

Potential pitfalls in an international regulation game with two regulators in a free-trade agreement

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Abstract: I propose an international regulation game between regulators in a free-trade agreement bloc. I develop a market model of the fishing industry to demonstrate that regulators can be stuck in an inferior equilibrium and international coordination may be needed to implement better regulation. Unlike traditional trade wars that exhibit Prisoner's Dilemma patterns, this industry game has two equilibria; thus coordination is necessary only to change the regulation, not to maintain it. I also show that the adoption of individual quotas in place of derby fishing can have features of "beggar-thy-neighbor" policy, and can be detrimental to global welfare and to the national welfare of the adopting country. The leading cause of these adverse effects is inelastic demand. Moreover, individual quotas are likely to facilitate transfer of wealth from consumers to producers. I calibrate the model so that it resembles the situation in the North Pacific halibut fishery and successfully verify its predictions using empirical evidence.

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1. Introduction

The growth of literature on the subject of policy coordination and the applications of game theory to international economics reflects a growing number of challenges faced by politicians and economists. The coordination of tax policy to prevent a “race to the bottom” (see for instance Baldwin and Krugman, 2002), the coordination of macroeconomic policy (Oudiz et al., 1984), the problems with the environment being a public good (Kolstad, 2014), as well as the presence of tariffs, international trade and foreign competition (Baldwin and Jaimovich, 2010) are some of the most notable examples. It is not surprising that these topics are of interest to economists, especially, in the wake of strengthening ties across borders.

Implementation of policies potentially improving welfare in the implementing country but diminishing it in other countries, commonly known as “beggar-thy-neighbor” policies, has been of interest recently, mostly in the context of macroeconomics, trade, and labor market policy (see for example Dinopoulos and Unel, 2014). Surprisingly, there is little literature on the interaction between industry regulators in countries forming a free-trade agreement bloc or participating in other forms of union that facilitates the transmission of policy effects. Many products or services traded between such countries are created in highly regulated industries, for example the automotive industry, chemical industry, food industry, mining, or pharmaceutical industry.² As regulation in one country changes, it is interesting to observe what effects it can have on the other country participating in the common market. Can adoption of potentially better regulation hurt the trading partner? Will the introduction of supposedly better regulation in just one country enhance or reduce total welfare? Can a country suffer internal welfare loss from adoption of potentially superior regulation because of the change it induces on the partner’s industry through the global market? If so, can regulators in the two countries be locked in an equilibrium whereby nobody has incentives to switch to superior regulation merely because of the nature of the market for the product? In this paper I explore possible answers to these questions using an example of interaction between separately regulated fisheries. Depending on the circumstances, I find that all of these questions can be answered “yes.”

Many economic problems arise in relation to fisheries. Probably the first to be noticed by the general public, and still pervasive, is the problem of overfishing. In this perfect example of a common-resource problem (see Clark, 1976, p. 32) the unregulated behavior of fishermen can, and often does,

² Also, many industries supplying a single market within one country, are split into segments that are separately regulated (e.g. by state or regional regulatory agencies).

lead to collapse of the stock. This problem arises as an effect of a stock externality (which is most generally defined as an inter-temporal externality; that is, actions of the present have unaccounted-for effects in the future). At least in theory, it can be effectively solved by imposing total annual catch limits or, in other words, seasonal quotas determined by biologists usually working with the fishery regulatory agency (Clark, 1980). Once this measure is effectively implemented, other economic problems draw attention. First, is the problem of derby fishing (Clark, 2006, p. 77): fishermen tend to increase their fishing effort to exorbitant levels as they try to catch as many fish as possible before the annual quota runs out. It is a simple game theory exercise to show that derby fishing is an equilibrium behavior. Derby fishing as well as other regulated open access regimes result in so-called *input stuffing*, where unregulated inputs (e.g., effort) replace regulated inputs (e.g., time or some types of gear) causing inefficiency in the production process and rent dissipation.

Initially, the inefficiency and welfare loss under derby fishing were attributed to the fact that very high levels of effort are not economically justified and result in rent dissipation even though a substantial profit could be made, given that the supply is limited (Weninger, 1998). The solution to this problem, originally suggested by Christy (1973), is to introduce individual quotas. This regulatory regime comes in many flavors, but the essence is that each fisherman (or fishing vessel) has a permit to catch a specific amount of fish within the season. This eliminates incentives for derby fishing, since nobody can increase their catch over the limit. As numerous studies show, this solution indeed generates rents from fishing, which can be proxied by price of individual quotas, as long as trading or leasing is possible (see, for example, Newell et al., 2005).

An unexpected consequence of the introduction of individual quotas is that they often lead to an increase in price, usually attributed to an increase in quality (see, for example, Herrmann, 1996). As the annual quota remains unchanged while season length expands, fishermen have more time to handle the fish and they do not glut the market with the annual catch over a short period of time. Thus, considerably more fish can be marketed as fresh rather than frozen, which contributes to higher prices and increased revenues. As a result of individual quotas, there are both cost savings and revenue increases.

Various studies have tried to estimate the effects of individual quotas and to build models that allows for useful predictions.³ These models are usually empirical and focus on making predictions with respect to a single variable. There is a lack of a theoretical model that would include both production efficiency gains and effects of price increases and allow for comprehensive welfare analysis. Such a model would assist in explaining the benefits of transition from derby fishing to individual quotas and would potentially improve further empirical practice. In this paper I attempt to fill this gap, propose such a model, and then use it to analyze a situation in a sample international fishery, in the context of an international regulation game.

A considerable number of papers attempt modeling a fishery in an inter-seasonal setting. This entire literature was launched by Gordon (1954) and further developed, most notably with milestone articles, by Copes (1970) and Clark (1980). Nonetheless, these articles focus on the stock externality, rather than production efficiency or consumer surplus. To proceed with a profit and consumer surplus analysis, it is necessary to construct an intra-seasonal model based on the assumption that the problem of overfishing already has been efficiently solved. One such model was proposed by Homans and Wilen (2005). Their work is probably the most closely-related to the model I develop herein. However, the authors focus mostly on the demand side and do not attempt modelling input stuffing. Moreover, the authors abstain from any analysis of consumer surplus.

The article by Homans and Wilen provides insights concerning the result of demand growth on the season length, but is difficult to adapt for welfare analysis and modeling of input stuffing. Also, as the authors point out, their model does not allow for any comparative statics. Modelling an international regulation game requires analysis of these three elements which in turn requires a completely new model. In contrast to their work, I decided to make the following assumptions on which to base my analysis. There is no discounting, because we are operating in a single period (that is one year). I neglect stock effects which were originally developed to facilitate inter-temporal analysis rather than to model single period equilibrium (see Clark, 2006). Moreover, the harvest rate is not proportional to instantaneous effort – congestion and hurry should contribute to decreasing returns to effort (the rationale behind input stuffing). Capital is not specialized to a single fishery with no alternative uses, but it can be rented or redeployed in a different fishery at a different time, which is consistent with other research (for example Casey et al., 1995). Homans and Wilen divide the trading season into two parts –

³ An example can be the effect of increasing the season length on ex vessel price and revenue per fishermen found by Herrmann and Criddle (2006).

one part when fresh fish is being traded and the other part when frozen fish is being traded. I assume that frozen fish can be consumed whenever fresh fish is consumed, which is justified by a variety in tastes and distant sources of demand, where product can be delivered only as frozen. This new set of assumptions justifies creating an entirely new model.

Homas and Wilen relate their study to the North Pacific halibut fishery. I do the same, since it is a well-studied fishery with easily available data. One of the reasons it has been so intensively scrutinized is the semi-natural experiment that has taken place there in the early 1990s. The fishery is split mainly between British Columbia and Alaska. An international regulatory body decides upon the total quota and splits it between Canada and the USA. Before 1991 there was derby fishing in both countries. Then British Columbia introduced Individual Vessel Quotas with initial restrictions on quota trade and leasing that were subsequently gradually lifted. Four years later, in 1995, Alaska followed suit and introduced Individual Fishing Quotas in its part.⁴ Both Alaskan and Canadian fish are sold mostly in the U.S. mainland market, where the price for the final product is determined (Herrmann and Criddle, 2006). Therefore, this case study is very suitable for comparing characteristics of individual quotas and derby fishing.

Calibrating the model to conditions in the North Pacific halibut fishery allows me to empirically verify its predictions. The model does a good job of predicting three separate phenomena: 1) the ratio of fish landed by Canadian vessels during Alaskan derby season while in Canada individual quotas were already in place, 2) the magnitude of the reduction in season length under derby fishing over time, and 3) incentives for Canada to adopt individual quotas as the first country. This gives credibility to the model as a general description of a situation when two fisheries participate in the common market for fish.

In general, I find that the introduction of individual quotas in a single fishery can yield undesired effects if the regulator is interested in maximizing only consumer surplus. On the other hand, if the

⁴ Both Alaska and British Columbia had regulated open access before introduction of individual quotas. In British Columbia, entry was restricted and in Alaska it was not. Under the new regulation, quotas were assigned to the registered vessels in Canada and to persons historically operating the fishery in the USA; hence the difference in naming of the regulatory schemes. The North Pacific halibut fishery is geographically split between Canada and the USA and thus can be treated both as a single fishery and as two separate fisheries, depending on the context. Both before and after implementation of individual quotas, the International Pacific Halibut Commission was charged with deciding the total allowable catch for each year in the parts of the fishery operated by the two countries. For more details on the implementation of individual quotas in the North Pacific halibut fishery, see Casey et al., (1995) and NRC (1999).

regulator maximizes total welfare or industry profits (due to regulatory capture), implementation of individual quotas is always perceived by the regulator as desirable. Thus, if in a manner similar to that found in the literature describing regulation of utilities, a weighted sum of consumer and producer surpluses is maximized, then the decision on adoption of individual quotas may depend on the particular weights assumed by the regulator.

I also find that if two fisheries under separate regulation (for example because they are in different countries) deliver product to the same market, a change in one fishery from derby fishing to individual quotas may reduce the trading partner's welfare, the welfare in the global economy, and even the welfare of the party adopting individual quotas. Furthermore, both fisheries may perceive the situation in this way, which leads to neither fishery willing to adopt more efficient regulation, even though the adoption of it by both fisheries simultaneously is desirable to them. Such a deadlock may require international coordination to resolve. Although these conclusions cannot be immediately generalized to other industries because of specific market structure in fisheries, they show that undesirable equilibria in international regulation games can in general arise.

The paper proceeds as follows. The second section describes the general ideas behind the model. It contains the description of the international regulation game between two regulators operating under free-trade conditions. I also characterize market equilibria in four distinct situations: 1) when a single fishery is regulated with individual quotas, 2) when a single fishery is governed by regulated open access with derby fishing, 3) when two separate but similar fisheries have different regulatory regimes but participate in a single market and there is a single price for both high- and low-quality fish, and 4) when two separate but similar fisheries have different regulatory regimes, participate in a single market, and the price for high-quality fish is different from the price for low-quality fish. The third section describes properties of market equilibria in this model, including existence and uniqueness as well as comparative static. It also provides initial insights into the incentives of regulators in an international setting. The fourth section contains numerical simulations which are based on the North Pacific halibut fishery. The results are verified against empirical evidence and compared to results obtained in other papers. Some new welfare-related results pertaining to the adoption of individual quotas are also presented. In the fifth section, I identify conditions under which individual quotas can be detrimental to profits, consumer surplus, or welfare. Finally, the sixth section provides a comprehensive analysis of strategic interaction between regulators in an international fishery under different types of regulators' objective function.

2. Model

The model consists of two layers. The outer layer of the model is similar to a Prisoner's Dilemma game used for modeling international trade relations and assumes that there are two countries (or states) trading with each other. However, I assume that the countries participate in a free-trade agreement, unlike what is found in traditional games in international economics. Both of the countries have an industry which produces the same product which is then sold on the international market. Each country has a separate industry regulator with a precisely-defined objective function. This objective function can be welfare, consumer surplus or industry profits (in case of regulatory capture). A regulator includes in the objective function only profits or surplus of the agents residing in the regulator's country. There are two types of regulation and each regulator chooses to implement one of them.

The model's goal is to investigate regulators' incentives to adopt one of the two types of regulation. Incentives are measured as a difference between the value of the regulators' objective function when one type of regulation is implemented versus the value when the other type of regulation is implemented. The regulator has incentives to implement regulatory regime with higher objective value and the magnitude of incentives is proportional to the difference between values of the objective function under different types of regulation.⁵ I assume that one of the types of regulations is called "legacy regulation" and the other is called "progressive regulation." This allows to focus on one particular direction of change and to test the hypothesis that progressive regulation is always recommended, given the circumstances.

I focus on the following questions:

- I. Is progressive regulation always desirable when both countries jointly adopt it?
- II. Can the adoption of progressive regulation in only one country be undesirable to the other country?
- III. Can the adoption of progressive regulation in only one country be globally undesirable?
- IV. Can the adoption of progressive regulation in only one country be undesirable to the adopting country?

⁵ One of the reasons why magnitude of incentives may matter for the outcome of the game are transition costs related to adoption of new regulation that are here not modelled explicitly.

Questions (II), (III), and (IV) consider only one country changing regulation and they don't mention what happens in the other country. Therefore, each of them must be broken down into two cases. In the first case, one country adopts progressive regulation while the other country stays with legacy regulation. In the second case, the country in questions adopts progressive regulation as the second to do so because the other country has already adopted. In contrast, question (I) has only one variant because it deals with both countries starting with legacy regulation and simultaneously switching to progressive regulation. Each question should be answered for all three types of possible objective functions. Thus, there are in total 21 variants of these questions.

As it is explained in the following sections of the paper, the answer to each of the questions (I)-(IV) can be either "yes" or "no," depending on the circumstances. An answer "no" to question (IV) is especially interesting, because it raises another question:

- V. Can the adoption of progressive regulation be undesirable to both countries if they do it separately, but desirable to them if they do it jointly?

That is, is international coordination in the implementation of progressive regulation needed? "Separately" is used here in game theory context and means "given other country does not change their regulation." The slightly weaker version of this question is:

- VI. If they do it separately, can the adoption of progressive regulations be undesirable to both countries, but desirable globally?

The difference between question (V) and question (VI) is that in question (V) we are asking whether the adoption in both countries of progressive regulations increases the value of the objective functions. In question (VI) we are asking whether the adoption in both countries of progressive regulation increases the sum of the objective values of the two countries. In other words, question (V) asks whether countries can be locked in a Pareto-inferior equilibrium and question (VI) asks whether countries can be locked in a Kaldor-Hicks-inferior equilibrium. Finally, the last question I ask is:

- VII. Given adoption in both countries is globally desirable, can the adoption of progressive regulations be desirable to the first-adopting country (hereafter "first-adopting") but undesirable to the second-adopting country (hereafter "second-adopting") even though the adoption by the second-adopting country is also globally desirable?

These seven questions allow us to fully describe the effects of implementation of progressive regulation in one country both on this country itself and on the trading partner. They can be put together in a game-theory framework presented on Figure 1.

		Country 2	
		Progressive regulation	Legacy regulation
Country 1	Progressive regulation	B C	D E
	Legacy regulation	F G	H I

Figure 1. International coordination game. Payoffs of Country 1 are below the diagonal lines and payoffs of Country 2 are above diagonal lines. Payoffs are values of corresponding regulators' objective functions.

Question (I) can be understood in two ways: when is switching from legacy regulation to progressive regulation desirable for both countries separately? That is, when $B > H$ and $C > I$ (progressive regulation is Pareto-superior)? Or when is switching from legacy regulation to progressive regulation globally desirable, that is when $B + C > H + I$ (progressive regulation is Kaldor-Hicks-superior)? Question (II) is not directly related to the international regulation game but it touches on a remarkable issue of the "beggar-thy-neighbor" type of policy. Similarly, question (III) is interesting from the point of view of the regulation in question. If adoption of this regulation is undesirable to the global economy, we have evidence that progressive regulation is not always desirable. Questions (IV) and (V) can be reformulated as: is it possible that $F < H$ or $E < I$? If so, is it possible that $F < H$ and $E < I$? This is of particular interest, especially when $B > H$ and $C > I$ (question (V)) or $B + C > H + I$ (question (VI)), because when if $F < H$ and $E < I$ it means that regulators can be locked in an inferior equilibrium and forego an improvement. A potential problem which would require international coordination to solve is that of regulators being locked in the legacy regulation equilibrium.

Finally, another possibility of regulators being locked in an inferior equilibrium occurs when they have asymmetric regulatory regimes and the second-mover has no incentive to switch to the progressive regulation. That is, either $G > I$ but $B < F$ or $D > H$ but $C < E$. It could be possible that $B + C < F + G$ or $B + C < D + E$ and then the players are not locked in the inferior equilibrium; rather, they are in the superior equilibrium. Hence, adoption by the second-mover must be globally desirable for this case to be

interesting. Also, cases where progressive regulation are not globally desirable (that is when $B+C < H+I$) are not interesting either, so I also rule out this possibility.

Thus, layer one of the model is effectively a game-theory framework for investigating the behavior of regulators in an international setting. Before it can be subjected to a useful analysis, it is necessary to provide the means of calculating the values of regulators' objective functions. This is the objective of the second layer of the model which is industry-specific. The industry I am using as an example is the fishing industry; hence layer two of my model contains description of fisheries under two types of regulation.

There are two countries in which there are fisheries for a particular species of fish. There is an international regulatory agency which is responsible for ensuring stock sustainability and provides numbers for total allowable catch for each fishery.⁶ The national regulators are responsible for the smooth operation of fisheries and for their organizational structure. Both countries participate in the common market. For simplicity, I assume that if both countries operate under the same regulation type, their industries are alike. That is, if both countries regulate their fisheries in the same way, they effectively can be treated as a single country. I explain in detail what is needed for this assumption to hold true after the introduction of details of the model. The legacy regulation is assumed to be derby fishing and the progressive regulation is assumed to be individual quotas.

Layer two of the model is based on two main components: an instantaneous aggregate utility (gross surplus) function⁷ $W(q_H, q_L)$ and an instantaneous aggregate production function $q(s, E)$. The instantaneous aggregate utility function (hereafter "utility function") represents aggregate gross utility derived by the entire buyer population on the common market from consuming q_H units of high-quality fish and q_L units of low-quality fish within a unit period of time. This is a partial equilibrium model, complete aggregate utility encompassing other goods is quasi-linear, and the value of W is expressed in monetary units (U.S. dollars). This simplifying assumption should closely approximate reality as long as consumption of fish constitutes a small fraction of the buyers' budgets and income effects of changes in fish prices are negligible. W satisfies standard properties of utility functions, that is, it is increasing in

⁶ The setting where there are an international agency responsible for sustainability of the fishery and country-specific regulatory agencies responsible for industry organization is common throughout the world. The European Union's Common Fisheries Policy is set up this way. The existence of the international regulator is specific to the fishing industry but does not affect layer one of the model which is not industry-specific.

⁷ For precise construction of such a function for heterogeneous consumers and its properties based on basic Microeconomic principles, see Appendix.

both goods and strictly concave. It is also twice continuously differentiable, the two goods are substitutes and cross price effects are weaker than their own price effects. If the prices for the two products are the same, the demand for the high-quality fish is at least as big as the demand for the low-quality fish.

The instantaneous production function $q(s, E)$ informs how much fish is captured in a unit of time given the effort E undertaken by the fleet and the fraction of the entire fishery, measured by area size, the fleet is operating in, s . I measure effort as the sum of variable costs (crew remuneration, fuel costs, etc.) and capital opportunity costs incurred by the fleet in a unit of time. I assume that the fishery is geographically homogeneous,⁸ so expanding both effort and size of the area in which the fleet operates by the same fraction should increase the yield by the same fraction. Therefore, q is homogeneous of degree 1, that is $q(ts, tE) = tq(s, E)$. For simplicity, q is also the same no matter in what part of fishery is the effort undertaken. These important assumptions greatly simplify modelling of two fisheries selling on a common market – when both of them operate under the same regulation, and the q function is the same in both of them, then they can be effectively treated as a single fishery.⁹

Moreover, $q(s, 0) = 0$, q is increasing in both arguments, and due to congestion and rising opportunity costs $\frac{\partial^2 q}{\partial E^2} < 0$.¹⁰ Note that, as often happens in a fishery, due to stock depletion, it may take more effort to obtain the same yield when there are fewer fish to catch, so the relation represented by q changes over time. However, in this model, q is kept constant as explaining effects of variation in stock is not an objective of this paper. I assume this problem already has been solved by the introduction of the appropriate total allowable catch.

Consumers maximize utility, therefore, for given wholesale prices of respectively high- and low-quality fish p_H and p_L , the demands can be found as solutions to the following maximization problem:

⁸ This somewhat strong assumption can be weakened and the analysis is still valid as long as parts of the fishery are similar in any relevant partitioning.

⁹ Many potential applications of this market model pertain to countries which participate in a single market e.g. member countries of the European Union or member states of the United States of America. Free flow of labor and capital is a strong argument in favor of similarity of industries in the two countries or states. If the two fisheries are in adjacent countries and belong to a bigger fishery split between these two countries as in the case of the North Pacific halibut fishery, this is also an argument in favor of treating the two fishing industries as very similar.

¹⁰ The expression $\left| \frac{\partial^2 q}{\partial E^2} \right|$ measures concavity of the instantaneous catch function and can be interpreted as the “congestion effect.” The bigger it is, the more total production can be increased by spreading the same effort over a bigger period of time.

$$\max_{q_H \geq 0, q_L \geq 0} [W(q_H, q_L) - p_H q_H - p_L q_L]$$

Denote the demands as $D_H(p_H, p_L)$ and $D_L(p_H, p_L)$ for high- and low-quality fish respectively. Let $D_L(+\infty, p_L)$ denote the demand for low-quality fish in the absence of high-quality fish, that is, the solution to the problem: $\max_{q_L \geq 0} [W(0, q_L) - p_L q_L]$. It is convenient to let the unit of time be a year, at least because total quotas usually match annual spawning cycles. Then, the fishing season length can be described by a variable $0 \leq T \leq 1$, and consuming q_H of high- and q_L of low-quality fish within this season yields a consumer surplus of $T[W(q_H, q_L) - p_H q_H - p_L q_L] = TV(p_H, p_L)$, where prices are assumed to be constant over the entire period.¹¹ $V(p_H, p_L) = \max_{q_H \geq 0, q_L \geq 0} [W(q_H, q_L) - p_H q_H - p_L q_L]$ is the instantaneous indirect aggregate utility function (or in other words instantaneous consumer surplus function). q_H and q_L are consumption rates (consumption levels per unit of time). Therefore, the consumption of high- and low-quality fish in the period of length T is Tq_H and Tq_L , respectively. Denote the total industry profits as Π , the total consumer surplus as Σ , and the total social welfare as Ω .

The fishermen maximize profits. They tend to equalize profit margins within the fishing season by shifting their efforts to more profitable moments of time. They also tend to increase their effort, as long as they can make a profit without violating quota constraints, because they perceive profit margins as constant and the increase in effort results in a higher catch, given the margin. For simplicity, assume that fresh fish are the high-quality fish and frozen fish are the low-quality fish, although in reality other factors can contribute to quality, for example, size and damage done to the fish on board. Fishermen catch the fish at sea, and then the yield can be marketed upon their return, either as fresh or as frozen (I assume the catch is homogeneous ex ante). Since fishermen are profit-maximizing, they choose the option that gives them the higher price. Therefore, if, at a particular point in the fishing season, both fresh and frozen fish are available, their ex vessel price must be the same. Fresh fish has to be consumed instantly after it is captured. Frozen fish can be stored and resold at any other time. Whoever holds inventories in frozen fish, they are selling it at a moment in time which gives them maximum profit, that is, when the price for frozen fish is the highest. This in turn equalizes the price of frozen fish. Thus, p_L is always constant over the entire year.

The instantaneous utility function does not change over the course of the year. Thus, as long as the marginal utility from consuming the first unit of a product is sufficiently high, this product, due to

¹¹ In reality, the fishing season often can be split into a few separate openings. This, however, does not have any effect on the model, as it does not depend on continuity of time.

price mechanisms, is consumed within the entire period when it is available. That is, fresh fish are consumed during the entire fishing season and frozen fish are consumed during the entire year. Hence, the year is divided into two periods: one during the fishing season when both fresh and frozen fish are consumed and a stock of frozen fish is accumulated for future resale, and the other outside the fishing season, when accumulated stock is resold. Low-quality fish is not traded during the fishing season, only if the marginal utility of consuming the first unit of it is smaller than the price of high-quality fish.¹²

Individual quotas

I assume that the fishery is operating under the individual-quotas regulatory system, which is implemented in the same way for all parts of the fishery, or alternatively, that we have two similar fisheries sharing a common market, both operating under individual quotas and both having the same q function.¹³ There is an exogenous season length T_{IQ} , determined by the regulator.¹⁴ Fishermen can expend their effort only within the season and each fisherman is allotted their own quota which sums to the total allowable catch Q . As mentioned before, the price of low-quality fish is constant within the whole year. High-quality fish cannot be traded outside the season. Whenever high-quality fish is traded, the rational behavior of fishermen results in their price being the same as the price of low-quality fish. Therefore, fishermen can get only a single price for their product, regardless of when they fish. The average profit margin per unit of effort, that is $\frac{p_{IQ}q(1,E)}{E} - 1$ is equalized over the entire season, which in turn means equalizing of effort since the price is constant and $\frac{q(1,E)}{E}$ is a strictly decreasing function of E .

Market equilibrium must satisfy two conditions. The markets must clear and the quota constraint must be met. These conditions are respectively:

¹² Some aspects of the model require discussion, as they may not seem realistic at first glance. The two features of the model, namely zero costs of keeping frozen fish and no processing sector, may seem to be overly simplistic. As long as freezing costs are very low, they can be neglected but in reality this is not likely to be the case. Moreover, it often happens that processors affect the market situation in the fishery and have a stake in controlling fishermen's behavior, for example by buying individual quotas and subsequently leasing them back to harvesters. I assume that there is either no processing sector and there isn't any other intermediary sector, and thus fish is sold directly to consumers, or the processing sector and other intermediaries are perfectly competitive and buy fish as long as its price is below their marginal valuation. This keeps my welfare calculations valid. Even if these assumptions fall short of reality, it is still reasonable to make them, since we are not interested in the interaction of the processing sector with the rest of the industry and such a simplification should still allow us to draw general conclusions.

¹³ Having the same q function is a sufficient condition to treat two fisheries under the same regulation as one.

¹⁴ Under individual quotas, season is limited usually to protect the population during time critical for its renewal. In case of North Pacific halibut, limits are put in place to protect the stock during the migration period.

- 1) $T_{IQ} \left(D_H(p_{IQ}, p_{IQ}) + D_L(p_{IQ}, p_{IQ}) \right) + (1 - T_{IQ})D_L(+\infty, p_{IQ}) = Q$
- 2) $T_{IQ}q(1, E_{IQ}) = Q$.

There are two endogenous variables in this system, the ex-vessel price p_{IQ} and the instantaneous effort E_{IQ} . Other variables (T_{IQ} and Q) are exogenous and set by a regulator. The market equilibrium is thus characterized by a system of two non-linear equations with two unknowns.

Note that if instead of just one fishery, we have two similar fisheries with the same season length and the common market, the equation (1) does not change. Equation (2) must be replaced with separate equations for the two fisheries, that is $T_{IQ}q_1(s, E_{IQ}^1) = \alpha Q$ and $T_{IQ}q_2(1 - s, E_{IQ}^2) = (1 - \alpha)Q$, where α and s are respectively relative share in the total allowable catch and relative share size of the fishery for the first country. E_{IQ}^1 and E_{IQ}^2 are instantaneous effort levels in the first and second country, respectively. If we assume that fisheries are similar, that is $q_1 \equiv q_2$, and that total quota is split proportionally to the size of the fisheries, that is $\alpha = s$, then we obtain $T_{IQ}q(\alpha, E_{IQ}^1) = \alpha Q$ and $T_{IQ}q(1 - \alpha, E_{IQ}^2) = (1 - \alpha)Q$. These two equations can be then simplified to $T_{IQ}q\left(1, \frac{E_{IQ}^1}{\alpha}\right) = T_{IQ}q\left(1, \frac{E_{IQ}^2}{1 - \alpha}\right) = Q$ which implies $\frac{E_{IQ}^1}{\alpha} = \frac{E_{IQ}^2}{1 - \alpha} = E_{IQ}$. Thus, the two separate equations can be replaced with single equation (2).

Derby fishing

Derby fishing is characterized by an endogenous season length. In reality, the regulator usually sets season length in anticipation of the fleet's behavior. The season can be then closed prematurely if the total allowable catch has been exceeded. It seems thus plausible to assume that market equilibrium fishing season length is fully endogenous (Homans and Wilen, 2005, p. 384).

As in case of individual quotas, there is a single price for both fresh and frozen fish. The rationale is exactly the same – fishermen deciding whether to market fish as low- or high-quality, effectively equalize their prices, and given the prices are equal, the efforts are equalized within fishing season. The additional feature of this system is that as long as the fishery is profitable, new effort enters the fishery. It can be in the form of new boats, bigger crews, more intensive efforts, etc. As a result, the fishery yields zero profit. This adds a new equation to the system characterizing market equilibrium:

- 3) $T_{DF} \left(D_H(p_{DF}, p_{DF}) + D_L(p_{DF}, p_{DF}) \right) + (1 - T_{DF})D_L(+\infty, p_{DF}) = Q$

$$4) T_{DF}q(1, E_{DF}) = Q$$

$$5) p_{DF}q(1, E_{DF}) = E_{DF}$$

where the equation (3) is the market clearing condition, (4) is the quota constraint, and (5) is the zero instantaneous profit condition. The endogenous variables are T_{DF} , p_{DF} , and E_{DF} and we have a system of three non-linear equations with three unknowns.

Similarly to the case of individual quotas, this system can describe both situation of a single fishery and situation of two or more fisheries sharing common market as long as they are considerably similar.

Mixed situation

The more complicated case is a mixed case, where one of the two countries adopts individual quotas while the other country retains its derby fishing regulation. There are two cases in this scenario, depending on the relative size of the fishery adopting the new regulatory system. In both cases, it is going to be assumed that the fishing season in the derby fishery is entirely within the fishing season of the individual quota fishery. The calculations are easier to understand if we think that both seasons start when the year starts (at time 0), then the season in the derby fishery ends at an endogenously determined time, T_{OLD} , followed by ending of the season in the quota fishery, at an exogenously determined time, T_{NEW} , where $0 < T_{OLD} \leq T_{NEW} \leq 1$. However, the calculations are still valid if neither season begins at time 0 (as long as we permit inter-temporal trade in fish), if the quota season is split into separate time intervals and if derby season has several separate openings. I call period from 0 to T_{OLD} the “derby season.” From T_{OLD} to 1 is the period “outside derby season,” from 0 to T_{NEW} is the “quota season,” and from T_{NEW} to 1 is the period “outside quota season.”

Let us begin with a case where the fishery that is the first to adopt quota regulation is a relatively big fishery. This case is characterized by the fact, that instantaneous production of this fishery is big enough to single-handedly satisfy the demand for high-quality fish at the price level of low-quality fish. In other words, inside the quota season and outside the derby season (that is from T_{OLD} to T_{NEW}), the quota fishery fishermen have to market their fish both as high- and low-quality. They obviously don't want to market their fish only as low quality, since the price of fresh fish would jump very high. Were they to market their fish only as high quality, the amount they produce would be so large, that the price they could get would be below the price of low-quality fish. Therefore they participate in both markets and the prices are equal. This implies that the price is the same for both types of fish and equal

throughout the entire quota season, and for low-quality fish throughout the rest of the year. From now on I will call this situation the “mixed regime with a single price.”

Fishermen in the derby fishery still enter the production and increase effort as long as profits can be made. In both fisheries quota constraint must be satisfied. Coupling with the market clearing condition, this yields a system of four non-linear equations with four unknowns:

$$6) T_{NEW}(D_H(p_M, p_M) + D_L(p_M, p_M)) + (1 - T_{NEW})D_L(+\infty, p_M) = Q$$

$$7) T_{NEW}q(\alpha, E_{NEW}) = \alpha Q$$

$$8) T_{OLD}q(1 - \alpha, E_{OLD}) = (1 - \alpha)Q$$

$$9) p_M q(1 - \alpha, E_{OLD}) = E_{OLD}$$

where (6) stands for the market clearing condition, (7) is the quota constraint for the quota fishery, (8) is the quota constraint for the derby fishery, and (9) is the zero profit condition for the derby fishery. The four endogenous variables are p_M , a single price for both high- and low-quality fish, E_{NEW} , instantaneous effort undertaken by fishermen in the fishery adopting individual quotas, E_{OLD} , instantaneous effort in the fishery staying with derby fishing, and T_{OLD} , season length in the latter fishery. The new variable that has been introduced is α and it denotes the relative size of the fishery as well as fraction of the total quota Q allotted to the fishery adopting new regulation.

As long as a solution to this system of equations exists, it can be tested whether it constitutes market equilibrium. A necessary condition for it to be a market equilibrium is that production of the quota-adopting fishery is enough to cover demand for high-quality fish, that is $q(\alpha, E_{NEW}) \geq D_H(p_M, p_M)$. If this inequality is not satisfied, then the second case must be considered.

In the second case, the demand for the high-quality fish is high enough in comparison to the production of the quota adopting fishery so that the price of high-quality fish outside derby season and inside quota season can be higher than price of the low-quality fish. Note that price of low-quality fish remains the same throughout the entire year and price of high-quality fish can be higher only if fishermen in the quota fishery market their fish solely as high-quality fish. The market equilibrium thus encompasses two prices $p_{LO} \leq p_{HI}$, the first one for high- and low-quality fish during the derby season and for low-quality fish outside the derby season and the latter for high-quality fish outside the derby season but inside the quota season. From now on I will call this situation the “mixed regime with two prices.”

When making the decision about when to undertake their effort, the fishermen in the quota country face two prices. They can get p_{LO} if they harvest during the derby season and they can get p_{HI} if they harvest outside of derby season. The level of effort is chosen, so that the profit margins are equalized within the entire quota season. Therefore, for different prices, efforts are also different but are constant within periods where price remains constant. Thus, two levels of effort are attained in the market equilibrium by the quota fishermen, E_{NEW1} and E_{NEW2} where the former is a level of effort undertaken inside derby season and the latter is the level of effort undertaken outside the derby season. These conditions can be summed up in the following system of equations characterizing market equilibrium:

$$\begin{aligned}
10) & T_{OLD}(D_H(p_{LO}, p_{LO}) + D_L(p_{LO}, p_{LO})) + (T_{NEW} - T_{OLD})(D_H(p_{HI}, p_{LO}) + D_L(p_{HI}, p_{LO})) + \\
& (1 - T_{NEW})D_L(+\infty, p_{LO}) = Q \\
11) & q(\alpha, E_{NEW2}) = D_H(p_{HI}, p_{LO}) \\
12) & T_{OLD}q(1 - \alpha, E_{OLD}) = (1 - \alpha)Q \\
13) & T_{OLD}q(\alpha, E_{NEW1}) + (T_{NEW} - T_{OLD})q(\alpha, E_{NEW2}) = \alpha Q \\
14) & p_{LO}q(1 - \alpha, E_{OLD}) = E_{OLD} \\
15) & \frac{p_{LO}q(\alpha, E_{NEW1})}{E_{NEW1}} = \frac{p_{HI}q(\alpha, E_{NEW2})}{E_{NEW2}}
\end{aligned}$$

where the equation (10) stands for the market clearing condition for the entire market, (11) stands for the market-clearing condition for the high-quality fringe outside derby season, (12) is the quota constraint for the derby fishery, (13) is the quota constraint for the quota fishery, (14) is the zero profit condition for the derby fishery, and (15) is the condition ensuring equal revenues per unit of effort for the fishermen in the quota country. The endogenous variables are p_{LO} , p_{HI} , T_{OLD} , E_{OLD} , E_{NEW1} , E_{NEW2} .

As long as a solution exists, it can be checked against the necessary condition $p_{HI} \geq p_{LO}$. If this condition is not satisfied, the solution does not characterize market equilibrium and mixed regime with a single price must be considered. Note that it is possible to obtain $p_{HI} = p_{LO}$ and $q(\alpha, E_{NEW2}) = D_H(p_{HI}, p_{LO})$ as a solution to the above system. In such an event, equation (10) becomes (6), (12) becomes (8), (13) becomes (7) and (14) becomes (9); thus the system of equations (6)-(9) should yield the same results with $p_M = p_{HI} = p_{LO}$ and $E_{NEW1} = E_{NEW2} = E_{NEW}$.

3. Analytical results

After setting up layer two of the model, it seems natural to explore its mathematical properties and to see if it produces predictions consistent with the intuition. In this section I also explore whether it can provide insights into how the market operates and whether we can obtain any initial findings relevant to layer one of the model.

Given no assumptions about functional forms, there is no closed form solution to any of the four systems of equations specified in the previous section. Only single regulator cases are simple enough to analyze them with comparative statics. However, before any analysis can be done, it is important to investigate the existence and uniqueness of the equilibria for these cases. This in turn requires me to introduce three useful lemmas whose proofs are available in the Appendix.

Lemma 1. Denote $D(p) = D_H(p, p) + D_L(p, p)$. Then $D'(p) < 0$.

Lemma 2. $D(p) > D_L(+\infty, p)$ for all $p > 0$.

Lemma 3. $\frac{d}{dp}V(p, p) < 0$ and $V(+\infty, p) < V(p, p)$.

Lemma 1 effectively shows that as long as there is a single price for the two fish types, the total instantaneous demand for fish, be it fresh or frozen, is a decreasing function of that price. This lemma is necessary for establishing uniqueness of the equilibrium. Lemma 2 indicates that for a given single price, the total amount of fish demanded in the fishing season is bigger than the total amount of fish demanded outside the fishing season. Lemma 3 proves that instantaneous consumer surplus decreases with price and for a given price it is bigger inside the fishing season than outside the fishing season. Lemma 2 and lemma 3 are useful for derivation of comparative statics (see Appendix).

Existence and uniqueness under individual quotas are straightforward. (2) is a single equation with one unknown, so E_{IQ} can be uniquely determined as long as this equation has a unique solution. Sufficient condition for existence of the solution is that $\lim_{E \rightarrow +\infty} q(1, E) > Q/T_{IQ}$ and sufficient condition for uniqueness is that q is a strictly increasing function of E . Similarly, (1) is a single equation with one unknown. Notice that in accordance with Lemma 1, the left-hand side of this equality is strictly decreasing with p_{IQ} . This guarantees uniqueness. For the solution to exist, there must be a price that yields demand high enough to satisfy the quota. However, even if a solution to the system of equations exists, one more condition must be met for this solution to be an equilibrium. Namely, $p_{IQ}q(1, E_{IQ}) \geq$

E_{IQ} . Otherwise, the fishermen lose money, have incentives to reduce their catch and not fulfill the quota. In this case, market equilibrium is described by a different system of equations. I will not pursue cases where these conditions are not satisfied because of their limited practical relevance.

Conditions characterizing market equilibrium in derby fishing are more complicated. Consider uniqueness first.

Proposition 1. There is a unique market equilibrium in a single derby fishery, as long as the equilibrium exists.

Once uniqueness has been established, let us investigate existence. Equation (5) has at least one solution, $E_{DF} = 0$, given price. This is not the solution in which we are interested, as it has little practical relevance (and can't be a stable equilibrium when another solution exists). A positive solution exists when the price is high enough to justify extraction at a rate allowing for meeting the quota within one year. Otherwise, the quota is not met. As in the case of individual quotas, this outcome will not be pursued because of its limited practical significance. Moreover, if function q has a limit as E tends to plus infinity, there may exist no level of effort that satisfies the quota (equation (4)). Therefore, the solution to this system may not exist under some circumstances. This is however not likely to happen for plausible functions and parameter values.

Consider comparative statics for derby fishing. The results are presented by Proposition 2. At least one result is not intuitive: as we increase the total quota, instantaneous effort decreases. The reason is that price decreases as well, so fishermen have to reduce their effort to break even at each instant of time. Furthermore, industry cost (total effort) can both increase or decrease with the increase of total allowable catch, and the decrease occurs when the demand is inelastic. Inelastic demand causes the price to drop significantly when we increase the total quota, which in turn results in a longer season and productivity of a unit of effort high enough so that the total effort actually drops while the catch increases.

Proposition 2. In a single derby fishery $\frac{dp}{dQ} < 0$, $\frac{dE}{dQ} < 0$, $\frac{dT}{dQ} > 0$, $\frac{d\Sigma}{dQ} > 0$. Also, $\frac{dET}{dQ} > 0$ as long as the annual demand is generally elastic and $\frac{dET}{dQ} < 0$ if the annual demand is generally inelastic.

Proposition 3. In a single individual quota fishery $\frac{dE}{dT} < 0$, $\frac{dE}{dQ} > 0$, $\frac{dp}{dT} > 0$, $\frac{dp}{dQ} < 0$, $\frac{d\Pi}{dT} > 0$, $\frac{d\Pi}{dQ} \geq 0$,

$\frac{d\Sigma}{dT} \leq 0$, $\frac{d\Sigma}{dQ} > 0$.

As we increase the length of the fishing season in the individual quotas fishery, the price increases as well. This is because an increase in the fishing season allows more fish to be marketed as fresh and since the price does not change within the year, the overall price should be higher (recall that demand for fresh fish is higher than for frozen fish and the total supply is constant). Note also that under both regulatory regimes, price decreases with an increase in total quota, which allows us to derive the annual inverse demand function mentioned in Proposition 2. This demand function is different under different regulatory regimes.

For an individual quota fishery, increasing the total quota initially increases profits but as the quota increases even further, the elasticity effect (that is additional revenues made due to higher quantity) becomes weaker and is eventually dominated by the effort effect (that is, industry marginal cost). At this point, profits become negatively related to quota. Increasing the quota even further can make both the elasticity effect and the effort effect negative.¹⁵ It is surprising that the effect of prolonging the season on consumer surplus is also ambiguous. This is because the negative effect of price increases can outweigh the positive effect of having more of higher-quality fish. It follows that because, mathematically, a derby fishing equilibrium is the same as an individual quotas equilibrium for $T_{IQ} = T_{DF}$, the effects of switching from derby fishing to individual quotas (as equivalent to prolonging quota season) on consumer surplus, are ambiguous.

Proposition 4. In an individual quota fishery $\frac{d\Omega}{dT} > 0$.

Proposition 5. If two fisheries operate initially under mixed regime with a single price and the only derby fishery adopts individual quotas in such a way that both countries have the same season length $T_{IQ} = T_{NEW}$, then $p_M = p_{IQ}$.

Theorem 1. Switching from derby fishing to individual quotas in a single fishery increases total welfare, ceteris paribus.

Theorem 2. In a mixed regime with a single price, adoption of individual quotas by the second country leads to an increase in global welfare. Profits and consumer surplus of the non-adopting country do not change. Consumer surplus in the adopting country does not change and the profits increase.

¹⁵ This is the same effect as the one observed when we force monopolist to increase production: initially marginal revenue is bigger than marginal cost, then it is smaller and then it becomes negative.

Proposition 4 tells us that an increase in the length of the season in an individual quotas fishery is always accompanied by an increase in total welfare, even when consumer surplus is decreasing. This finding has practical consequences for regulators – while deciding about the length of the individual quotas season, there is a need to take account of the trade-off between natural factors that tend to limit the length of the season and economic forces that suggest that season length should be expanded.

Theorem 1 and Theorem 2 describe scenarios in which adoption of individual quotas over derby fishery certainly leads to an increase in the global welfare. Theorem 1 relates to a situation when a single fishery adopts individual quotas or two fisheries sharing common market adopt jointly individual quotas. This proves that naming individual quotas as progressive regulation, and derby fishing as legacy regulation, is justified and can be used as an argument for the adoption of individual quotas in the fisheries that are still governed as derby fisheries.

Proposition 5 describes what happens when we switch from a mixed regime with a single price to individual quotas. It follows that the price does not change, and the period of time in which fresh fish is available does not change either. Theorem 2 builds on Proposition 5. Consumer surplus is the same before and after the change. Moreover, the only way implementation of individual quotas can change the situation in the country that has already adopted them is through prices. And since they don't change, the industry profit of the non-adopting country stays the same. Hence, the only effect adoption of individual quotas under these circumstances has on the values of the objective functions of the regulators, is that profit in the industry of the adopting country increases.

These findings allow us to initiate analysis within layer one of the model. Question (I) asks, “Is progressive regulation always desirable when both countries jointly adopt it?” According to Theorem 1, the answer is yes, as long as the objective functions focus on welfare. When consumer surplus is the only component of the objective functions, adoption of individual quotas can have an ambiguous effect (see Proposition 3), that is, either $B+C>H+I$ or $B+C<H+I$ can be true (see Figure 1). Whether any of these two situations can happen and how likely they are to do so, is analyzed later with numerical simulation. Finally, when the objective functions include only industry profits, then always $B+C>H+I$. This is simply because under derby fishing there is rent dissipation while in individual quotas, fisherman can accumulate supernormal profits.

At this point, the only results pertaining to strategic interaction that allow me to fill in gaps in the layer one of the model are Proposition 5 and Theorem 2. Theorem 2 partially addresses questions

(II), (III) and (IV). When regulators care about welfare or industry profits, and we consider the second-moving country and the market is initially in mixed regime with a single price, then (II) adoption of individual quotas does not change the situation in the other country, (III) adoption of individual quotas increases world welfare, and (IV) adoption of individual quotas is desirable to the adopting country. When regulators care only about consumer surplus, adoption of individual quotas by the second-mover does not change the value of the objective function, since the price and thus consumer surplus do not change.

We still need to acquire more information about what is the answer to question (I), if regulators care about consumer surplus. We also need much more information about what is the answer to questions (II)-(IV). At this point, we only know what happens if we consider second-mover and if the market is initially in mixed regime with a single price. This is just one of the four possible combinations. I address them in the following sections, using numerical simulations. Only once we know the answers to questions (I)-(IV) does it make sense to consider questions (V)-(VII) as their answers are interdependent.

4. Modelling the North Pacific Halibut Fishery

It is interesting to see how this model can relate to a real-world situation. I employ numerical methods to calibrate the second layer of the model to the North Pacific halibut fishery using data points from the literature, to test it with additional data points, and to experiment with parameters to see what predictions it gives.¹⁶

After the parameters of the model have been found, I test the model's predictions against an additional data point. I use a ratio of Canadian production rate outside Alaskan derby season, to Canadian production rate inside Alaskan derby season, during the mixed-regulation period. I use Figure 3 from Casey et al., (1995) as a rough indicator of what was this ratio in practice. As the model yields equilibrium effort levels of 1.98 and 11.25 million USD/year for the inside and outside of the Alaskan derby season respectively, the corresponding instantaneous catches, given estimated parameters of the model, are 3.20 and 14.31 million pounds a year. Their ratio is 0.22.¹⁷ This indeed roughly corresponds

¹⁶ The detailed description of simulations can be found in the Appendix.

¹⁷ I do not compare absolute values and focus on the ratio instead because the aforementioned Figure 3 was created only for year 1993 which had a higher total quota than the 45 million pounds assumed by me for calibration purposes, as the average for the mixed regulation period.

to what we observe on Figure 3 in Casey et al., when we compare the average catch in March, April, May, July and October, to the average catch in June, August and September. This constitutes the first empirical test for reliability of the model.

In the first simulation, I compare the calibrated model against the results obtained by Homans and Wilen (2005). In their paper, the authors show how an increase in demand can affect the length of the season under derby fishing. The authors do not analyze the effects of joint increases in demand and show separately effects of an increase in the demand for high-quality fish and effects of an increase in the demand for low-quality fish. This would be difficult to do in my model, because demands for low- and high-quality fish, as demands for substitute goods, are determined jointly by a single utility function. Nevertheless, the comparison of the results is interesting. Figure 2 shows how price and season length change with increasing demand. The increase in demand in this simulation is modeled by multiplying vertical intercepts of the inverse demand functions by the *demand multiplier*.¹⁸ Note that demand multiplier equal to one yields a season length of 0.03 (11 days), but decreasing demand level by 30% results in the season length of 0.19 which corresponds to almost 70 days. The season length increases dramatically as we proceed further with the decrease in demand. When demand drops by slightly more than half (demand multiplier < 0.48) the potential season length exceeds one year, and equilibrium given by the system of equations (3)-(5) cannot be reached – the fishery is no longer able to meet the quota constraint and delivers less than the total allowable catch. This dramatic change is consistent in direction and inconsistent in magnitude with the findings of Homans and Wilen (2005). The results of their simulations are that season length is more than a month (more than 0.14). Even for increases in demand scaling parameter (which correspond in interpretation to my demand multiplier) of the magnitude of 10, the change in their model is not so dramatic as with the demand rising by several percent in my model. In reality, we did observe dramatic changes and the reduction of season length from several weeks down to just 11 days. As it is likely that over several years prior to the introduction of individual quotas, the demand increased by several percent in the North Pacific Halibut Fishery, rather than more than tenfold, prediction of my model appears to be consistent with another piece of empirical evidence.

¹⁸ In this particular case the intercepts are the a and b parameters of the utility function for the high- and low-quality products respectively. See Appendix for details. Since assumed utility function is quadratic, the demands are linear and multiplying vertical intercepts by a constant, the results in the horizontal intercept being multiplied by the same constant.

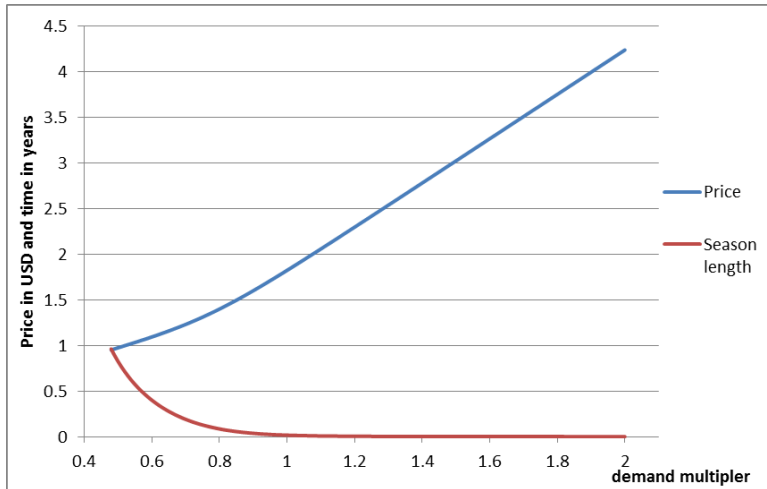


Figure 2. Relation between the demand multiplier (horizontal axis) and price / season length (vertical axis) under derby fishing. Assumed quota is 45 million pounds.

It is also interesting to see the effects of increasing quota in a derby fishery. Figure 3 shows that price decreases with the quota but season length as well as consumer surplus per unit of output increase with the quota. It is notable, that consumer surplus per unit of output is increasing but at a decreasing rate. The other two endogenous variables change as predicted by the comparative statics. We can see here again, that as long as quota gets high comparable to the demand level, the season length increases considerably.

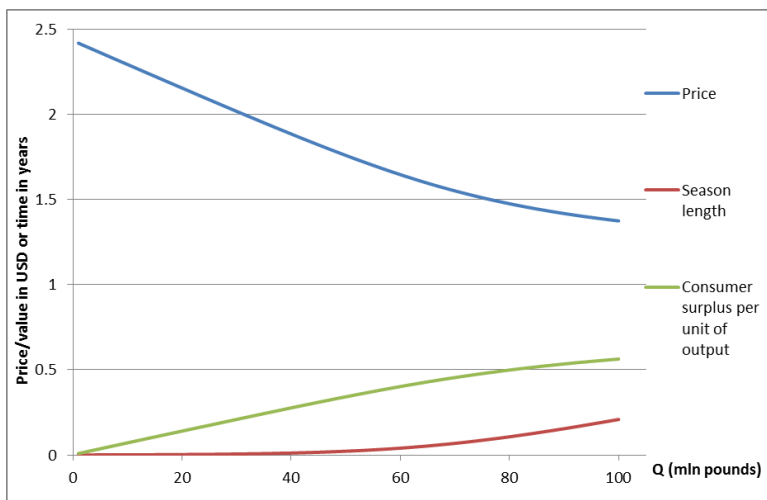


Figure 3. Relationship between prices, season length, and consumer welfare per unit of output and quota (in million pounds) in a derby fishery.

The next simulation presents how season length under individual quotas affects prices, profits, consumer surplus and total welfare. The results are presented in Figure 4. Consistent with the results of comparative statics obtained in the previous section, price and profits are increasing with season length in the individual quota fishery. Moreover, we can see that, also consistent with the predictions of comparative statics, consumer surplus is decreasing initially and then rebounds. Total welfare increases with season length, as predicted by Proposition 4.

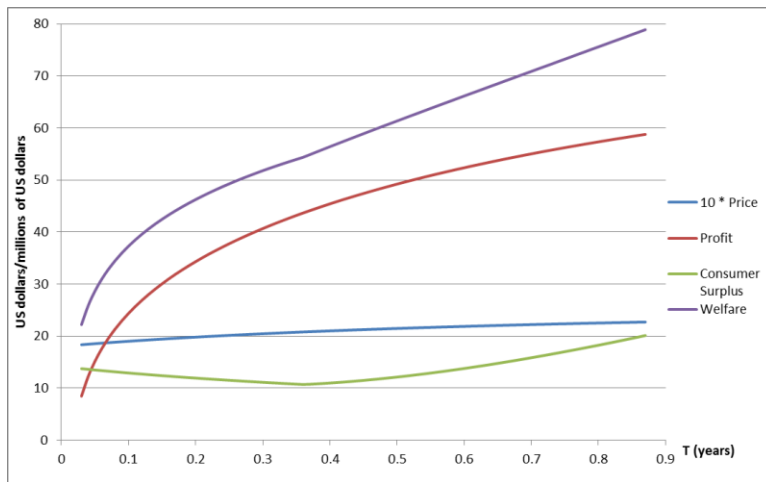


Figure 4. Relationship between prices, profits, consumer surplus, and total welfare and length of the season under individual quotas. On the horizontal axis is T_{IQ} (that is a variable set exogenously by a regulator). Price in U.S. dollars is multiplied by 10, and profits, consumer surplus, and welfare are in millions of U.S. dollars.

Now, focus on the incentives each country faces while adopting the individual quotas. These are depicted in Figure 5. Gains in the industry profit from being the first country to adopt the progressive regulation, are always greater than from being the second country to adopt the progressive regulation, but the difference is small. Total welfare gains are considerably higher when the country is the second one to adopt individual quotas. In our example only one country is considered to be the recipient of consumer surplus. The reason is that in the North Pacific halibut fishery, most of the product from both Alaska and British Columbia is subsequently sold in the U.S. market (Herrmann and Criddle, 2006).

Figure 5 depicts only incentives for Alaska (whose share in the fishery is $1 - \alpha$); Alaska is identified as the entity that cares about the entire consumer surplus – British Columbia does not care

about it at all. British Columbia was dropped from the picture as it has only industry incentives which are perfectly symmetric to incentives of Alaska (with respect to α). Arabic numbers next to series titles on the legend indicate whether Alaska is the first or the second to adopt the individual quotas. Incentives, as changes in profits and welfare, are in millions of dollars. Assumed quota is 60 million pounds. Note “anomalies” at $\alpha = .12$ and $\alpha = .88$ which are a result of switching between (6)-(9) and (10)-(15) that is between mixed regime with a single price and mixed regime with two prices. There are no differences in industry gains between being the first or the second if $\alpha < .12$ and there are no differences between industry and welfare gains for being the second if $\alpha > .88$ because mixed regime with a single price results in a price that is the same as the price under individual quotas. This is consistent with Theorem 2.

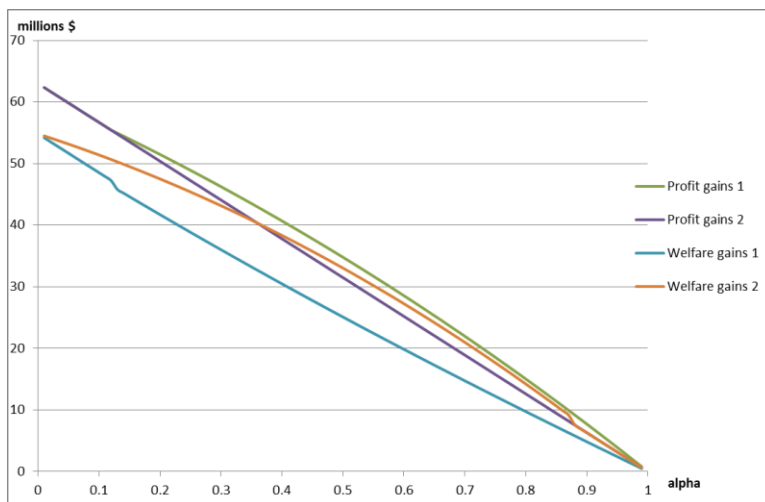


Figure 5. Profit gains 1 and Profit gains 2 are profit gains of Alaska from the adoption of individual quotas as the first or the second country, respectively. Welfare gains 1 and Welfare gains 2 are welfare gains for the USA from adoption of individual quotas as the first or as the second country, respectively. The variable on the horizontal axis indicates the counterfactual relative size of British Columbia. The vertical axis is in millions of USD.

It is intriguing to analyze counterfactual outcomes to see what would happen if neither or just one of the adoptions did not take place. What would be the situation in late 1990s, when quota was around 60 million pounds? The results are summarized in Table 1.

	Derby in both	IQ only in Canada	IQ only in Alaska	IQ in both
Canadian season	15 days	248 days	3 days	248 days
Alaskan season	15 days	11 days	248 days	248 days

Canadian profit	\$0	\$12.62 million	\$0	\$10.51 million
Alaskan profit	\$0	\$0	\$53.17 million	\$52.56 million
Consumer surplus	\$24.10 million	\$19.57 million	\$14.59 million	\$14.98 million
Total welfare	\$24.10 million	\$32.19 million	\$67.76 million	\$78.06 million
Low price	\$1.65	\$1.72	\$2.07	\$2.10
High price	\$1.65	\$2.32	\$2.11	\$2.10

Table 1. Results of a simulation of counterfactual regulation in the post-ITQ period. Comparison of different regulatory settings, given the total allowable catch is set to 60 million pounds. See Appendix for details.

Table 1 provides important insight into how the situation could have unfolded. Both British Columbia and Alaska have incentives to adopt individual quotas when both countries are under derby fishing (unless consumer surplus is considerably more valuable to the regulator than industry profit). Moreover, both regulators have incentives to switch to individual quotas once the neighbor has done so. This is obvious for British Columbia, whose fishermen can only gain. The Canadian adoption as a second country has a slight negative effect on Alaskan profits and a slight positive effect on consumer surplus. When Alaska adopts as a second country, the situation is a bit more complicated but still unambiguous. U.S. consumers lose if Alaska adopts individual quotas but the loss is an order of magnitude smaller than efficiency gains. Besides, Alaskan adoption reduces Canadian profits by almost 17%. This may help explain why British Columbia was first to adopt individual quotas – it had more to gain from the transitory period when the countries had different regulatory designs. This is the third empirical fact consistent with predictions of the model.

It is possible to perform decomposition of the welfare gains from adoption of individual quotas into a part that can be attributed to increase in average quality and to the part that can be attributed to higher production efficiency. Consider two cases: 1) when the entire North Pacific halibut fishery is under derby fishing (before 1991) and 2) when it is entirely under individual quotas (after 1995). In both cases, let us calculate gross consumer utility (assuming demand and total allowable catch do not change). Under derby fishing it is \$122.83 million and under individual quotas it is \$141.06 million. Thus, the change in the consumption pattern – more high-quality product available over a longer period of time – contributed \$18.23 million to the welfare gain.

Similarly, we can calculate the total industry cost. Under derby fishing it is \$98.72 million and under individual quotas it is \$63.00 million. This is a contribution of \$35.72 million to the total welfare. These two contributions add up to \$53.96 million which is exactly what we get when we subtract total welfare from in the first column of Table 1 from the total welfare from the last column in Table 1. Thus, we can estimate that consumption of more valuable goods contributed around 1/3 of the entire welfare gain and more efficient production contributed roughly 2/3 of the entire welfare gain.

However, due to implementation of individual quotas, total profits increased from zero to \$63.07 million. That is, because the total quota is limited, adoption of individual quotas allowed fishermen to capture the entire welfare gain as well as facilitate transfer of further \$9.11 million of wealth from consumers to the production sector.

Finally, let us examine the findings from this section in the context of layer one of the model. According to the simulation, consumer surplus decreased with the adoption of individual quotas. This gives us a clue on how to resolve ambiguity in the answer to the consumer surplus version of question (I). Adoption of individual quotas in British Columbia is undesirable to the consumers in the USA when British Columbia adopts individual quotas as a first country but is desirable to the consumers in the USA when British Columbia adopts individual quotas as a second country. Adoption of individual quotas by Alaska is always undesirable to U.S. consumers, regardless what is the order of adoption. Consistently with the findings in the previous section, adoption of individual quotas is always desirable to the adopting country in terms of profits, regardless of what is the order of adoption. However, the second-moving country decreases industry profits in the trading partner. Finally, global welfare seems to increase whenever a country adopts individual quotas. However, this is not true for the welfare pertaining to particular countries, which depends on how customers are partitioned. In this case all customers are assigned to Alaska, thus implementation of individual quotas in British Columbia reduces American welfare regardless what is the order of adoption. On the other hand, the adoption of individual quotas in Alaska does not affect British Columbia, if Alaska is moving first but is reducing Canadian welfare if Alaska moves second.

5. Individual quotas: beneficial or harmful?

In the previous section, using the example of the North Pacific halibut fishery, I demonstrate how individual quotas can be both desirable and undesirable, depending on the circumstances and the

objective function that is used by the regulators. In this section, I develop a more comprehensive analysis. Numerical simulations are used to explore what is possible in each case. Recall, that we are interested in answering questions (I)-(IV) using all three possible regulators' objective functions. That is, we are interested in finding out whether adoption of individual quotas can be desirable or undesirable to (I) a single fishery, (II) the other country, (III) the global economy, and (IV) the adopting country. To achieve this, I set up the following five optimization problems:

$$16) \min(G_{IQ} - G_{DF})(-1)^k$$

$$17) \min(G_{M1} - G_{DF})(-1)^k$$

$$18) \min(G_{M2} - G_{DF})(-1)^k$$

$$19) \min(G_{IQ} - G_{M1})(-1)^k$$

$$20) \min(G_{IQ} - G_{M2})(-1)^k$$

where G_{IQ} is the total or country-specific welfare, profit, or consumer surplus under an individual-quotas regime (when equilibrium is described by equations (1)-(2)), G_{DF} is the analogous quantity under derby fishing regime (equations (3)-(5)), G_{M1} is calculated under a mixed regime with a single price (equations (6)-(9)), and G_{M2} is calculated under mixed regime with two prices (equations (10)-(15)). k indicates the direction of search. If $k = 0$ and the value of the minimized expression is negative, it is evidence that adoption of individual quotas can be undesirable. If negative value could not be found, it is a strong argument that individual quotas cannot be undesirable. If $k = 1$ and the value of the minimized expression is negative, it is evidence that adoption of individual quotas can be desirable. If a negative value could not be found, it is a strong argument that individual quotas cannot be desirable.

In a nutshell, I am searching for model parameters (within plausible ranges) that would facilitate increase or decrease in the regulators' objective functions after implementing individual quotas (wherever it cannot be deduced from the analysis carried out to this point). Problem (16) tries to establish whether introduction of individual quotas in a single fishery, or joint introduction of individual quotas in two similar fisheries, can be desirable or undesirable. Problem (17) investigates whether it is desirable or undesirable when both countries start with derby fishing, one of them switches to individual quotas, and the market ends up in a mixed regime with a single price. Problem (18) is analogical to (17) but the market ends up in a mixed regime with two prices. Problem (19) assumes that the initial state is mixed regime with a single price, and one country adopts individual quotas so that both countries have it. Similarly, problem (20) assumes that the market begins with a mixed regime with

two prices and ends up with individual quotas in both countries. These five problems are an exhaustive list of ways individuals quotas can be introduced in two countries with separate regulators. I begin with profit analysis, and then proceed to consumer surplus and welfare. The results are summarized in Table 2.

When (I) both fisheries adopt individual quotas jointly, profits must increase. Also, when both countries initially have derby fisheries and one country implements individual quotas, then (II) the situation in other country does not change, (III) global profit increases, and (IV) profit in the adopting country always increases. When the two countries are initially in a mixed regime, then profits in the adopting country always increase.

As we have seen in the previous section, the profits of the non-adopting party can decrease when the starting point is the mixed regime with two prices. However, solving a corresponding variant of the problem (20) shows that it can also increase (see Appendix for sample parameter values). Also, in the previous section we find that total profit increases; however solving the appropriate variant of the problem (20) shows that it can also decrease. In addition, when a mixed regime with a single price is the initial situation, then by Proposition 5, profit of the other country does not change and thus the profit in the world economy increases.

An analysis of consumer surplus is slightly more complicated because it requires us to decide to whom should we assign consumer surplus and in what proportion. For instance, as in the North Pacific halibut fishery, consumer surplus can be entirely assigned to one country. Nevertheless, the case when countries jointly adopt individual quotas is straightforward. In the previous section we saw an example when global consumer surplus decreases and the application of problem (16) shows that it can increase.

In the example of the North Pacific halibut fishery, adoption of individual quotas by the second country decreases consumer surplus when the second-mover is Alaska, but if the second-mover is British Columbia, consumer surplus increases. Since in general we can attribute consumer surplus to any country, for second-mover, any outcome is possible. On the other hand, we have seen that adoption of individual quotas by first-mover can lead to a decrease in consumer surplus. However, solving problem (17) for this case shows that consumer surplus can increase; hence, the effects of the adoption of individual quotas on consumer surplus are generally ambiguous.

Order of adoption	Who is the	Profits	Consumer surplus	Welfare
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	subject?			
Jointly	Global economy	Always increase	Can increase or decrease	Always increases
As a first country	Adopting country	Always increase	Can increase or decrease	Can increase or decrease
	Non-adopting country	Do not change		Can increase or decrease
	Global economy	Always increase		Can increase or decrease
As a second country	Adopting country	Always increase	Can increase or decrease	Probably always increases
	Non-adopting country	Can increase or decrease		Can increase or decrease
	Global economy	Can increase or decrease		Probably always increases

Table 2. Is adoption of individual quotas desirable or undesirable? “Probably” indicates that the conclusion was drawn from an inability to find a counterexample.

The most interesting is the issue of welfare since individual quotas as progressive regulation are supposed to increase it. I was unable to find parameters for demands and production function that would yield global welfare loss in cases (16), (19), and (20), that is, for situations in which both fisheries end up covered by individual quotas either by implementing it simultaneously in both countries or by implementing it in the second-mover. Those results, at least with respect to (16) and (19) are not surprising, as they are predicted by Theorem 1 and Theorem 2 respectively. However, surprisingly, problems (17) and (18) yielded negative objective values (see Appendix).

If just one country switches to individual quotas, it can lead to global welfare loss. Increase in price caused by additional high-quality fish attracts additional effort to the derby fishery whose output remains the same but cost increases. This increase in inefficiency can be stronger than efficiency gains from the individual quotas country and changes in consumer surplus.

Let us again consider the North Pacific halibut fishery to see if this can happen under plausible real-life circumstances, that is, using plausible parameter values. Note that implementation of individual

quotas in British Columbia indeed led to price increases and a further reduction of the Alaskan derby season length (Herrmann and Criddle, 2006). This however was accompanied by a welfare gain as the calculations from the previous section show.

Before proceeding with the analysis, three potential sources of welfare loss must be identified: a) market demand, b) instantaneous catch function, and c) season length for individual quota fisheries. Neither (a) nor (b) can be easily influenced by regulators, but they can be measured and investigating effects of demand and supply shocks on the market performance is in line with mainstream economics. (c) is a variable whose value is explicitly determined by regulators. Other potential parameters that can influence market outcome are d) relative size of the countries and e) total allowable catch. The first seems unlikely to vary significantly over time and the second is redundant given full flexibility of demand. Hence, my analysis consider only (a), (b), and (c).

To identify circumstances under which global welfare loss can occur, I solve problem (18) with α and Q set at the values used in the previous section for the North Pacific halibut fishery. This indeed yields global welfare loss from adopting individual quotas by British Columbia (see details in the Appendix). All combinations of factors (a), (b), and (c) are investigated and the results are presented in Table 3.

a) Demand	Yes	Yes	Yes	No	Yes	No	No
b) Production	Yes	Yes	No	Yes	No	Yes	No
c) Season Length	Yes	No	Yes	Yes	No	No	Yes
Loss?	Yes	Yes	Yes	No	Yes	No	No

Table 3. Given that we allow variation of a) demand, b) instantaneous catch function, and c) season length in British Columbia, after implementation of individual quotas, is it possible that there is a welfare loss generated by the implementation of individual quotas by British Columbia?

I observe that vertical intercepts of the inverse demand functions hit their upper boundary in the search of maximum welfare loss. A conclusion follows that it is the decrease in elasticity of demand that is likely to facilitate or increase welfare loss. Reduction in the amount of available frozen fish is likely to increase prices and this increase is higher if elasticity of demand is low. On the other hand, bigger efficiency gains from spreading production over time can lead to smaller welfare loss, which is confirmed by bigger welfare loss accompanied by smaller congestion effects. Season length in British Columbia becomes considerably short, although it does not hit the constraint while searching for the

maximum welfare loss. Its effect on welfare loss is thus, in general, ambiguous, although it probably needs to be significantly smaller than conventional values (around 0.2, that is, 70 days in my experiments, as opposed to 0.68, that is, 243 days as a conventional value). Overall, it seems that changes in demand (that is making it less elastic) are a necessary and sufficient condition for global welfare loss to occur if we start with the situation as it was in the North Pacific halibut fishery. The other factors, such as shortening of the fishing season and smaller congestion effects can exacerbate the problem.

To investigate how much different the situation in the demand for North Pacific halibut would have to be, to facilitate welfare loss, a series of minimizations problems have been solved. All these problems derive from (18) and each problem allows for a slightly greater (in percentage points) deviation from the original parameters of the model derived in the previous section. I was able to find welfare loss of a small but numerically reliable magnitude for the demand parameters deviating from the original parameters by no more than 41%. The demand is weaker, compared to the original case; that is, vertical intercepts of the inverse demand function are smaller and slope coefficients are bigger (making their constraints binding; see Appendix for details). This suggests that global welfare loss from adoption of individual quotas can occur under plausible circumstances that are beyond the regulators' control. Any potential transition costs further extend the range of circumstances under which this can happen.

The remaining elements of Table 2 that need addressing are results of adopting individual quotas on own or neighbor's welfare. Since welfare is sum of profits and consumer surplus and we can attribute consumer surplus in any possible way depending on where majority of consumers reside, welfare of non-adopting country when the first-mover switches to individual quotas changes in the same way as consumer surplus, because profits don't change. Moreover, first-mover always experiences increase in national welfare if consumers are located in the other country but can also experience decrease in national welfare if all consumers are within its borders. Then, the change in national welfare equals the change in the global welfare which we already found capable of decreasing.

When we consider the second-mover, the example of the North Pacific halibut fishery shows that national welfare of the non-adopter can be diminished because of a drop in both profits and consumer surplus. But as we have already seen, the profits of the non-adopting country can also increase. In such a situation, if we attribute the entire consumer surplus to the adopting country, the national welfare of the non-adopting country increases. Finally, note that when the initial situation is a

mixed regime with a single price, the adoption of the second-mover cannot be undesirable to the adopting country. Here, pursuant to Theorem 2, consumer surplus stays the same and the adoption of individual quotas cannot reduce profits. Similarly, using problem (20) to find model parameters that minimize welfare gain for the adopting country, I was unable to obtain objective value lower than zero. Hence, the second-mover probably cannot reduce its welfare with the adoption of individual quotas.

6. Strategic interaction

In the previous section I provide answers to questions (I)-(IV) and structure them in the form of Table 2. In this section I focus on questions (V)-(VII). If the answer to question (IV) (“Can adoption of individual quotas be undesirable to adopting country?”) is “no,” then the answer to questions (V), (VI), and (VII) is also “no.” However, as presented in the previous section, question (IV) can be answered “yes” unless regulators care only about industry profits. Questions (V) and (VI) ask whether regulators can be stuck in an inferior equilibrium by sticking to the legacy regulation when progressive regulation is Pareto- or Kaldor-Hicks-superior. Question (VII) asks if regulators can be stuck in an inferior equilibrium where one country uses progressive regulation while the other uses legacy regulation. This three questions result in an exhaustive list of possibilities where regulators can be stuck in an inferior equilibrium. If they are, international coordination may be required. The results are summarized in Table 4.

	Profits	Consumer surplus	Welfare
(V) Can countries be stuck in a Pareto-inferior (derby, derby) equilibrium?	No	Yes	Yes
(VI) Can countries be stuck in a Kaldor-Hicks-inferior (derby, derby) equilibrium?	No	Yes	Yes
(VII) Can countries be stuck in a Kaldor-Hicks-inferior (derby, quotas) equilibrium?	No	No	No

Table 4. When international coordination may be needed to facilitate an improving switch from legacy to progressive regulation.

We already know that the answer to question (VI) when regulators care only about industry profits is “no,” and thus it is also the answer to question (V). Similarly, the answer to question (VII) is also “no.” Investigating consumer surplus and welfare is, however, more complicated and require solving optimization problems from the previous section in search of adverse incentives.

Consider Figure 1. To answer question (V) we are looking for model parameters for which $D < H$ and $G < I$, yet $B > H$ and $C > I$. To answer question (VI) we are looking for model parameters for which $D < H$ and $G < I$, yet $B + C > H + I$. Finally, to answer question (VII) we are looking for model parameters for which $C < E$ and $D > H$ but $B + C > D + E$ and $B + C > H + I$ or $B < F$ and $G > I$ but $B + C > F + G$ and $B + C > H + I$.

For consumer surplus, it is easy to find sets of plausible parameters which satisfy conditions for question (V) and (VI) (see Appendix). Assuming that fisheries are symmetric in size and consumers are split evenly between the two countries, it is enough to merely use problem (18). I found parameters for which global consumer surplus decreases with adoption of individual quotas by the first-mover but then increases more than offsetting the initial decrease as the second-mover adopts individual quotas. Since consumers are split evenly, we need not worry about attributing the consumer surplus to a specific country. Nor should we care about which country is the first-mover and which is the second-mover, because countries are indistinguishable.

Consumers in a particular country cannot be affected differently than consumer in the other country. A change in consumer surplus in one country means a change in the same direction in the other country and a change in the same direction in the global consumer surplus. Thus, it is impossible to have $C < E$ and $B + C > D + E$ at the same time (or $B < F$ and $B + C > F + G$). Conditions necessary for question (VII) to have answer “yes” can never be satisfied, hence the answer is “no.” Similar conclusion arises when we try to answer question (VII) with respect to welfare. Adoption of individual quotas as a second-mover probably always leads to an increase in national welfare (see Table 2), that is $C > E$ and $B > F$.

To address questions (V) and (IV) in context of welfare, I use optimization problem (18). I was able to find parameters of the model and partitioning of consumer surplus which guarantee that adoption of individual quotas by any country as a first-mover is undesirable to the adopting country as well as it reduces global welfare. Moreover, welfare in both countries when both adopt individual quotas jointly, is higher than when both use derby fishing. That is, I found a situation in which $B > H > D$ and $C > I > G$ (see Appendix). In turn, the answer to both question (V) and question (VI) is “yes”.

The parameters I found for this deadlock are close to the boundaries of their respective ranges and decrease in welfare is small. This may suggest that a situation in which welfare-oriented regulators are locked in an inferior equilibrium is unlikely. Nevertheless, the existence of more plausible parameter values that produce such a deadlock cannot be excluded. Any transition costs are likely to widen the range of parameters that facilitate it. In such an instance, international coordination is needed.

Note the difference between strategic interactions in the case considered herein and traditional international economics approach. Game theory models of trade wars usually follow the Prisoner's Dilemma pattern in which adoption of progressive regulation (no trade barriers) is dominated by adoption of legacy regulation (high trade barriers). The need to coordinate policy in these games has given rise to the formation of international organizations, such as the WTO, which are not only responsible for adoption of globally desirable policies but also for preventing the participants from sliding back into the welfare-reducing equilibrium. Here however, whenever coordination is needed, there are two equilibria. Once countries switch to progressive regulation, there is no longer a need to coordinate to maintain industries in the desired conditions, as it is also an equilibrium.

7. Summary and conclusions

In this article, I develop a model of strategic interaction between regulators in two countries participating in a free-trade agreement bloc. Unlike as found in traditional trade literature, the interaction does not necessarily exhibit the pattern of Prisoner's Dilemma, where the strategy of adopting progressive regulation (e.g., reduction of trade barriers) is dominated by the adoption of legacy regulation (strong trade barriers). Depending on circumstances, both countries adopting progressive regulation can be an equilibrium or there can be two equilibria: both countries use progressive regulation and both countries use legacy regulation. In the latter case, international policy coordination may be needed to induce countries to adopt better regulatory regimes.

I perform this analysis using fishery as a sample industry. I construct a market model for a fishery that allows to quantify consumer surplus and production efficiency gains under different regulatory regimes. Derby fishing takes the role of legacy regulation and individual quotas takes the role of progressive regulation. I calibrate the model to the situation of the North Pacific halibut fishery in the early 1990s and compare its predictions to known facts about that fishery. The model does a good job of predicting the phenomena against which I verify it.

I confirm that in a closed economy, implementation of individual quotas always leads to an increase in national welfare, which justifies the status of individual quotas as a progressive regulation. However, even though individual quotas are virtually unequivocally considered by the economists to be better than derby fishing, I find a set of circumstances under which their introduction decreases the regulators' objective function. Among others I find that:

1. Implementation of individual quotas in a closed economy can be detrimental to consumer surplus and facilitate transfer of wealth from consumers to producers.
2. Implementation of individual quotas in an open economy can be a "beggar-thy-neighbor" type of policy, that is, it can reduce wealth in other countries.
3. Implementation of individual quotas in an open economy can reduce both the global welfare and national welfare of the country adopting it.
4. Implementation of individual quotas can be perceived by two trading partners as detrimental to their national welfare, even though the global welfare increases when both of them adopt it.

I also find that if adoption of individual quotas is driven by the regulators' care about profits of the fishermen, then no coordination problems can occur, even though adoption of individual quotas sometimes decreases industry profits in the neighboring country. As introduction of individual quotas has been driven to this point by a willingness to counter profit dissipation in the industry, that is, wastes and dangers associated with derby fishing, it is likely that profit has been the regulators' driving motivation to date. Once it is known that introduction of individual quotas can have unintended consequences on consumer surplus, regulators' attitude to the problem may require readjustment.

This finding advises caution for the regulators implementing individual quotas, especially in markets that are shared between separately-regulated fisheries. It may turn out that implementation of individual quotas is against the regulators' objectives if the trading partner does not follow suit. This, in general, demonstrates that investigation of strategic interaction between industry regulators is an important topic, even though it seems to have been neglected by mainstream economics.

A question related to this analysis that begs an answer is whether there are other industries that can be analyzed in a similar way. There are a great many countries participating in various free-agreement blocs throughout the world. Moreover, this framework applies also to other entities belonging to a single country and participating in common markets (for example states, regions,

territories) that can independently regulate their industries. A number of such industries participate in common markets throughout the world. Changes in their regulation (with an especially interesting case being adoption of potentially welfare-improving regulation) can have unintended consequences which in turn can be transmitted through market mechanism to trading partners and then return to the adopting country in a harmful way. This I leave for further research.

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Appendix

Construction of the aggregate utility function. Assume there are N individuals in the market for two substitute goods. Individual i has a concave utility function $u_i(x, y)$ that equals individual i 's dollar value (reservation price) of a bundle (x, y) . Define aggregate utility function as $U(x, y) = \sum_{i=1}^N u_i(x_i, y_i)$

where x_i and y_i solve $x = \sum_{i=1}^N x_i$ and $y = \sum_{i=1}^N y_i$ (total demands equal sum of consumption for individuals) and $\frac{\partial u_i}{\partial x} = \frac{\partial u_j}{\partial x}$ and $\frac{\partial u_i}{\partial y} = \frac{\partial u_j}{\partial y}$ for every i and j (marginal utilities are equal to price).

Note that this definition is synonymous to

$$U(x, y) = \max_{x_1, \dots, x_N, y_1, \dots, y_N} \sum_{i=1}^N u_i(x_i, y_i)$$

Subject to $x = \sum_{i=1}^N x_i$ and $y = \sum_{i=1}^N y_i$.

Does $U(x, y)$ have the properties of a utility function? Using Envelope Theorem, it is straightforward that $U(x, y)$ is increasing in both arguments and its derivatives are equal to prices. Let us prove that $U(x, y)$ is concave.

$$\begin{aligned} tU(x^1, y^1) + (1-t)U(x^2, y^2) &= t \sum_{i=1}^N u_i(x_i^1, y_i^1) + (1-t) \sum_{i=1}^N u_i(x_i^2, y_i^2) \\ &= \sum_{i=1}^N t u_i(x_i^1, y_i^1) + (1-t) u_i(x_i^2, y_i^2) \leq \sum_{i=1}^N u_i(tx_i^1 + (1-t)x_i^2, ty_i^1 + (1-t)y_i^2) \\ &\leq U(tx^1 + (1-t)x^2, ty^1 + (1-t)y^2) \end{aligned}$$

Q.E.D.

Proof of Lemma 1. Note that $\lim_{p \rightarrow +\infty} D(p) = 0$ and $\forall p \geq 0 D(p) \geq 0$. Assume now that there exists a positive length interval $A = (\underline{p}, \bar{p})$ such that $\forall p \in A D'(p) \geq 0$. Since D is not decreasing in this interval and we know that it must eventually decrease to zero as price tends to plus infinity, from the continuity of D , either it is increasing in A and it must have a peak somewhere or it must be constant in A . Either way, there exist $p_1 < p_2$ such that $D(p_1) = D(p_2)$. Let us investigate consumption bundles corresponding to price levels p_1 and p_2 . Consumption bundle corresponding to p_1 can be found by solving $\max_{q_H \geq 0, q_L \geq 0} W(q_H, q_L)$ s.t. $q_H + q_L = D(p_1)$ and consumption bundle corresponding to p_2 can be found with $\max_{q_H \geq 0, q_L \geq 0} W(q_H, q_L)$ s.t. $q_H + q_L = D(p_2)$. These in fact are the same optimization problems, and since objective function is strictly concave, the bundles are the same. Denote consumption of this bundle as (q_H^*, q_L^*) . Note that $\frac{\partial W}{\partial q_H}(q_H^*, q_L^*) = p_1$ and $\frac{\partial W}{\partial q_H}(q_H^*, q_L^*) = p_2$ must be satisfied at the same time which contradicts $p_1 \neq p_2$ and thus by contradiction A cannot exist. ■

Proof of Lemma 2. It is sufficient to prove that $\frac{\partial D_H}{\partial p_H} + \frac{\partial D_L}{\partial p_H} < 0$, that is as we increase the price of the high-quality good, the total consumption decreases. Note that demands are characterized by the following system of two equations and two unknowns:

$$\begin{cases} \frac{\partial W}{\partial q_H}(q_H, q_L) = p_H \\ \frac{\partial W}{\partial q_L}(q_H, q_L) = p_L \end{cases} \Rightarrow \begin{cases} \frac{\partial^2 W}{\partial q_H^2} dq_H + \frac{\partial^2 W}{\partial q_L \partial q_H} dq_L = dp_H \\ \frac{\partial^2 W}{\partial q_L \partial q_H} dq_H + \frac{\partial^2 W}{\partial q_L^2} dq_L = dp_L \end{cases}$$

Which in turn can be solved for dq_H and dq_L :

$$\begin{cases} dq_H = \frac{\frac{\partial^2 W}{\partial q_L^2} dp_H}{\frac{\partial^2 W}{\partial q_H^2} \frac{\partial^2 W}{\partial q_L^2} - \left(\frac{\partial^2 W}{\partial q_L \partial q_H}\right)^2} - \frac{\frac{\partial^2 W}{\partial q_L \partial q_H} dp_L}{\frac{\partial^2 W}{\partial q_H^2} \frac{\partial^2 W}{\partial q_L^2} - \left(\frac{\partial^2 W}{\partial q_L \partial q_H}\right)^2} \\ dq_L = \frac{\frac{\partial^2 W}{\partial q_H^2} dp_L}{\frac{\partial^2 W}{\partial q_H^2} \frac{\partial^2 W}{\partial q_L^2} - \left(\frac{\partial^2 W}{\partial q_L \partial q_H}\right)^2} - \frac{\frac{\partial^2 W}{\partial q_L \partial q_H} dp_H}{\frac{\partial^2 W}{\partial q_H^2} \frac{\partial^2 W}{\partial q_L^2} - \left(\frac{\partial^2 W}{\partial q_L \partial q_H}\right)^2} \end{cases}$$

Notice that $\frac{\partial D_H}{\partial p_H} + \frac{\partial D_L}{\partial p_H} = \frac{dq_H}{dp_H} + \frac{dq_L}{dp_H} = \frac{\frac{\partial^2 W}{\partial q_L^2} \frac{\partial^2 W}{\partial q_L \partial q_H}}{\frac{\partial^2 W}{\partial q_H^2} \frac{\partial^2 W}{\partial q_L^2} - \left(\frac{\partial^2 W}{\partial q_L \partial q_H}\right)^2} = \frac{dq_H}{dp_H} + \frac{dq_L}{dp_L} < 0$ since own price effects are stronger than cross-price effects. ■

Proof of Lemma 3. Recall that $V(p, p) = \max_{q_H \geq 0, q_L \geq 0} W(q_H, q_L) - p(q_H + q_L)$ and since W is concave and increasing in both arguments, this optimization problem is equivalent to $\max_{q_H \geq 0, q_L \geq 0} W(q_H, q_L)$ subject to $q_H + q_L \leq D(p)$. Since $D'(p) < 0$ (Lemma 1), increase in p means decreasing the size of the constraint set which in turn means decrease in the objective value as solution is always on the outer boundary.

$$\text{Also, } V(+\infty, p) = \max_{q_L \geq 0} W(0, q_L) - q_L p \leq \max_{q_H \geq 0, q_L \geq 0} W(q_H, q_L) \text{ s.t. } q_H + q_L = D(+\infty, p)$$

$$< \max_{q_H \geq 0, q_L \geq 0} W(q_H, q_L) \text{ s.t. } q_H + q_L = D(p)$$

$$= \max_{q_H \geq 0, q_L \geq 0} W(q_H, q_L) - p(q_H + q_L) = V(p, p)$$

■

Proof of Proposition 1. Two different market equilibria need to have two different prices, since (5) relates uniquely price to effort and (4) relates uniquely effort to season length. Let us assume that there are two market equilibria with two different prices $p_1 < p_2$. According to (5) this implies that corresponding efforts are $E_1 < E_2$ and corresponding season lengths according to (4) are $T_1 > T_2$. The two equations (4) and (5) can be in fact combined to create a strictly decreasing function $T(p)$. I am going to prove that the similar function implicit in equation (3) is strictly increasing which contradicts both p_1 and p_2 being solutions. Let us solve for T using (3):

$$T = \frac{Q - D_L(+\infty, p)}{D_H(p, p) + D_L(p, p) - D_L(+\infty, p)} = \frac{Q - D_L(+\infty, p)}{D(p) - D_L(+\infty, p)}$$

Note that the numerator as well as the denominator is positive, in accordance with Lemma 2. Let us differentiate this expression with respect to p .

$$\frac{dT}{dp} = \frac{-\frac{\partial}{\partial p} D_L(+\infty, p)(D(p) - D_L(+\infty, p)) - \left(D'(p) - \frac{\partial}{\partial p} D_L(+\infty, p)\right)(Q - D_L(+\infty, p))}{(D(p) - D_L(+\infty, p))^2}$$

$$\frac{dT}{dp} = \frac{\frac{\partial}{\partial p} D_L(+\infty, p)(Q - D(p)) - D'(p)(Q - D_L(+\infty, p))}{(D(p) - D_L(+\infty, p))^2} > 0$$

The above expression is greater than zero since derivatives of both demand functions are negative. Moreover, since quota is a weighted average of the two demands, and $D(p) > D_L(+\infty, p)$, then $Q - D(p) < 0$ and $Q - D_L(+\infty, p) > 0$. ■

Proof of Proposition 2. We can totally differentiate the system

$$\begin{cases} qdp & + & (pq' - 1)dE & + & 0dT & = & 0 \\ 0dp & + & Tq'dE & + & qdT & = & dQ \\ \left[TD'(p) + (1 - T)\frac{\partial}{\partial p} D_L(+\infty, p)\right]dp & + & 0dE & + & [D(p) - D_L(+\infty, p)]dT & = & dQ \end{cases}$$

Let us solve for implicit derivatives using Cramer's rule.

$$W = \begin{vmatrix} q & (pq' - 1) & 0 \\ 0 & Tq' & q \\ TD'(p) + (1-T)\frac{\partial}{\partial p}D_L(+\infty, p) & 0 & D(p) - D_L(+\infty, p) \end{vmatrix} = \begin{vmatrix} q & b & 0 \\ 0 & c & q \\ e & 0 & f \end{vmatrix} = q(cf + be) > 0$$

since $q > 0$, $c > 0$, $f > 0$ (see Lemma 2), $b < 0$ (from (5) and concavity of q), and $e < 0$ (as weighted average of two negative numbers). Then

$$W_p = \begin{vmatrix} 0 & b & 0 \\ dQ & c & q \\ dQ & 0 & f \end{vmatrix} = b(q - f)dQ, W_E = \begin{vmatrix} q & 0 & 0 \\ 0 & dQ & q \\ e & dQ & f \end{vmatrix} = q(f - q)dQ, W_T = \begin{vmatrix} q & b & 0 \\ 0 & c & dQ \\ e & 0 & dQ \end{vmatrix} = (qc + be)dQ$$

Additionally $q - f = q - D(p) + D_L(+\infty, p_{DF}) > 0$ hence:

$$\frac{dp}{dQ} = \frac{W_p}{W} = \frac{b(q - f)}{q(cf + be)} < 0, \frac{dE}{dQ} = \frac{W_E}{W} = \frac{f - q}{cf + be} < 0, \frac{dT}{dQ} = \frac{qc + be}{q(cf + be)} > 0$$

Now, let us focus on $\frac{d\Sigma}{dQ}$.

$$\frac{d\Sigma}{dQ} = \frac{d}{dQ} [TV(p, p) + (1 - T)V(+\infty, p)] > 0$$

since $\frac{dT}{dQ} > 0$, $\frac{dp}{dQ} < 0$ and $\frac{d}{dp}V(p, p) < 0$, $\frac{d}{dp}V(+\infty, p) < 0$, and $V(+\infty, p) < V(p, p)$ (Lemma 3).

Consumer surplus is a weighted average and by increasing total quota we increase both components of this average and put more weight on the bigger component.

Finally, note that $TE = pQ$, hence $\frac{dTE}{dQ} = \frac{dpQ}{dQ} = Q\frac{dp}{dQ} + p$. If the demand is generally elastic, we have

$$\frac{dQ}{dp} \frac{p}{Q} < -1 \Leftrightarrow \frac{dp}{dQ} \frac{Q}{p} > -1 \Leftrightarrow Q\frac{dp}{dQ} > -p \Leftrightarrow Q\frac{dp}{dQ} + p > 0 \Leftrightarrow \frac{dTE}{dQ} > 0, \text{ as long } p > 0. \text{ Analogous}$$

reasoning holds for demand generally inelastic, that is $\frac{dQ}{dp} \frac{p}{Q} > -1$. ■

Proof of Proposition 3. Let us totally differentiate (2):

$$q(1, E)dT + Tq'(1, E)dE = dQ$$

Therefore $\frac{dE}{dT} = -\frac{q(1, E)}{Tq'(1, E)} < 0$ and $\frac{dE}{dQ} = \frac{1}{Tq'(1, E)} > 0$. Now, let us totally differentiate (1):

$$TD'(p)dp + D(p)dT + (1 - T) \frac{\partial}{\partial p} D_L(+\infty, p)dp - D_L(+\infty, p)dT = dQ$$

Hence we have $\frac{dp}{dT} = -\frac{D(p) - D_L(+\infty, p)}{TD'(p) + (1-T)\frac{\partial}{\partial p} D_L(+\infty, p)} > 0$ and $\frac{dp}{dQ} = \frac{1}{TD'(p) + (1-T)\frac{\partial}{\partial p} D_L(+\infty, p)} < 0$.

The profit is defined as $\Pi = Qp - ET$. Let us totally differentiate: $d\Pi = Qdp + pdQ - EdT - TdE$.

Now, $\frac{d\Pi}{dT} = Q \frac{dp}{dT} - E - T \frac{dE}{dT}$. The last two terms could be aggregated to $E + T \frac{dE}{dT} = E - \frac{q(1, E)}{q'(1, E)} < 0 \Leftrightarrow$

$\frac{q(1, E)}{E} > q'(1, E)$ and the latter inequality is always true since q is strictly concave and $q(s, 0) = 0$. Note

also that $\frac{dp}{dT} > 0$ therefore $\frac{d\Pi}{dT} > 0$ as it is a sum of two positive expressions.

$\frac{d\Pi}{dQ} = Q \frac{dp}{dQ} + p - T \frac{dE}{dQ}$ where the first two terms can be interpreted as elasticity effect and their sum can

be either positive or negative. The last term can be interpreted as effort effect and is always negative.

Thus the sign of the whole expression is ambiguous.

Consumer surplus is represented by $\Sigma = TV(p, p) + (1 - T)V(+\infty, p)$. When we totally differentiate it,

we get $d\Sigma = T \frac{d}{dp} V(p, p)dp + V(p, p)dT + (1 - T) \frac{d}{dp} V(+\infty, p)dp - V(+\infty, p)dT$. In turn, we get:

$$\frac{d\Sigma}{dT} = V(p, p) - V(+\infty, p) + \left(T \frac{d}{dp} V(p, p) + (1 - T) \frac{d}{dp} V(+\infty, p) \right) \frac{dp}{dT}$$

Note that the difference between the first two terms is always positive (Lemma 3) and the last term is always negative. Therefore the effect of expanding season length on consumer surplus is ambiguous. On the other hand,

$$\frac{d\Sigma}{dQ} = \left[T \frac{d}{dp} V(p, p) + (1 - T) \frac{d}{dp} V(+\infty, p) \right] \frac{dp}{dQ} > 0$$

since both multiplicands are less than zero. ■

Proof of Proposition 4. Using expressions calculated in the proof of Proposition 3:

$$\begin{aligned}
\frac{d\Omega}{dT} &= \frac{d}{dT}(\Pi + \Sigma) \\
&= Q \frac{dp}{dT} - E - T \frac{dE}{dT} + V(p, p) - V(+\infty, p) \\
&\quad + \left(T \frac{d}{dp} V(p, p) + (1 - T) \frac{d}{dp} V(+\infty, p) \right) \frac{dp}{dT} \\
&> Q \frac{dp}{dT} + \left(T \frac{d}{dp} V(p, p) + (1 - T) \frac{d}{dp} V(+\infty, p) \right) \frac{dp}{dT} = \\
&= \left(Q + T \frac{d}{dp} V(p, p) + (1 - T) \frac{d}{dp} V(+\infty, p) \right) \frac{dp}{dT}.
\end{aligned}$$

Note that by Envelope Theorem, $\frac{d}{dp} V(p, p) = -D(p)$ and $\frac{d}{dp} V(+\infty, p) = -D_L(+\infty, p)$. Thus,

$$\begin{aligned}
\left(Q + T \frac{d}{dp} V(p, p) + (1 - T) \frac{d}{dp} V(+\infty, p) \right) \frac{dp}{dT} &= (Q - TD(p) - (1 - T)D_L(+\infty, p)) \frac{dp}{dT} \\
&= (Q - Q) \frac{dp}{dT}
\end{aligned}$$

where the last equality is guaranteed by equation (1). Thus, $\frac{d\Omega}{dT} > 0$. ■

Proof of Proposition 5. If $T_{NEW} = T_{IQ}$, then equation (1) and equation (6) are exactly the same equation of one variable with one unknown. Since the solution must be unique (as Lemma 1 guarantees that the left-hand side of the equation is a strictly decreasing function of p_{IQ} or p_M), p_{IQ} and p_M must be equal. ■

Proof of Theorem 1. From a mathematical point of view, the only difference between the two regimes is that under derby fishing, there is the additional equation (5) and the length of season is endogenous, while under individual quotas, season length is exogenous. If season length determined by derby fishing is T_{DF} , and we introduce individual quotas and constrain season length to $T_{IQ} = T_{DF}$, then the system of equations (1)-(2) yields exactly the same solution as system (3)-(5): given $T_{IQ} = T_{DF}$, equation (2) yields $E_{IQ} = E_{DF}$ because it has a unique solution; then equation (1) has a unique solution (by Lemma 1) at $p_{DF} = p_{IQ}$.

Thus, to prove the claim made by the theorem it is sufficient to prove that increase in season length in the individual quota regime always results in increase in welfare. This in turn is proved by Proposition 4. ■

Proof of Theorem 2. By Proposition 5 we have $p_M = p_{IQ}$. In turn, demands are exactly the same under the individual quotas and under the mixed regime. Thus, consumer surplus is exactly the same. Note however, that the country adopting individual quotas experiences increase in production efficiency due to prolonged fishing season (as long as $T_{NEW} = T_{IQ} > T_{OLD}$), while profits of fishermen in the country that already has adopted individual quotas does not change. Thus, the total welfare increases. ■

Simulations

A. General description

To do numerical simulations that allowed me to generate figures from Section 4, I wrote a C++ application. The code is available upon request. The program computes equilibria in all three cases (derby fishing, individual quotas, and mixed setting regime) for a given utility function W , yield-effort function q , and exogenous variables like α , T_{IQ} , etc. It consists of three layers. The first layer is responsible for numerical optimization of the utility function and for computing demanded quantities, given prices. The second layer implements an algorithm for solving systems of equations using contracting mapping and thus finds a market equilibrium in each of the three cases (derby fishing, individual quotas, and mixed). It calls the first layer whenever demands must be evaluated. The third layer consists of a loop which allows for doing comparative statics. It iteratively solves for equilibria and changes parameters. The second layer is called upon each iteration of the third layer.

For a numerical simulation to succeed, one must specify functional forms. A quadratic utility function of $W(q_H, q_L) = aq_H + bq_L - cq_H^2 - dq_L^2 - eq_Hq_L$ is used to approximate the true utility function. This function is strictly concave for $4cd - e^2 > 0$ and is increasing in the relevant range, that is, for quantities corresponding to positive prices. This functional form is also useful because it allows for the use of analytical demands rather than numerical demands, which improves the speed and numerical precision of the simulations. The functional form of the instantaneous catch function is assumed to be $q(s, E) = As^{1-\rho}E^\rho$.

The model has been calibrated to resemble the historical situation in the North Pacific halibut fishery from the early 1990s. Five data points based on figures from Herrmann and Criddle (2006) were used to generate a system of five equations and five unknowns and determine the unknown parameters of the utility function. Please keep in mind that the numbers below are “rough” and are used for illustration. Before IVQs were introduced in British Columbia, of the total quota of 55 million pounds, 3.85 million

pounds were sold fresh and 51.15 million pounds were sold frozen. The average ex-vessel price in that period was \$1.70 per pound and the season length was 0.03 of a year which corresponds to 11 days. Moreover, during the period between 1991 and 1995, when British Columbia enjoyed quotas while Alaska was still in derby fishing, the amount of fish sold by Canadian fishermen as high-quality fish was 7.05 million pounds (I consider that to be the amount sold outside the derby season in Alaska; this is an approximation which seems appropriate because the quantity sold during Alaskan derby season by Canadian fishermen must have been relatively small) while total quota was 45 million pounds. The price for that fish was \$2.40 and the price for the rest of the fish was \$1.90. Finally, after both countries ended up with quota systems, the price of fish stabilized at \$2.10 with the season length of 0.68 (248 days) and total quota of 60 million pounds. I assume that $\alpha = \frac{1}{6}$. The five data points are summarized in the table below.

Period	Interpretation	Equation
Pre-IVQ	Total fresh sales.	$0.03D_H(1.7,1.7) = 3.85$
Pre-IVQ	Total frozen sales.	$0.03D_L(1.7,1.7) + 0.97D_L(+\infty, 1.7) = 51.15$
Mixed	Fresh sales outside Alaskan derby season.	$(0.68 - 0.03)D_H(2.4,1.9) = 7.05$
Mixed	Remaining sales.	$0.03(D_H(1.9,1.9) + D_L(1.9,1.9)) + (0.68 - 0.03)D_L(2.4,1.9) + 0.32D_L(+\infty, 1.9) = 37.95$
Post-ITQ	Total sales.	$0.68(D_H(2.1,2.1) + D_L(2.1,2.1)) + 0.32D_L(+\infty, 2.1) = 60$

Assuming quadratic utility function, the above system of equations turns out to be a system of five non-linear equations with five unknowns. It was solved with Excel and MATLAB. The results are shown in the frame below.

a = 2.62521
b = 2.43121
c = 0.00339742
d = 0.00698308
e = 0.00437402

Note the consistency with the assumption that demand for high-quality fish is in general higher – here expressed by bigger intercept and flatter slope of the demand function. Condition for strict concavity is also satisfied.

The parameters of the instantaneous production function are determined based on situation between Canadian adoption of IVQ in 1991 and American adoption of ITQ in 1995. During the derby period, total revenues and the season length are used to determine level of instantaneous effort: $E_{DF} = \frac{p_{DF}Q_{DF}}{T_{DF}} = 1.7 \times \frac{55}{0.03} = 3116\frac{2}{3}$ (interpretation: over 3 bln USD/year; I ignore processing costs as well as costs of other intermediaries). During the individual quotas period, it is assumed that profits constitute 50% of revenues, based on the historical quota leasing prices (Pinkerton and Edwards, 2009). Therefore, the instantaneous effort is determined as $E_{IQ} = \frac{p_{IQ}Q_{IQ}}{2T_{IQ}} = \frac{2.1 \times 60}{2 \times 0.68} \approx 92.6471$. These values are then used to determine two parameters of the instantaneous production function by solving the system of two non-linear equations with two unknowns with Excel and MATLAB.

$$\begin{cases} q(1, E_{DF}) = \frac{Q_{DF}}{T_{DF}} \\ q(1, E_{IQ}) = \frac{Q_{IQ}}{T_{IQ}} \end{cases} \Rightarrow \begin{cases} A \left(3116\frac{2}{3}\right)^\rho = 1833\frac{1}{3} \\ A (92.65)^\rho = 88.2353 \end{cases} \Rightarrow \begin{cases} A = 1.77162 \\ \rho = 0.862948 \end{cases}$$

Once the model has been parameterized, it is possible to do simulations to see how changes in exogenous variables affect endogenous variables. I use the above values and then change a parameter of interest, iteratively solving the appropriate system of equations using my C++ program.

To solve the optimization problems from Section 5 and Section 6 we also need the parametrized version of the model, that is the version assuming $W(q_H, q_L) = aq_H + bq_L - cq_H^2 - dq_L^2 - eq_Hq_L$ and $q(s, E) = As^{1-\rho}E^\rho$. The optimization takes place over the model parameters, that is $a, b, c, d, e, A, \rho, Q, \alpha$, and exogenous variables like the length of the season. Each optimization contains two nested problems in which solutions of the corresponding systems of equations are found for given model parameters. In practice, it is possible to simplify the entire process by using equations (1)-(15) as constraints to the corresponding optimization problems rather than nesting system of equations inside objective functions.

The solving of optimization problems from Section 5 and Section 6 has been completed using Microsoft Excel and its optimization add-on, Solver (the spreadsheet containing data and models is available from the author upon request). The more detailed description of simulations is organized below into four sections that roughly correspond to sections 3, 4, 5, and 6 of the main body of the paper.

A. Analytical demands

For the precision and speed of calculations, analytical demands are derived using Kuhn-Tucker conditions. For the case outside fishing season, demand function is

$$D_L(+\infty, p) = \max\left(0, \frac{b - p}{2d}\right).$$

Inside the fishing season, there are four possibilities:

1) Interior solution:

$$q_L = \frac{2c(b - p_L) - e(a - p_H)}{4cd - e^2} > 0$$

$$q_H = \frac{2d(a - p_H) - e(b - p_L)}{4cd - e^2} > 0.$$

2) Corner solution 1:

$$q_L = \frac{b - p_L}{2d} > 0$$

$$q_H = 0, a - eq_L - p_H \leq 0.$$

3) Corner solution 2:

$$q_H = \frac{a - p_H}{2c} > 0$$

$$q_L = 0, b - eq_H - p_L \leq 0.$$

4) Corner solution 3:

$$q_L = 0, b - p_L \leq 0$$

$$q_H = 0, a - p_H \leq 0.$$

For the purpose of simulations, it is necessary to combine these possibilities into a single formula of demands as functions of p_L and p_H . Note that strict concavity of the objective function guarantees a unique maximum. Thus:

$$D_L(p_H, p_L) = \begin{cases} 0 & \Leftrightarrow b - p_L \leq 0 & \wedge & a - p_H \leq 0 \\ 0 & \Leftrightarrow b - e \frac{a - p_H}{2c} - p_L \leq 0 & \wedge & a - p_H > 0 \\ \frac{b - p_L}{2d} & \Leftrightarrow b - p_L > 0 & \wedge & a - e \frac{b - p_L}{2d} - p_H \leq 0 \\ \frac{2c(b - p_L) - e(a - p_H)}{4cd - e^2} & \Leftrightarrow \frac{2c(b - p_L) - e(a - p_H)}{4cd - e^2} > 0 & \wedge & \frac{2d(a - p_H) - e(b - p_L)}{4cd - e^2} > 0. \end{cases}$$

$$D_H(p_H, p_L) = \begin{cases} 0 & \Leftrightarrow b - p_L \leq 0 & \wedge & a - p_H \leq 0 \\ \frac{a - p_H}{2c} & \Leftrightarrow b - e \frac{a - p_H}{2c} - p_L \leq 0 & \wedge & a - p_H > 0 \\ 0 & \Leftrightarrow b - p_L > 0 & \wedge & a - e \frac{b - p_L}{2d} - p_H \leq 0 \\ \frac{2d(a - p_H) - e(b - p_L)}{4cd - e^2} & \Leftrightarrow \frac{2c(b - p_L) - e(a - p_H)}{4cd - e^2} > 0 & \wedge & \frac{2d(a - p_H) - e(b - p_L)}{4cd - e^2} > 0. \end{cases}$$

Or, after simplifications:

$$D_L(p_H, p_L) = \begin{cases} \frac{b - p_L}{2d} & \Leftrightarrow b - p_L > 0 & \wedge & a - e \frac{b - p_L}{2d} - p_H \leq 0 \\ \frac{2c(b - p_L) - e(a - p_H)}{4cd - e^2} & \Leftrightarrow \frac{2c(b - p_L) - e(a - p_H)}{4cd - e^2} > 0 & \wedge & \frac{2d(a - p_H) - e(b - p_L)}{4cd - e^2} > 0 \\ 0 & \text{otherwise} \end{cases}$$

$$D_H(p_H, p_L) = \begin{cases} \frac{a - p_H}{2c} & \Leftrightarrow b - e \frac{a - p_H}{2c} - p_L \leq 0 & \wedge & a - p_H > 0 \\ \frac{2d(a - p_H) - e(b - p_L)}{4cd - e^2} & \Leftrightarrow \frac{2c(b - p_L) - e(a - p_H)}{4cd - e^2} > 0 & \wedge & \frac{2d(a - p_H) - e(b - p_L)}{4cd - e^2} > 0 \\ 0 & \text{otherwise} \end{cases}$$

Instantaneous consumer surplus is

$$V(p_H, p_L) = (a - p_H)q_H + (b - p_L)q_L - cq_H^2 - dq_L^2 - eq_Hq_L$$

Where $q_H = D_H(p_H, p_L)$ and $q_L = D_L(p_H, p_L)$.

B. Table 1

In case of the content of Table 1, a phantom variable (that is a reference to a constant cell) is minimized, given equations (1)-(15) as constraints. First, a situation where Canada is the first country to adopt

individual quotas is considered. For the given parameters, $\alpha, a, b, c, d, e, A, \rho, Q, T_{IQ}, T_{NEW(6-9)}, T_{OLD(10-15)}$ the following values were found as a description of market equilibrium:

Symbol	Type	Value	Value
α	Parameter	0.166666667	0.833333333
a	Parameter	2.62521	2.62521
b	Parameter	2.43121	2.43121
c	Parameter	0.00339742	0.00339742
d	Parameter	0.00698308	0.00698308
e	Parameter	0.00437402	0.00437402
A	Parameter	1.77162	1.77162
ρ	Parameter	0.862948	0.862948
Q	Parameter	60	60
T_{DF}	Variable	0.040195989	0.040195989
p_{DF}	Variable	1.645387305	1.645387305
E_{DF}	Variable	2456.047004	2456.047004
T_{IQ}	Parameter	0.68	0.68
p_{IQ}	Variable	2.101217529	2.101217529
E_{IQ}	Variable	92.64664746	92.64664746
$T_{NEW(6-9)}$	Parameter	0.68	0.68
$T_{OLD(6-9)}$	Variable	0.008619385	0.008619385
p_M	Variable	2.101217529	2.101217529
E_{NEW}	Variable	15.44110791	77.20553955
$E_{OLD(6-9)}$	Variable	12188.90672	2437.781351
$T_{NEW(10-15)}$	Parameter	0.68	0.68
$T_{OLD(10-15)}$	Variable	0.029914736	0.00934986
p_{LO}	Variable	1.724424361	2.074245433
p_{HI}	Variable	2.320991306	2.113902191
$E_{OLD(10-15)}$	Variable	2882.232272	2218.477427
E_{NEW1}	Variable	1.846303375	67.36201198

E_{NEW2}	Variable	16.13488587	77.34405121
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These values satisfied equations (1)-(15) with precision better than 1×10^{-6} each, where precision is understood as an absolute value of the difference between the left-hand side and right-hand side of the equation. Condition for the system (6)-(9), that is $q(\alpha, E_{NEW}) \geq D_H(p_M, p_M)$, is not satisfied while the condition for the model (10)-(15) that is $p_{LO} \leq p_{HI}$ is satisfied. Hence values from model (10)-(15) are used. These values yields the following market outcomes which are the basis of Table 3:

	ITQ	DF	(10)-(15), $\alpha = 1/6$	(10)-(15), $\alpha = 5/6$
Consumer Surplus	14.9863609	24.10201362	19.5683167	14.59377379
Total profit	63.07333149	0	12.62364685	53.170249
Profit_alpha	10.51222191	0	12.62364685	53.170249
Profit_(1-alpha)	52.56110957	0	2.70006E-13	1.65379E-11
Welfare	78.05969239	24.10201362	32.19196355	67.76402279

For the situation in which Alaska is the first state to adopt individual quotas, only one parameter has been modified, namely $\alpha = 5/6$. This produced exactly the same results for derby fishery and individual quotas cases. This also resulted in (10)-(15) being the system describing market equilibrium.

C. Search for welfare loss and answering questions (I)-(IV)

During the search for welfare loss, the method used was GRG Nonlinear with multistart. The evolutionary method was also used for robustness but it did not introduce any additional value. All 27 variables (or actually, the relevant subset thereof) are used to optimize over and equations (1)-(15) are used as constraints. Also, additional bounds are placed on each variable. The table below contains examples mentioned in the main body of the paper. Column A describes a situation when switching from a mixed regime with two prices to individual quotas in both countries, increased profit of the non-adopting party. Column B describes a situation where switching from a mixed regime with two prices to individual quotas, decreased profits in the global economy. Column C describes a situation when adoption of individual quotas jointly in both countries increased global consumer surplus. Column D describes a situation in which switching from derby fishing in both countries to mixed regime with a single price increased global consumer surplus.

Variable	Lower bound	Upper bound	A	B	C	D
α	0.1	0.9	0.142063967	0.9	0.166666667	0.879558022
a	b	10	2.153412418	2.256760304	7.24811227	10
b	1	10	2.153412418	1.850012571	2.009105794	7.154950054
c	0.0001	0.1	0.001305044	0.004002128	0.013097515	0.015616025
d	c	0.1	0.006643629	0.007624648	0.013097515	0.015616025
e	0.0001	0.1	0.005888664	0.002970977	0.0001	0.078649582
A	0.5	2	1.736860645	0.647457319	2	0.5
ρ	0.5	0.999	0.88321168	0.996056178	0.999	0.892920912
Q	60	60	60	60	60	60
T_{DF}	0	1			0.00992492	0.036539902
p_{DF}	0	10			0.504027094	5.281027086
E_{DF}	0	1000000			3047.039627	8671.660521
T_{IQ}	T_{DF}	1	0.68	0.679319399	0.3	
p_{IQ}	0	10	1.942598282	1.609489239	2.009106111	
E_{IQ}	0	1000000	85.39804345	139.0973824	100.4620421	
$T_{NEW(6-9)}$	$T_{OLD(6-9)}$	1				0.5
$T_{OLD(6-9)}$	0	1				0.005
p_M	0	10				6.70355208
E_{NEW}	0	1000000				407.2965207
$E_{OLD(6-9)}$	0	1000000				9688.668891
$T_{NEW(10-15)}$	$T_{OLD(10-15)}$	1	0.68	0.679319399		
$T_{OLD(10-15)}$	0	1	0.026081297	0.006995829		
p_{LO}	0	10	1.48959778	1.603651723		
p_{HI}	0	10	1.859217751	1.613651723		
$E_{OLD(10-15)}$	0	1000000	2939.99095	1375.378081		
E_{NEW1}	0.1	1000000	1.884823583	26.09637714		
E_{NEW2}	0.1	1000000	12.57498832	126.2211416		
Objective value			0.756485293	-0.014208156	105.3299775	32.3958446

Findings of the search for counterfactual welfare loss in the North Pacific halibut fishery are summarized in the table below.

Variable	Lower bound	Upper bound	(17) and (18) yield values less than 0	(18) (abc)	(18) (ac)	(18) (a)
α	0.01	0.99	0.132114765	0.166666667	0.166666667	0.166666667
a	b	10	1.261050364	10	10	10
b	1	10	1.261050364	10	10	10
c	0.0001	0.1	0.002281127	0.075102971	0.070467492	0.097106033
d	c	0.1	0.005874622	0.075102971	0.070467492	0.097106033
e	0.0001	0.1	0.003899867	0.0001	0.0001	0.070890154
A	0.5	2	1.575581895	2	1.77162	1.77162
ρ	0.5	0.999	0.973858781	0.8853459	0.862948	0.862948
Q	45 or 60	45 or 60	45	60	60	60
T_{DF}	0	1	0.034540782	0.02809278	0.026287094	0.651408171
p_{DF}	0	10	0.760101563	1.233588659	1.760194361	1.057183169
E_{DF}	0	1000000	990.2662427	2634.674088	4017.624052	97.37518336
T_{IQ}	T_{DF}	1	0.387590847			
p_{IQ}	0	10	0.935081792			
E_{IQ}	0	1000000	82.70360588			
$T_{NEW(6-9)}$	$T_{OLD(6-9)}$	1	0.060325475			
$T_{OLD(6-9)}$	0	1	0.013835185			
p_M	0	10	0.779000232			
E_{NEW}	0	1000000	73.79623631			
$E_{OLD(6-9)}$	0	1000000	2199.011184			
$T_{NEW(10-15)}$	$T_{OLD(10-15)}$	1	0.060387165	0.200106504	0.200113511	0.68
$T_{OLD(10-15)}$	0	1	0.013810974	0.000124435	0.001012966	0.471188818
p_{LO}	0	10	0.779036857	2.488702923	2.952250811	1.112985103
p_{HI}	0	10	0.779104297	2.488702923	2.952250811	1.410360807

$E_{OLD(10-15)}$	0	1000000	2202.969602	1000000	145723.057	118.1039381
E_{NEW1}	0.1	1000000	73.53071759	47.80651815	63.72068577	6.694832424
E_{NEW2}	0.1	1000000	73.7746105	47.80651815	63.72068577	37.68063802
Welfare loss			Around 0.246 in both	22.33279479	18.99055566	0.580913683

While searching for minimum of (19) and (20), additional constraints are imposed to guarantee rationality of the result. Namely $T_{NEW(6-9)} = T_{NEW(10-15)} = T_{IQ}$.

The parameters of demand found for the allowed variation of 41% while searching for welfare loss in the (18) problem are $a = 1.616282338$, $b = 1.616282338$, $c = 0.004790362$, $d = 0.009846143$, $e = 0.002580672$. The welfare loss found is 0.00014053, that is, \$1405.30.

D. International strategic interaction

The below table shows parameters of the model for which countries are locked in an inferior (derby, derby) equilibrium. Parameters in columns “Welfare 1” and “Welfare 2” pertain to the same market (note that parameters of demand and catch function are the same) but to two countries, depending on which country is the first-mover. Countries have different share in the total quota and their respective share in consumer surplus is the same as their share in the total quota.

Variable	Consumer surplus	Welfare 1	Welfare 2
α	0.5	0.3	0.7
a	1.537418863	1	1
b	1.273808692	1	1
c	0.003357562	0.000143193	0.000143193
d	0.003357562	0.00395657	0.00395657
e	0.004883694	0.000936333	0.000936333
A	2	1.303153953	1.303153953
ρ	0.92621496	0.999	0.999
Q	60	60	60
T_{DF}	0.025684503	0.040914627	0.040914627
p_{DF}	0.87767193	0.772784861	0.772784861
E_{DF}	2050.275865	1133.264447	1133.264447

T_{IQ}	0.67806541	0.040924627	0.040924627
p_{IQ}	1.049646172	0.772813815	0.772813815
E_{IQ}	59.83605424	1132.98727	1132.98727
$T_{NEW(10-15)}$	0.67806541	0.040924627	0.040924627
$T_{OLD(10-15)}$	0.012570164	0.024592883	0.002996888
p_{LO}	0.929081981	0.773178726	0.774809523
p_{HI}	1.144304671	0.779697704	0.778979638
$E_{OLD(10-15)}$	2217.350508	1320.443232	4653.684477
E_{NEW1}	1.810053534	0.192393578	3.990867769
E_{NEW2}	30.48314012	852.2142817	855.5055431
Objective for DF	6.108353126	2.044936252	4.771517922
Objective for mixed	5.608353127	2.03959407	4.398039314
Objective for IQ	6.608353124	2.045200054	4.77213346