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Individual Transferable Quota Markets under Illegal Fishing

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Abstract. The use of individual transferable quotas in fisheries has been considered an opportunity to achieve a given total allowable catch with a maximum social benefit. One of the assumptions used in obtaining that result is that the system is in perfect compliance. The presence of violations and the need for enforcement of tradable property rights systems in fisheries has not received much attention in the literature. The incidents of non-compliance, however, may affect the performance of transferable property rights-based fisheries in unexplored ways. In this paper, we adapt previous literature on enforcing emissions trading programs to analyze a positive model of fisherman behavior that operates under a perfectly competitive individual transferable quota system, while recognizing the opportunities for violations of quota holdings, given incomplete enforcement. Considering a poorly enforced, individual transferable quota system we are able to obtain a number of implications for the current and future equilibrium of the quota market, the time paths of the fishery, and the proper design of a policy rule on total allowable catch (TAC).

Key words: enforcement, illegal fishing, individual transferable quotas, quota markets

JEL classifications: L51, Q22

Abbreviation: ITQ – individual transferable quotas

1. Introduction

The use of individual quotas as regulatory instrument in fisheries is one of the most important innovations in the management of natural resources. Currently there are more than 60 property rights-based fishery programs in about 15 countries, which pursue efficiency gains by the creation and allocation of property rights in those fisheries. This implies that over 10% of the global ocean fish harvest is currently taken under a property rights management system (Arnason 2001). The imposition of a restriction in the aggregate catch level in a fishery, or the use of command-and-control type of regulations, are not able to eliminate the common property characteristics inherent in the exploitation of fishing resources. Unfortunately, these characteristics might cause negative economic effects, such as over-investment, excess of fishing capacity, seasonality of landings, and the alike; thus reducing the social benefits of the fishery. In this context, it is possible that the total allowable catch (TAC) may be achieved by maximizing the social benefit through regulatory policies based on the use of property rights.

The idea that a transferable property right system (also called an individual transferable quota [ITQ] system) would offer a regulator the opportunity to optimally organize the fishing activity was primarily proposed by Moloney and Pearse (1979). In their contribution, they were able to show that a competitive, transferable harvest rights system in fisheries would guarantee an equilibrium distribution of fishing rights among fisherman that maximizes aggregate net revenue. The harvest of a given total allowable catch would be attained in a socially efficient manner. Furthermore, they also show that the efficiency result is independent of the initial allocation of rights, which impacts only the distribution of rents from the fishery. The presumption of a well-behaved market for fishing rights, as well as the efficiency result obtained by these authors, assumed that a fisherman "is prohibited from catching in excess of his holding rights" [p. 366]. The incidents of non-compliance, however, may affect the performance of transferable property rights-based fisheries in unexplored ways.[1]

The theoretical and practical relevance of non-compliance in natural resource management programs and environmental regulations has been previously documented. For a recent review of this literature see Cohen (2000); in the specific area of non-compliance and enforcement of fisheries regulation see, for example, Sutinen and Andersen (1985), Anderson and Lee (1986), Milliman (1986), Anderson (1989), and more recently Charles et al. (1999). Furthermore, the presence of transgressions of individual quota holdings appears to be a relevant issue in the context of ITQ programs. In effect, Copes (1986) was one the first to point out a critical view regarding the operation of a property rights program in fisheries. Among his main concerns was the possibility of non-compliance behavior.

In practice, incidence of non-compliance has been reported in ITQ programs. For example, in the cases of the Herring fishery at Bay of Fundy, Canada, the program ended because fishermen acknowledged generalized transgressions of individual rights from their peers (Copes 1986). More recently, in the case of Chile, which has relatively new, less documented individual transferable quota systems, the incidence of violations and the need for a better enforcement design have been reported as relevant issues. For example, in the case of the Black Hake fishery, one of the fisheries being regulated under ITQ systems in the country, *"...presumed illegal catch has been estimated to reach up to 100% of TAC"* (Bernal et al. 1999, p. 137). Furthermore, in the Chilean case, from the four ITQ programs implemented during the 1990s, to our knowledge no active quota market has ever developed, and in two of them the fisheries were closed a few years after their implementation because of critical reductions in biomass. We tend to believe that the observed lack of quota market development, as well as the systematic reductions in biomass over time, may be related, at least partially, to enforcement problems.[2]

Despite the growing interest in ITQ systems and the evidence that non-compliance does exist and might be important, to our knowledge relevant questions remain unexplored in the literature. First, what are the effects that non-compliance behavior might have on the equilibrium of the quota market? Second, in the presence of quota violations, what are the effects that a change in TAC and biomass might cause in the equilibrium price of the quota, the level of harvest, and the extent of violations? Third, considering a plausible policy rule on TAC, what are the consequences of incomplete enforcement on compliance behavior, quota market equilibrium, and abundance of fish stocks over time? Fourth, what are the implications, if any, of incomplete enforcement in ITQ systems for designing a policy rule on TAC?

In this paper, we construct and analyze a model of fisherman behavior that operates under a perfectly competitive individual transferable quota system, while recognizing the opportunities for violations of quota holdings given fixed enforcement strategies that are insufficient to induce perfect compliance. We do so by adapting and combining previous work that explores causes and consequences of non-compliance in the context of markets for pollution rights, as well as literature that explores, from an economic perspective, the illegal behavior and the need for enforcement in the case of fisheries regulation (Sutinen and Andersen 1985; Malik 1990; Charles et al. 1999; Stranlund and Dhanda 1999). Considering a positive choice model of a risk-neutral individual fisherman in the context of an incompletely enforced transferable property rights-based fishery, we are able to obtain implications for the performance of the quota market, the consequences of changes in fish stock abundance, the time paths of the fishery, and the proper design of a policy rule on TAC.

The layout of the paper is as follows. In Section 2, we reconsider previous work that allows for non-compliance in the context of transferable emissions systems to study individual fisherman behavior. We specifically allow for the possibility that a fisherman chooses a level of fishing effort that induces a harvesting level that exceeds quota holdings. We assume there, and throughout the paper, a given fixed enforcement strategy which is insufficient to guarantee full compliance.

Considering the structure of the positive behavioral model, we then proceed in this section to consider individual fisherman's choices. Specifically, we examine choices of fishing effort, quota demand, and quota violation. These results were primarily obtained by Stranlund and Dhanda (1999) in the context of a transferable emissions permit system. Similar to what has been shown in the previous literature, in our context the extent of an individual violation of quota holdings is a choice that depends on the market conditions for landed fish, the enforcement pressure from the regulatory authority, the price of the quota, and the biological as well as the environmental conditions prevailing in the fishery. Although our analysis in this section is not original, the purpose of it is to set the stage in order to examine the effects of quota transgressions on quota market equilibrium; the consequences of changes in TAC and biomass on the equilibrium quota price, harvest level, and violations when enforcement is incomplete; and the equilibrium of the fishery over time under both, a plausible TAC rule and the presence of quota violations.

In Section 3, we start examining the consequences of the presence of quota violations on the equilibrium of the quota market. We show that an enforcement strategy that is insufficient to induce compliance will affect the equilibrium quota price in the current compliance period in a very specific manner: the equilibrium level of quota price will be lower than the equilibrium price in an otherwise perfect compliance system. Then, considering fixed, insufficient enforcement to induce perfect compliance, together with the equilibrium condition in the quota market, we explore how exogenous changes in TAC and biomass affect variables of interest: equilibrium quota price, harvest level, quota holdings, and the extent of the quota violation. While we show that an increase in the TAC will reduce both the equilibrium quota price and the extent of quota violation, we found, perhaps surprisingly, that an exogenous increase in the level of biomass will increase the equilibrium price of the quota, inducing higher levels of quota violation in the fishery. Policy recommendations from our findings are stressed. Further, we end this section by exploring the policy option to tie penalties for non-compliance to the equilibrium price of the quota in order to stabilize the level of quota transgressions.

Considering as given a plausible TAC policy rule, in Section 4 we investigate new time path possibilities for the fishery under the presence of non-compliance in a dynamic setting. Interestingly, we are able to show that, in our context, the presence of quota violations, combined with the use of a TAC rule based only on the result of a biological assessment, might induce future reductions in TAC, and depending on the specific situation, creating also greater incentives for quota transgressions through an increase in the equilibrium price of the quota. Furthermore, in light of these results and from a normative perspective, we identify and discuss how the TAC should be set in this context. Conclusions, implications, and possible extensions of this research are presented in Section 5.

2. A Model of Compliance in an ITQ System

The purpose of this section is to present a conceptual model of the individual fisherman's behavior and choices under an imperfectly enforced individual transferable quota (ITQ) system. The model that we present, as well as the analysis of individual choices, is largely based on the work of Stranlund and Dhanda (1999), and Malik (1990) in the context of transferable emissions permit systems.[3]

2.1. A MODEL OF FISHERMAN'S BEHAVIOR

To analyze the individual fisherman's compliance behavior, a regulated individual fisherman is considered. The analysis is based on a static model of a risk-neutral fisherman who operates under a perfectly competitive ITQ system. The fisherman's benefits are given by the difference between total revenue and total costs from fishing activity. Harvest level, $h(e, B)$, is a function of fishing effort, e, and biomass B, the latter assumed constant during the compliance period of analysis. The harvest level is strictly increasing and concave in fishing effort e; that is $h_e > 0$ y $h_{ee} < 0$. Cost of harvesting, $c(e)$, is strictly increasing and convex in the fishing effort e. Let q_0 be the number of fishing quotas allocated to the individual fisherman, and let q be the number of fishing quotas that the fisherman holds after transactions. Possession of a quota confers the legal right to harvest one unit of fish, for example, a ton.[4] We assume that total allowable catch (TAC), Q, is fixed, and that quotas trade at a competitive price w, while landed fish trade at a competitive price p. Finally, there are n fishermen participating in the fishery.

A violation of the individual quota holdings occurs whenever the fisherman's harvest level exceeds the number of quotas he holds; that is $[h(e, B) - q > 0]$. We assume that a system is in place to track the number of quotas that a fisherman holds.

In addition, we assume that the regulatory authority conducts random audits; that is, the fisherman is audited with probability θ. To simplify the analysis, we assume that an audit perfectly uncovers the presence and the extent of a quota violation, if it does exist.

From previous literature on enforcing environmental policies and natural resource management programs, if a violation is detected, a penalty $f(h(e, B) - q)$ is imposed (see, for example, Sutinen and Andersen 1985; Malik 1990; Keeler 1991; Stranlund and Dhanda 1999). We assume that the penalty is zero for zero quota violation $[f(0) = 0]$, but that the marginal penalty for zero quota violation is greater than zero $[f'(0) > 0]$. For positive quota violation, the penalty function is strictly increasing and convex.

As it is standard in the literature, we assume that an enforcement authority commits itself to a strategy and communicates this strategy to all fishermen. We assume that each fisherman chooses positive fishing effort and quota holdings and never over-complies. A fisherman chooses his fishing effort e (and consequently his level of harvest h) and his quota demand q to solve (1), taking the enforcement strategy as given.

$$\max_{e,q} ph(e,B) - c(e) - w(q - q_0) - \theta f(h(e,B) - q) \tag{1}$$

$$s.t.\ h(e,B) - q \geq 0.$$

The Lagrange equation for (1) is $L = ph(e,B) - c(e) - w(q - q_0) - \theta f(h(e,B) - q) + \mu (h(e,B) - q)$, and the Kuhn–Tucker conditions are:

$$L_e = ph_e(e,B) - c_e(e) - \theta f'(h(e,B) - q)h_e(e,B) + \mu h_e(e,B) = 0 \tag{2a}$$

$$L_q = -w + \theta f'(h(e,B) - q) - \mu = 0 \tag{2b}$$

$$L_\mu = (h(e,B) - q) \geq 0,\ \mu \geq 0,\ \mu \times (h(e,B) - q) = 0. \tag{2c}$$

Given the assumptions about the convexity of the functions, Equations (2a–c) are necessary and sufficient to determine the fisherman's optimal choices of fishing effort and the demand of quota.

2.2 FISHERMAN'S CHOICES: FISHING EFFORT, QUOTA DEMAND, AND QUOTA VIOLATION

In what follows we briefly analyze the fisherman's choices regarding fishing effort, quota demand, and the extent of quota violation. Our analysis here follows the contribution of Stranlund and Dhanda (1999) on an individual firm's choices in the context of an imperfectly enforced, transferable emissions permit system. Because we only reconsider some of their results in an ITQ context, we have decided to present them here and relegate the proofs to the Appendix A.

To begin, we consider a fisherman's choice of fishing effort (harvest). In our context, a fisherman chooses his fishing effort according to the result that follows.

Result 1. *Given an optimal choice of quota demand* (q) *and regardless of his compliance status, a fisherman chooses his fishing effort* (e) *so that*

$$w = p - [c_e(e)/h_e(e,B)] \tag{3}$$

From Result 1, it follows that the fisherman's choice of fishing effort is a function of the price of landed fish (p), the price of quota (w), and the level of biomass (B); then we write $e(p, w, B)$. It is easy to show that given strict convexity of harvest and cost functions, fishing effort is increasing in p and decreasing in w. In addition, it is also easy to show that an increase in biomass is likely to increase the optimum level of fishing effort, as long as more fish abundance increases the marginal productivity of effort (that is, $h_{eB} > 0$).[5]

Considering the analysis on the optimal choice of fishing effort, we are ready to study the demand for fishing quota for a fisherman operating under an ITQ system. Because Result 1 implies that $e(p, w, B)$, then, if the fisherman is compliant, it follows that $h(e(p,w, B),B) = q(p, w, B)$. However, if the fisherman is in violation, his demand for quota will depend not only on the net price of harvested fish, but also on the enforcement effort from the regulator. This is implied by the following result.

Result 2. *Given an optimal choice of fishing effort, a non-compliant fisherman will demand quota so that*

$$\theta f'(h(e(p, w, B), B) - q) - w = 0. \tag{4}$$

The marginal condition in (4) suggests that a non-compliant fisherman's quota demand is a function of the quota price, the price of landed fish, monitoring effort, and level of biomass; that is, $q^{nc}(w, p, \theta, B)$. It is possible to show that the quota demand under non-compliance is decreasing in quota price, and increasing in the price of landed fish, the monitoring effort, and the level of biomass.[6]

The previous analysis in the context of a transferable emissions permit system was further extended by Stranlund and Dhanda (1999) to study the determinants of the extent of a violation for a non-compliant firm. We restate that result in an ITQ context.

Result 3. *A non-compliant fisherman chooses the extent of the violation so that*

$$w = \theta f'(h(e(p, w, B), B) - q(w, \theta, p, B)). \tag{5}$$

Result 3 suggests that a non-compliant fisherman will harvest in excess of quota holdings up to the point where the marginal benefit from violating is equal to the expected marginal cost of the violation. Furthermore, Result 3 implicitly defines the extent of quota violation, $v = h(\bullet) - q(\bullet)$, as $v(w, p, \theta, B)$. Specifically, considering the effects of the exogenous variables on fishing effort and quota demand, as it was primarily shown by Stranlund and Dhanda (1999) in the context of market-based environmental policies, the extent of quota violation, v, is increasing in the price of the quota, and decreasing in enforcement effort. Further, in our context, while fishing effort and quota demand depend both on the price of landed fish and biomass level, the extent of quota violation does not.[7] We formalize these observations in the next result.

Result 4. *The optimal choice of quota violation implicitly defined by Result 3 as $v(w, p, \theta, B)$ is an increasing function of the quota price, and a decreasing function of the enforcement pressure perceived by the fisherman. Further, the extent of the quota violation is independent of the level of both the price of landed fish and the biomass, so that we can write, $v(w, p, \theta, B) = v(w, \theta)$.*

Fisherman behavior, as characterized by the previous restated results from the transferable emission permits literature to the ITQ context, is summarized by the representation in Figure 1. Let us assume for simplicity that $h = e$, and that the initial quota allocation is zero; that is, $q_0 = 0$. Further, we consider a given enforcement strategy which is insufficient to induce perfect compliance, θ_0. Then it is possible to see that the fisherman optimally chooses a level of effort (harvest) h^*, up the point where marginal benefit ($h(p,w,B)$) is equal to the equilibrium quota price. We notice here that the desired harvest level is independent of the enforcement effort θ_0 and the marginal penalty function, $f'(v)$. Further, the optimal violation level is determined at the point where the quota price equals the expected marginal penalty. The quota demand is given by the difference between them. Figure 1 also allow us to see that the quota demand under non-compliance, $q(\theta,w,p,B)$, is lower than the quota demand under perfect compliance, which is given by the marginal net benefit function. As we will see in section 3, this is important for understanding the effects of violations on the equilibrium price in the quota market.

3. Equilibrium in the Quota Market under Non-Compliance

In this section, we initially study the effects of the presence of non-compliant fisherman on the equilibrium of the quota market. Next, considering the presence of quota violations, we analyze the impact that changes in TAC and biomass might have on the equilibrium of the system. We end this section by exploring opportunities to stabilize quota violations in the face of exogenous fluctuations.

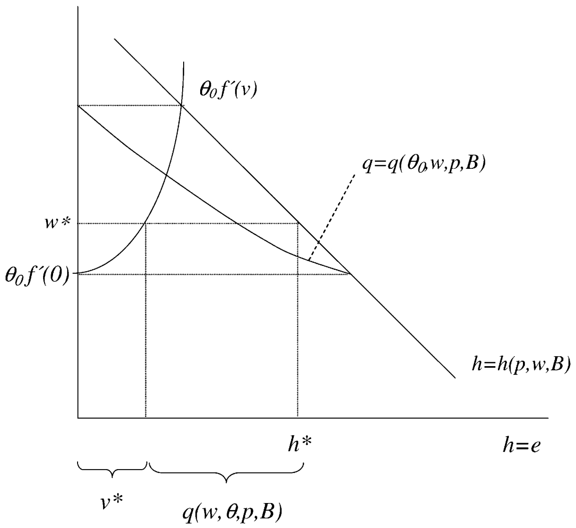

Figure 1. Fisherman’s behavior under imperfectly enforced ITQ system.

3.1 QUOTA VIOLATIONS AND THE EQUILIBRIUM QUOTA PRICE

We explore here the consequences of an ill-enforced transferable property rights-based fishery on the equilibrium quota price. Our primary purpose is to show that, in our context, the presence of non-compliance will alter the equilibrium quota price in a very specific manner.[8]

Let us assume a regulator who is implementing two alternative enforcement strategies, which are denoted, respectively, by θ^{c} and θ^{nc}. The strategy θ^{c} allows the regulator to achieve perfect compliance; while under the strategy θ^{nc} every fisherman is non-compliant. From Result 4, it must be true that $\theta^{c} > \theta^{nc}$. Furthermore, assume that all other variables remain constant, except the enforcement strategy. Using Result 2, we conclude that in such a situation quota demand under compliance is greater than quota demand under non-compliance; that is $h^{c}(e^{c}) = q^{c} > q^{nc}$. Then, the equilibrium quota price in a compliant market (w^{c}) and the equilibrium quota price in a non-compliant market (w^{nc}) are implicitly defined by the following equations,

$$\sum_{i=1}^{n} h_i^{c}\left(e_i^{c}(w^{c})\right) = Q \tag{6}$$

$$\sum_{i=1}^{n} q_i^{nc}(w^{nc}) = Q \tag{7}$$

We are now ready to establish that the presence of non-compliance alters the equilibrium quota price in a very specific manner. We restate Malik's (1990) proposition regarding the effect of non-compliance on the equilibrium quota price. To our context, the following proposition holds:

Proposition 1. *The equilibrium quota price in the presence of quota violations will be lower than the equilibrium quota price of an otherwise compliant ITQ system.*

Proof of Proposition 1. Consider the market clearing condition for a compliant quota market and a non-compliant quota market given by Equations (6) and (7), respectively. From the fact that $h^{c}(e^{c}) > q^{nc}$, and because $h^{c}(e^{c}(w))$ is strictly decreasing in w, it follows that in equilibrium $w^{nc} < w^{c}$ QED.[9]

In addition, by definition, aggregate harvest must be higher for an ITQ fishery in which fishermen are non-compliant; that is, the following relationship must hold:

$$\sum_{i=1}^{n} h_i^{nc}\left(e_i^{nc}(w^{nc}\right) > \sum_{i=1}^{n} q_i^{nc}(w^{nc}) = Q \tag{8}$$

The quota market equilibrium in the context of incomplete enforcement of an ITQ system is represented in Figure 2. Given incomplete enforcement, the

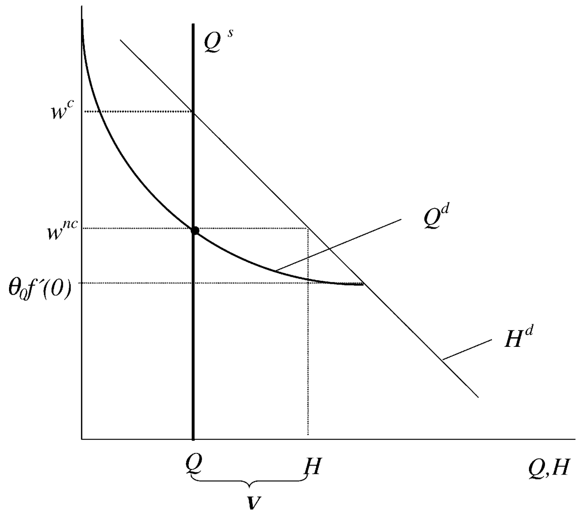

Figure 2. Equilibrium quota market under non-compliance.

individual quota demand, $q(\theta_0,w,p,B)$, is lower than the optimal level of harvest, $h(p,w,B)$, for each fisherman. Naturally, this holds at the aggregate level as well. Considering that the TAC level is given by Q, the equilibrium price of the quota market under non-compliance, w^{nc}, is lower than the equilibrium price under perfect compliance w^c. As a result, aggregated harvest, H, under non-compliance is greater than the TAC, Q; consequently, the level of aggregated violation, V, is given by, $V = H - Q$, with $V \equiv n \times v$.[10]

Considering the result in Proposition 1, we are able to argue that weak enforcement of an ITQ system might become a serious impediment for quota market development. To see that, let us assume that the expected marginal penalty tends to zero for all levels of v. In that case, it will be always better for a fisherman to incur a violation than to buy quota, harvesting until marginal net benefit of doing so is zero. This also implies that the harvest level will be equal to the harvest level attained under open-access. Under this situation no quota market will emerge.[11]

The previous hypothesis offers an explanation for the lack of quota market development observed in cases where ITQ systems have been implemented. Weak enforcement and institutions that are unable to induce adequate levels of compliance make it less likely that a market will succeed.[12]

3.2 EFFECTS OF CHANGES IN TOTAL ALLOWABLE CATCH AND BIOLOGICAL CONDITION OF THE FISHERY

In a market-based system, firms' choices and characteristics are linked together by a market. In an unpublished working paper, Stranlund (1998) has examined some of the linkages among firms in a market-based system for pollution control and their implications for enforcement. He is, to our knowledge, the first to notice that the presence of non-compliant individuals might impact the level of the choice variables of other members of the regulated population through the effect that violations of property rights have on the equilibrium price. Market effects are also present in an ITQ system. Specifically, in our context, we anticipate that fluctuations in total allowable catch (TAC), Q, and the level of biomass, B, might influence the choices of fishing effort, level of harvest, quota holdings, and the extent of violation, through effects on the equilibrium quota price.[13]

We start considering quota market equilibrium and individual choice equilibrium, and then move on to analyze the impact that changes in TAC, and changes in the level of biomass, might have on the equilibrium of the system in a given compliance period.[14] Considering only the variables of interest to simplify the notation, the equilibrium price of a quota is given by $w^{\text{nc}}(Q,B)$. Further, according to (8), the equilibrium quota price satisfies:

$$\sum_{n=1}^{n} q_i(w^{\text{nc}}(Q,B),B) = Q \tag{9}$$

The equilibrium price of the quota defines the equilibrium choices of the fisherman; namely, harvesting level, quota holdings, and the extent of quota violation, which are given by, $h^{\text{nc}}(Q,B) = h(e^{\text{nc}}\,(Q,B),B), q^{\text{nc}}(Q,B) = q(w^{\text{nc}}\,(Q,B),B)$, $v(Q,B) = v(w^{\text{nc}}(Q,B))$, respectively.

We are now ready to explore the impacts of exogenous changes in TAC and level of biomass on the equilibrium price, and on the equilibrium choices, while considering quota market effects in the presence of violations. Specifically, we offer the following proposition:

Proposition 2. *An increase in total allowable catch (Q) reduces equilibrium quota price, increases equilibrium harvest, increases equilibrium quota demand, and reduces the extent of the equilibrium quota violation.*

Proof of Proposition 2. First, to see how changes in total allowable catch affect equilibrium quota price, differentiate Equation (9), with respect to Q to obtain,

$$\frac{\mathrm{d}w^{\text{nc}}}{\mathrm{d}Q} = \frac{1}{\sum_{i=1}^{n}\left(\frac{\partial q_i}{\partial w^{\text{nc}}}\right)} < 0 \tag{10}$$

The sign of the above follows from the fact that individual quota demand under non-compliance is a decreasing function of quota price.

Second, to derive the effect of a change in TAC on the equilibrium fishing effort, equilibrium harvest, equilibrium quota demand, and equilibrium violation, differentiate the equilibrium choices with respect to Q to obtain,

$$\mathrm{d}h^{\mathrm{nc}}/\mathrm{d}Q = h_e \times e_w \times \mathrm{d}w^{\mathrm{nc}}/\mathrm{d}Q > 0 \tag{11a}$$

$$\mathrm{d}q^{\mathrm{nc}}/\mathrm{d}Q = \mathrm{d}q/\mathrm{d}w^{\mathrm{nc}} \times \mathrm{d}w^{\mathrm{nc}}/\mathrm{d}Q > 0 \tag{11b}$$

$$\mathrm{d}v/\mathrm{d}Q = \mathrm{d}v/\mathrm{d}w^{\mathrm{nc}} \times \mathrm{d}w^{\mathrm{nc}}/\mathrm{d}Q < 0, \text{ Q.E.D.} \tag{11c}$$

The increase in TAC reduces the equilibrium level of quota price, thus increasing the equilibrium level effort and quota demand. Furthermore, because violations are increasing in equilibrium quota price, a reduction of price, induced by greater level of TAC, will reduce the level of harvest that exceeds the quota holdings. The result suggests that, holding everything else constant, bad fishing seasons in terms of lower TAC will induce more quota transgressions. This is so because a lower level of TAC will generate upward pressure on the equilibrium quota price, i.e., a greater incentive to violate the quota holdings.[15]

Considering that biomass is exogenous, we also study the impact of changes in biological or environmental conditions on the equilibrium choice variables and quota market results, in an ITQ system under non-compliance. That leads us to our next proposition:

Proposition 3. *An increase in the level of biomass increases the equilibrium price of the quota, and increases the extent of the quota violation.*

Proof of Proposition 3. To see how changes in biomass (B) affect the equilibrium quota price, we proceed as follows. Differentiating Equation (9) with respect to B to obtain,

$$\frac{\mathrm{d}w^{\mathrm{nc}}}{\mathrm{d}B} = \frac{\sum_{i=1}^{n}\left(\frac{\partial q_i}{\partial B}\right)}{\sum_{i=1}^{n}\left(\frac{\partial q_i}{\partial w^{\mathrm{nc}}}\right)} > 0 \tag{12}$$

The sign of the above follows from the fact that individual quota demand under non-compliance is an increasing function of biomass, and a decreasing function of quota price.

Next, consider $v(w(B,Q))$ and differentiate it with respect to B. From Result 4, the choice of quota violation is increasing in quota price, we obtain

$$\mathrm{d}v/\mathrm{d}B = \mathrm{d}v/\mathrm{d}w^{\mathrm{nc}} \times \mathrm{d}w^{\mathrm{nc}}/\mathrm{d}B > 0. \text{ QED} \tag{13}$$

Proposition 3 suggests that, in equilibrium, an increase in the level of biomass increases the level of quota violation. This is because although a greater level of biomass increases both the level of harvest and the demand for quota under non-compliance, it puts upward pressure on the equilibrium quota price. These effects generate an increase in the chosen level of the extent of the violation of quota holdings.

The result might perhaps contradict the intuition that a good fishing season in terms of resource availability is expected to induce a lower level of violations. However, we should remember that only the relation between the marginal expected penalty and the equilibrium level of quota price gives the optimum level of violation.

Interestingly, our result in Proposition 3 suggests that an exogenous increase in biomass that is not coupled with an increasing TAC will induce more violation in the fishery. The result has important policy implications. In real settings, the level of TAC is usually announced before a given fishing season starts and is set based on biological assessments. If unexpected changes in biomass occur within the compliance period, the regulated population of fishermen will perceive them while they are fishing. Thus, given a fixed TAC, we anticipate a greater level of quota holdings violations. Therefore, considering an imperfectly enforced ITQ system in the face of a biomass increase, it would be desirable that the regulator responds by adjusting the TAC accordingly during the season. In contrast, when facing a reduction in biomass, our model predicts a reduction in violations. In that case, our result suggests that the regulator should be able to keep the same levels of non-compliance when contracting the TAC. Clearly, our result calls for using a flexible TAC rule that allows changing the TAC within a given compliance period.[16]

3.3 STABILIZING QUOTA HOLDINGS VIOLATIONS UNDER INCOMPLETE ENFORCEMENT

From the last two propositions we infer that a change in any exogenous variable that affects the equilibrium quota price will finally affect equilibrium violations because an increase in the equilibrium quota price implies a greater incentive to increase harvest level above quota holdings. Considering the relevance of equilibrium prices on compliance decisions in the context of market-based environmental policies, Stranlund and Chavez (2000) have suggested tying marginal penalties to equilibrium prices to stabilize compliance incentives, and implementing monitoring requirements to ensure full compliance. Following that suggestion, the effect of a change in the equilibrium quota price on the equilibrium choice of violation can be avoided, thus isolating the extent of non-compliance from any exogenous fluctuation on the system. For example, suppose that the penalty for quota violation is linearly tied to the equilibrium quota price; that is, $f(v) = wg(v)$, where $g(0)=0$, $g'(0) > 0$, $g''(v) > 0$. From Result 4, we know that the optimal level of quota violation is fully determined by $w = \theta f'(v)$. Under the proposed penalty structure, it follows that the quota violations is given by $w = \theta wg'(v)$, which implicitly defines $v^* = v(\theta)$, suggesting that the extent of the equilibrium quota violation is independent of the equilibrium quota price. As we discuss later in Section 4, the suggestion on how to set the penalty structure in the context of an ill-enforced ITQ system also has important implications for the stabilization of the level of harvest over time when a biomass-based TAC rule is used.

4. Violations and Quota Market over Time: An Exploratory Analysis

In this section, we explore the effects that incomplete enforcement, combined with a plausible TAC rule, will have on future compliance behavior in an ITQ system.[17] The analysis assume a naive regulator who, when setting the TAC, ignores the presence of violations. Specifically, we investigate the consequences that the presence of quota transgressions on a given compliance period might have on future compliance behavior through quota market effects. To do so we introduce a dynamic analysis. We show that different time paths are possible. Considering our results, we are able to propose an alternative rule to be used for the definition of the TAC when perfect compliance cannot be guaranteed.

Let us assume that an ITQ system is being implemented and the regulator ignores potential quota violations when deciding the TAC. The regulator is assumed to set the TAC level based on the result of a biological assessment of biomass in the fishery. Specifically, let $Q(B_t)$ denote the TAC level as a function of the observed biomass B_t, with $Q'(B_t) > 0$. Further, as before, assume that the enforcement strategy is insufficient to induce perfect compliance with quota holdings, so that violations of the quota occur.

To simplify the analysis, assume that the fishery is under a steady state equilibrium in biomass with the TAC level equal to biomass growth, $Q(B_t) = F(B_t)$, where $F(B_t)$ denotes the growth in biomass at period t, with $F'(B_t) > 0$. In this context the regulator expects that the level of biomass and the TAC will remain constant for the next period. Because enforcement is insufficient to avoid illegal fishing, the aggregate level of violations of quota holdings in period t is greater than zero ($V_t > 0$). To simplify the notation, we focus on variables of interest by, which aggregate harvest in the fishery in period t is given by

$$H_t(Q_t(B_t), B_t) = Q_t(B_t) + V_t(w^{\mathrm{nc}}(Q_t(B_t), B_t) \tag{14}$$

Consequently, the biomass level in period $t+1$ will be lower than the regulator expects it to be. That is,

$$B_{t+1} = B_t + F(B_t) - Q_t(B_t) - V_t = B_t - V_t < B_t \tag{15}$$

From Equation (15), we found that in the presence of incomplete enforcement, biomass necessarily decreases over time. Interestingly, in our context it also suggests that if a regulator fails to take into account quota violations when setting the TAC, sooner or later the fishing activity will be banned to allow the recovery of the fishery. However, as we will see shortly, how quickly this happens will depend on the net effect on the equilibrium quota price from both, the biomass reduction and the regulator response in terms of adjusting the level of TAC. To see this, consider further, that at the beginning of period $t+1$ a new biological assessment of the fishery is performed, the reduction in biomass is revealed, and a new TAC level is set based on the new information available. Thus, TAC level for period $t+1$ will be lower than TAC in period t, i.e.,

$$Q_{t+1}(B_{t+1}) = F(B_{t+1}) < F(B_t) \tag{16}$$

What will be the effect of enforcement that is insufficient to induce perfect compliance and a biomass-based TAC on the equilibrium quota price, level of harvest, quota holdings violations, biological conditions of the fishery, and TAC level over time? The incidence of violations in period t will reduce the biomass level assessed starting in period $t + 1$, consequently reducing the TAC in $t + 1$; in turn, both changes will affect the equilibrium quota price in $t + 1$. Two effects on equilibrium quota price, having opposite sign, are likely to occur. First, there is a "supply" side effect. This effect occurs because of the reduction in TAC induced by the biomass reduction given quota holdings violations in the previous period. According to Proposition 2, this effect puts upward pressure on the equilibrium quota price. Second, there is a "demand" side effect. This effect occurs because the reduction in biomass caused by violations in the previous period will reduce both the harvest level and quota demand, creating downward pressure on the equilibrium quota price. The net effect is case-specific. Consequently, equilibrium quota price may increase or decrease in $t + 1$. Furthermore, because the choice of the violation in that period is an increasing function of the equilibrium quota price, the effect of weak enforcement and the assumed TAC policy rule on compliance behavior is also case-specific.

Our analysis suggests that different paths for variables of interest are possible. In case the equilibrium quota price increases over time, a lower level of biomass that reduces TAC will increase the aggregate level of violation. This in turn implies further reductions in biomass, increases on equilibrium quota price over time, and further increases in the level of violations. In contrast, in the case in which reductions in biomass that reduce TAC cause a reduction in the equilibrium quota price over time, the extent of quota violations will fall over time. We present this result in the following proposition.

Proposition 4. *Under an ITQ system where enforcement is insufficient to induce perfect compliance, and the TAC level is set based on the result of a biological assessment of the fishery, biomass levels will be reduced over time, TAC will be reduced over time, equilibrium quota price will increase (decrease) over time, and quota violations will increase (decrease) over time.*

Proof of Proposition 4. Let suppose that the enforcement strategy is insufficient to induce perfect compliance. Further, assume that TAC is set based on information from the biological assessment. In this context, Equations (15) and (16) indicate that biomass and TAC decrease over time. Proposition 2 and Proposition 3 suggest that while TAC reductions tend to increase the equilibrium quota price, biomass reductions tend to decrease it. Therefore, the effect of weak enforcement on equilibrium quota price is case-specific. According to Result 4, if equilibrium quota price increases (decreases), then the level of violations increases (decreases). QED.

The result in Proposition 4 suggests that the actual time path for variables of interest critically depends on the effect of biomass changes over equilibrium quota price. We found that actual paths for variables of interest are especially sensible to the level of two specific parameters from both the "demand" and "supply" sides. As for the "demand" side, the effect of a change in biomass on equilibrium quota price depends on the sensibility of fishermen's marginal benefits to biomass fluctuation, which in our context is represented by the sensitivity of the marginal productivity of the effort with respect to changes in biomass. As for the "supply" side, the effect depends partially on the regulator's response in terms of the change in the level of TAC with a declining level of biomass. Furthermore, the result in Proposition 4 also indicates that how equilibrium quota price move over time, i.e., whether it increases or decreases, will influence how fast biomass reduction occurs. For example, if equilibrium quota price increases, it will trigger an increase in violations over time, and consequently a faster reduction in biomass compared to a situation where equilibrium quota price decreases over time. A biomass-based TAC under an ill-enforced ITQ system will induce the regulator to reduce the TAC in the presence of biomass reduction. This will put upward pressure on the equilibrium quota price, inducing a faster biomass decline over time.

We noticed that in the presence of quota violations, the regulator could not guarantee that the aggregate harvest level follows the TAC (and biomass) over time. Specifically, it is possible that the aggregate harvest remains constant, or even increases, while the regulatory authority is tightening the TAC over time. However, as we have suggested in Section 3.3, there is a way to avoid this undesirable effect. By tying the penalty function to the quota price, the regulator will be able to stabilize compliance incentives, thus isolating quota compliance choices from quota price over time. In that case, aggregate violations will remain constant, and will be independent of the fluctuations of any exogenous variable except monitoring effort. Furthermore, in that situation changes in TAC over time will cause a change in the aggregate level of harvest of the same magnitude.

The previous analysis accounts for the biological and economic interactions relevant to individual fisherman behavior under an imperfectly enforced ITQ system in fisheries. It suggests that setting TAC levels based exclusively on observed biological conditions might end worsening the situation in the fishery over time, up to a period when the activity needs to be banned to allow the recovery of the species.

To our context, when setting the TAC, the regulator should explicitly consider not only the biological information on biomass assessment, but also the expected level of violation for the current compliance period (V_t^e). In effect, by using Equation (16) it is clear that if the regulator sets the TAC as

$$Q_t = F(B_t) - V_t^e \tag{17}$$

it would avoid, at least partially, the negative biological consequences of the violations. Naturally, the suggestion is useful only if the regulator is able to adequately estimate current period aggregate violation. Although the discussion on how to estimate the aggregate level of violation in an ITQ fishery is far from our purpose, the previous analysis might be useful in identifying key factors determining the expected fishermen's compliance behavior. Of course, it is clear that the expected level of violation in any given compliance period is likely to depend on the degree of enforcement pressure and institutional weakness, and on the expected level of equilibrium quota price.

5. Conclusions

In this paper, we have analyzed a positive choice model of a fisherman regulated under an individual transferable quota system with opportunities for violations of quota holdings. In our context, we reconsider individual choices of fishing effort, quota demand, and the extent of the violation. Furthermore, we explore the equilibrium quota market in the presence of non-compliant fishermen, and we compare it with a perfect compliance situation. Considering equilibrium choices of fishermen, we then study how these choices interact with two particularly interesting exogenous variables of the model; namely, TAC, which is under regulator control, and biological conditions in the fishery, which is likely to depend on environmental conditions.

We obtain several implications from our work. First, we have been able to show that, in our context, the presence of non-compliance will affect the equilibrium quota price in a very specific manner: it will reduce the equilibrium quota price compared to a situation of full compliance. Second, we show that equilibrium choices of a fisherman depend not only on economic conditions in the fishery, but also on the TAC's regulatory control, and biological and environmental conditions.

Considering the compliance decision in a given period, we found that a good fishing season, characterized by a greater level of biomass, might increase violations because it puts upward pressure on quota price through the increase in quota demand. Increasing the total allowable catch might mitigate that effect. This result is useful for policy-makers, because in the context of information problems, a regulator facing an unexpected increase in biomass would want to increase TAC within the fishing season period, when it is probably more likely to be better informed.

Furthermore, when considering an ill enforced ITQ system, as well as TAC, harvest, and biomass over time, we obtain different possible time paths for the fishery. We were able to propose an alternative TAC policy rule, one in which the regulator explicitly takes account of the expected violations during the season. In addition, we also discuss the desirability of tying penalties to the equilibrium quota price in the context of an imperfectly enforced ITQ system. By doing so a regulator will be able to ensure that violation choices are independent of exogenous variables except monitoring effort, and that the aggregate level of harvest adjusts over time exactly as it is defined by the TAC. This result is interesting because it suggests that by providing a proper TAC rule, even with incomplete enforcement, an ITQ program will be able to ensure biomass recovery.

Our work can be extended in a number of ways. Let us to mention three of them. One of the major concerns in the literature about implementation of ITQ systems has to do with the possibility of concentration of quota and the exercise of market power. Re-examining our results in the context of market power will be worth pursuing. In addition, exploring how less than perfectly enforced ITQ systems interact with other types of violations that are common in fisheries, like bycatch discards and highgrading, is another possible road of future research. Finally, we think it will be also interesting to complement the conceptual analysis of this paper with empirical work. Using numerical simulations that will require specific parameter estimations, we will be able to analyze quota market performance and fisherman behavior over time. Two basic elements that we are considering in defining the setting are different types of weak enforcement strategies and alternative TAC policy rules. We plan to implement this analysis for the case of the prawn fisheries in central-south Chile where, as we have previously mentioned throughout the paper, ITQ systems were introduced to allow the recovery of the biomass, but unfortunately the programs failed and the fisheries have been temporally closed. We think that our model of incomplete enforcement – a feature that is likely to be found in developing countries because of institutional weakness, budget constraints, and absence of expertise – might help to explain this regulatory failure.

The use of transferable property rights to regulate fisheries has been moving from the academic agenda to the realm of policymakers who are responsible for the regulation and management of fisheries. Exploring these and other issues might contribute to a better design of these programs.

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Notes

1. In this paper, the only non-compliance behavior explored is quota holdings transgressions. However, other important enforcement problems in fisheries are bycatch discard (catching and discarding nontargeted species for which no quota exists) and highgrading (discarding lower-valued members – younger fish, for example – of the targeted species). We acknowledge that although these types of non-compliance might be affected by individual transferable quotas, the model in this paper has nothing to say about these particular problems. We are grateful to an anonymous referee for this observation.
2. Interestingly, in the Chilean case three of the four ITQ programs implemented in the last decade were intended to allow the recovery of biomass in overexploited fisheries.
3. These contributions are primarily focused on the analysis of the causes and consequences of non-compliance, and the proper design of enforcement strategies to induce adequate levels of compliance.
4. We do not consider the possibility of quota banking or borrowing.
5. Interestingly, an important implication for an ITQ system also follows from Result 1. Since all fishermen face the same price of quota as well as the same price of landed fish, in equilibrium, fishermen's marginal net benefits are all equal. This is the standard condition for maximizing social benefit, so that, even under non-compliance the distribution of effort between fishermen is optimal.
6. For a thorough proof of these comparative static results see Stranlund and Dhanda (1999).
7. The exploration of this issue was motivated by the results of Stranlund and Dhanda (1999). In the context of a transferable emissions permit system, they were able to show the surprising result that the choice of a violation is independent of the exogenous individual firm's characteristics. As in their work, in our context the optimal level of violation is determined at the point where the quota price equals the expected marginal penalty. The marginal benefit of being non-compliant is the forgone cost of being in compliance, which

is the quota price. The expected marginal penalty represents the expected cost of being caught harvesting without holding that unit of quota. Holding everything else constant, a change in the price of landed fish will not affect the extent of individual violation because it will cause the same changes (in magnitude and direction) on both the optimal level of harvest and the optimal level of quota demand. In the same fashion, although an exogenous change in the level of biomass will change both the individual choice of harvest and quota demand, it will not have any effect on the optimal choice of quota holdings transgression. As we will see in Section 3, this result does not hold when considering the quota market equilibrium condition together with the equilibrium choices. This is so because in that situation, the change in quota demand will modify the equilibrium price of the quota, thus changing the marginal benefit of being non-compliant with quota holdings.

8. The implications of the presence of violations for the performance of a pollution permits market have been previously analyzed in the literature (see Malik 1990; Keeler 1991). We shall notice that although the analysis on the effect of non-compliance on the quota market equilibrium is not original, it is a departure point for the analysis of the consequences on the equilibrium of the quota market from exogenous changes in both total allowable catch and the level of fish abundance.
9. Malik (1990) is, to our knowledge, the only one in this literature who considers risk attitudes. In fact, our Proposition 1 holds because of the assumption of risk neutrality. Although not proved here, this also holds under risk aversion; however, it may not hold under risk-loving preferences.
10. As primarily noticed by Stranlund and Dhanda (1999), if all agents face the same price and the same expected marginal penalty, they will choose the same compliance status. Furthermore, if they choose to be in violation, the extent of the property rights transgression will not differ among them.
11. Weak enforcement, characterized as perceived low expected marginal penalty, may appear either because of the low perceived probability that a violation will be discovered, or because of the perceived notion that if a violation is discovered, penalties and/or sanctions will likely be low. This might be a relatively more serious issue in the context of developing countries, where there are usually weak institutions, as well as less experience with markets and enforceability of property rights.
12. The "Red Prawn" and the "Yellow Prawn" fisheries in Chile provide an example of this situation. In both cases ITQ systems were introduced as a management tool in 1992 and 1997, respectively. The use of transferable property rights was intended to allow the recovery of biomass. Unfortunately, both fisheries were closed in 2001 after critical reductions in biomass were identified. A non-official explanation for these significant reductions in biomass levels is the presumed high level of non-compliance. In both cases, to our knowledge, no quota market ever emerged.
13. While in real settings the TAC is typically chosen by the regulatory authority, the level of biomass fluctuates depending upon biological and environmental conditions. In that sense our exploration of the effect of changes in these variables is motivated by the possibility of changes in both fisheries policy as well as biological or environmental conditions. A relevant example of the latter is climate change.
14. We are not considering potential dynamic effects. Even though compliance is a period-by-period decision, the level of biomass in any given compliance period is probably determined by the level of biomass, TAC, and aggregate harvest in the previous period. In Section 4, we explore the effects of weak enforcement on the equilibrium of a property rights-based fishery from a dynamic perspective.
15. The result has policy implications for the design of enforcement strategies in a fishery regulated with transferable property rights. Our result implies that a reduction in the TAC

may need to be coupled with more enforcement effort, which would require an adjustment in the enforcement budget and/or a reallocation of enforcement effort among regulated fisheries.

16. Practical problems for implementation of this suggestion are not discussed here. For example, our suggestion would require continuous biological assessments within the compliance period. In addition, once the TAC is set for the season, it may be politically more viable to increase it than to reduce it.
17. We are grateful to an anonymous referee of this journal for suggesting that we explore this issue.

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Appendix

Proof of Result 1: Suppose that the fisherman is non-compliant so that $h(e, B) - q > 0$. Then (2c) requires $\mu = 0$. Thus, (2a) becomes $ph_e(e,B) - c_e(e, B) - \theta f'(h(e, B) - q)h_e(e,B) = 0$, and (2b) becomes $- w + \theta f'(h(e, B) - q) = 0$. Taking together, (2a) and (2b) then imply $(p - w) h_e(e,B) - c_e(e, B) = 0$. Now suppose that the fisherman is in compliance. In this case its objective function reduces to $ph(e,B) - c(e, B) - w(h(e,B) - q_0)$, the maximization of which requires $w = p - [c_e(e) / h_e(e,B)]$. QED.

Proof of Result 2: To obtain this note from (2b) and (2c) so that $h(e(p, w, B), B) - q) > 0$ implies $\mu = 0$ and $L_q = - w + \theta f'(h(e, B) - q) = 0$. Substituting the fisherman's fishing effort choice yields $\theta f'(h(e(p, w, B), B) - q) - w = 0$. QED.

Proof of Result 3: From Result 2 note that the demand of quota for a non-compliant fisherman is implicitly defined as $q^{\mathbf{nc}}(w, \theta, p, B)$. Replacing this in Equation (4) yields

$$w = \theta f'(h(e(p, w, B), B) - q^{\text{nc}}(w, \theta, p, B)).\ \text{QED.}$$

Proof of Result 4: The optimum level of violation, v, is given by

$$v(p - w, w, \theta, B) = h(e(p - w, B), B) - q^{\text{nc}}(w, \theta, p, B) \tag{A1}$$

Taking the derivative in (A.1) with respect to p, we have

$$\text{d}v/\text{d}p = h_e e_p - \text{d}q^{\text{nc}}/\text{d}p$$

Differentiating Equation (5) in the text with respect to p, we found that $\text{d}q^{\text{nc}}/\text{d}p = h_e e_p$, so that

$$\text{d}v/\text{d}p = 0 \tag{A2}$$

Taking the derivative in (A.1) with respect to B, we have

$$\text{d}v/\text{d}B = h_e e_B + h_B - \text{d}q^{\text{nc}}/\text{d}B$$

Differentiating Equation (5) in the text with respect to B, we found that $\text{d}q^{\text{nc}}/\text{d}B = h_e e_B + h_B$, so that

$$\text{d}v/\text{d}B = 0 \tag{A3}$$

Taking the derivative in (A.1) with respect to w, we have

$$\text{d}v/\text{d}w = -h_e e_p - \text{d}q^{\text{nc}}/\text{d}w$$

Differentiating Equation (5) in the text with respect to w, we found that $\text{d}q^{\text{nc}}/\text{d}w = -[1/\theta f''(v) + h_e e_p]$, so that

$$\text{d}v/\text{d}w = 1/\theta f''(v) > 0 \tag{A4}$$

Taking the derivative in (A.1) with respect to θ, we have

$$\text{d}v/\text{d}\theta = -\text{d}q^{\text{nc}}/\text{d}\theta$$

Differentiating Equation (5) in the text with respect to θ, we obtain

$$\text{d}q^{\text{nc}}/\text{d}\theta = f'(v)/\theta f''(v),\ \text{so that}$$

$$\text{d}v/\text{d}\theta = -f'(v)/\theta f''(v) < 0$$

From (A.2) to (A.5) we have that for an optimal choice of quota violation $v(w, p, \theta, B)$; the following comparative static result hold:

	w	p	θ	B
v	+	0	−	0

QED.