are willing to pay for quotas. This affects the quota price, which in turn affects firm behavior. This is the focus of the following analysis.

We start out by analyzing the effect on quota demand of an increase in the level of physical capital k_0, which is fixed in the short run:

$$\frac{\partial Q_c}{\partial k_0} = F'_K + F'_L \frac{\partial L}{\partial k_0} > 0 \tag{25}$$

$$\frac{\partial Q_n}{\partial k_0} = \frac{1}{2}\left[\frac{\gamma f}{aF\left(k_0, L\right)}\right]^{\frac{1}{2}} \left(F'_K + F'_L \frac{\partial L}{\partial k_0}\right) > 0, \tag{26}$$

where subscript (c, n) denote compliant and non-compliant firms, respectively.

In addition, some firms that are on the margin between non-compliance and compliance, change compliance behavior if their short-run level of capacity is increased. This is clear by taking the partial of $\bar{\alpha}$ with respect to k_0, that is, the value of the productivity parameter in (18) that makes a firm indifferent between compliance and non-compliance:

$$\frac{\partial \bar{\alpha}}{\partial k_0} = -\frac{\gamma f}{aG(k_0, L)^2}\left(G'_K + G'_L \frac{\partial L}{\partial k_0}\right) < 0 \tag{27}$$

The marginal productivity is positive both for capital and variable inputs. In addition, input substitutability means that the use of the variable input increases with the use of capital ($\frac{\partial L}{\partial K} > 0$). Hence, the partial derivative (27) is negative, implying that more firms may violate quotas if their level of physical capital increases.

The effect on quota demand of more firms becoming violators depends on which of the following two factors dominate. First, a firm produces more when violating than when complying with quotas. This follows from the fact that ϕ in optimality condition (10) must decrease for a firm that becomes compliant if we increase k_0. Formally, $\phi_n^0 > a > \phi_n^1$, where ϕ_n^0 and ϕ_n^1 denote the firm's value of ϕ under non-compliance before and after an increase in k_0, respectively. This implies increased use of the variable input, and hence, production. Second, firms' relative quota coverage decreases as they go from compliance to non-compliance. All else constant, the first effect increases quota demand, while the second effect decreases quota demand.[8]

The total effect of higher short-run capital level on quota demand can be represented by equation (22). We have established that $\Delta Q_{cc} > 0$ and $\Delta Q_{nn} > 0$. Hence, the total demand effect depends on the term ΔQ_{nc}. Although this term may be positive or negative, we do not consider the unlikely case that the term ΔQ_{nc} is negative and larger in absolute value than $\Delta Q_{cc} + \Delta Q_{nn}$. This would imply that even though all firms produce more than before, the aggregate quota demand goes down. Unless the marginal firms that change compliance behavior make up a large share of the market and reduce their quota demand significantly,

[8]From the optimality conditions for compliance and non-compliance, we have that $\Delta Q_{nc} = Q_n^1 - Q_c^0 = \sqrt{\frac{\gamma f Y_n^1}{a}} - Y_c^0$, where superscript $(0, 1)$ denote before and after the increase in k_0, respectively. Hence, the larger $\frac{\gamma f}{a}$, the more likely the demand effect ΔQ_{nc} is positive.

this will not happen.[9]

We therefore focus on the case where $\Delta Q > 0$, which implies a positive shift in quota demand following an increase in the short-run capital level of the industry. As we established in the above analysis of market response to changes in enforcement level, input use and production is decreasing in quota price for all active firms. Furthermore, the increase in quota price affects $\bar{\alpha}$, and hence, the number of firms that comply. Regardless of whether $\bar{\alpha}$ shifts up or down, the production level decreases for the firms that change compliance behavior following the increase in quota price.

We can conclude that the effect of higher levels of current production capacity (k_0) is an initial increase in the demand for quotas. This yields an increase in the quota price, which in turn has a negative effect on input use and production levels. We summarize these effects in table 2.

Table 2: Partial effects of higher capital level on firms' in the short run by compliance behavior. *Notation: Compliant firms (C), non-compliant firms (N) and firms that shift between compliance and non-compliance (N↔C). Positive (+), negative (−) and no (0) effect.*

	Input use (K, L)			Production (Y)			Quota (Q)		
	C	N	N↔C	C	N	N↔C	C	N	N↔C
1) Higher capital level ($k_0 \uparrow$)	+	+	+	+	+	+	+	+	+(−)
2) Higher quota price ($a \uparrow$)	−	−	−	−	−	−	−	−	−
Total effect	+(−)			+(−)			0		

It follows from table 2 that a higher level of current production capacity in an industry not necessarily leads to an increase in total production in the case of transferable quotas. The reason is that while firms' initial reaction to high capital levels is to increase production and quota purchases, this implies increased quota demand, which raises the equilibrium

[9] Only for the quota demand effect of these firms to be positive requires that inequality (23) holds, with a_0 instead of a and γ instead of γ_0. In addition, the negative demand effect of these firms must outweigh the positive effect on demand of all other firms (compliant and non-compliant). This would generally not happen.

quota price. The higher quota price counteracts the incentive to increase production. The total effect depends on several factors, including the sensitivity of quota demand (and quota price) to increased production, which in turn depends on the current aggregate production level relative to the total quota. This result is summarized in proposition 5.

Proposition 5. *When quotas are transferable, the incentives to increase production as industry-level capacity increases are counteracted by an increase in the quota price.*

The main implication of proposition 5 is that quota tradability and well-functioning quota markets reduce the potential negative effects of excess capacity on illegal production (quota violations). This is a new argument for tradable quotas, in addition to the main argument that tradability increases efficiency in production as more efficient firms can buy quotas from less efficient firms.

6 Concluding remarks

We develop a stylized model of a quota regulated industry and analyze the relationship between enforcement, compliance and firm-level capacity. We show why in the short run, a high level of capacity strengthens the firms' incentives to violate quotas, and why firms' incentives to build up capacity in the long run are stronger if the expected punishment of quota violations is low. Hence, imperfect quota enforcement has implications both for capacity development and production level in the industry.

The cost of quota enforcement might differ considerably across resource industries. In the US sulfur dioxide program, authorities enforce quotas by requiring the installation of continuous emissions monitoring systems (CEMS) or equivalent devices. This enables the authorities to measure emissions in real time. Hence, enforcement is relatively cheap and can ensure close to full compliance. In fisheries, on the other hand, enforcement costs are significantly higher as the fishing operations are far more difficult to control (see e.g. Arnason et al., 2000). In such cases, it is unlikely that the economic gains of full compliance justifies the associated enforcement cost. Perfect quota enforcement is therefore far less likely in the fishing industry than in the US sulfur industry. In general, we have that when the cost of enforcement is relatively low, production quotas alone can ensure efficiency both in production and capital investment. However, when enforcement costs are high, quota enforcement is imperfect and the quota instrument alone is not sufficient to ensure efficiency.

Enforcement costs are considerable in fisheries, and hence, our results are highly relevant for this industry. In many fisheries worldwide excess capacity is a serious problem. According to a recent report from the United Nations Environmental Program, the current level of capacity in world fisheries is 1.8 to 2.8 times the desired level (UNEP, 2010). This estimate includes fisheries that are not quota regulated, however, capacity estimates for quota regulated fisheries show that excess capacity is widespread also in these fisheries. Quotas are a common instrument to limit total extraction in fisheries. However, if there was excess capacity in the fishery when individual quotas were introduced, the irreversibility of capital that characterizes many fisheries leaves firms with few incentives to reduce their capacity level in the short run. The investment is a sunk cost and disinvestment only happens gradually as the capital approaches the end of its economic lifespan (Clark et al., 1979). Hence, it may take many years from individual harvest rights are introduced until the capacity level has reached its long-run level. Our results show that the higher the level of current capacity, the stronger the firms' incentives to violate quotas. This has at least two policy implications for fisheries. First, policies aimed at reducing fishing capacity will also reduce illegal fishing. Second, assigning individual rights to quota shares at an early stage may reduce the problem of illegal fishing. Third, if quotas are transferable, the quota price will adjust and counteract the incentives to harvest illegally due to excess capacity.

In the long run, our results show that firm-level optimal capacity is lower under perfect enforcement than imperfect enforcement. Furthermore, we find that the lower the expected punishment of violating quotas, the stronger the firms' incentives to increase the level of capital (physical production capacity). If quotas are non-transferable, a change in expected punishment does not affect firms that comply with their quotas, since these firms are constrained by the quota and not by the expected punishment. However, when quotas are transferable, a change in expected punishment affects all firms operating in the quota market. More lenient enforcement causes non-compliant firms to decrease their demand for quotas. This causes the quota price to fall, which affects both compliant and non-compliant firms. In fact, the indirect market response to the change of enforcement acts as a multiplier that strengthens the initial response of firms.

In addition, if firms increase their capital level as a consequence of more lenient enforcement, they have stronger incentives to violate quotas once this higher level of capital is operational (short-run result). This result implies that assigning property rights to quotas is not enough to ensure efficient levels of capacity and production when enforcement is imperfect. Tradability and well-functioning quota markets improve the allocative efficiency in production and the non-compliance problem, but additional management instruments may nonetheless be necessary to ensure efficiency.

When quotas alone cannot ensure efficiency, capacity management is an option that may correct firms incentives to behave in socially desirable ways. Capacity management is, however, not straightforward as capacity in the real world, as opposed to our stylized model, typically is a multi-dimensional concept. Experiences from capacity management in fisheries show that when regulations are imposed on one dimension, such as the length of the vessels, the firms expand capacity along other unregulated dimensions, such as horsepower or vessel width. Consequently, all dimensions must be regulated to avoid the build-up of excess capacity. However, it may not be economically efficient to impose technological restrictions if these increases production costs. Hence, more work is needed to develop appropriate regulation and enforcement schemes in these situations.

We abstract from technological improvement in our analysis. Capital augmenting technological improvement increases the technical efficiency of a firm. For a constant technology level, we show that a compliant firm's incentives to violate the production quota increases with the level of physical capacity. Furthermore, a non-compliant firm's level of illegal production is increasing in the level of physical capital. If we think of technological progress as another input in production, the main results of the paper still hold. With technological progress, firms invest in a combination of capital and technology, generating the same relationship between non-compliance and investment in a combination of capital and technology.

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