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Abstract

In this working paper we model the case of an international non-renewable resource monopolist as a dynamic game between a monopolist and *n* importing countries' governments, and we investigate whether a tariff on resource imports can be advantageous for the consumers of the importing countries when the monopolist sets the price and the importing countries' governments act in a non-cooperative way. We find that a tariff is advantageous for the consumers even when there is no commitment to the trade policy, although the part of the rent that can be reaped by the importing countries decreases substantially with the number of importing countries. The optimality of the tariff in our dynamic game is explained by the fact that through the tariff the governments of the importing countries can influence the dynamics of the accumulated extractions and hence the extraction costs and the evolution of the monopolist price.

Resumen

En este documento de trabajo se analiza el caso de un monopolio internacional como un juego dinámico entre un monopolista y los gobiernos de *n* países importadores, y se investiga si un arancel sobre las importaciones del recurso puede ser ventajoso para los consumidores de los países importadores cuando el monopolista fija el precio y los gobiernos de los países importadores actúan de forma no cooperativa. Un arancel es ventajoso para los consumidores incluso cuando los países importadores no disponen de una ventaja estratégica, aunque la parte de la renta del monopolista que pueden capturar los países importadores disminuye sustancialmente con el número de países importadores. El hecho de que la política comercial óptima consista en fijar un arancel se explica por el hecho de que a través de él los gobiernos de los países importadores pueden influir en la dinámica de las extracciones y de ahí los costes de extracción y la evolución del precio del monopolista.

Key words

Tariffs, non-renewable resources, depletion effects, price-setting monopolist, differential games, linear strategies, Markov-perfect Nash equilibrium.

Palabras clave

Aranceles, recursos no renovables, efectos agotamiento, monopolista fijador del precio, juegos diferenciales, estrategias lineales, equilibrio de Nash Markov-perfecto.

On Capturing Rent from a Non-Renewable Resource International Monopoly: A Dynamic Game Approach

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C O N T E N T S

1. Introduction

AN issue that is very important to the Western countries is how to react optimally to the existence of a non-renewable natural resource cartel or monopoly. The OPEC vs. the West is still a good example. One option that the Western countries have is to use strategically a tariff on resource imports to affect the extraction behavior of the monopolist and the international price of the resource which would allow them to capture a part of the seller's rent [1]. This paper analyzes this issue solving a dynamic game among a resource monopolist and the governments of the importing countries.

We assume that consumption takes place only in the importing countries which are not endowed with the resource and that the utility function is linear-quadratic [2]. The monopolist extracts the resource at an average cost that is constant with respect to the extraction rate but increasing with respect to the accumulated extractions (depletion effects) and sells it in an integrated international market.

In section 2 we present the model where we assume that the monopolist sets the price and the market the extraction rate whereas the governments of the importing countries fix a tariff on resource imports. In section 3 we derive the Markov-perfect Nash equilibrium in linear strategies of the dynamic game between the monopolist and the governments of the importing countries. As we use Markov strategies we obtain a subgame perfect equilibrium for the dynamic game that is dynamically consistent. In section 4 we show that the optimal tariffs of the Markov-perfect Nash equilibrium are not zero. This is the major contribution of this paper since we find, contrarily to what is obtained in a static setting, that even when the monopolist chooses the price and the importing countries' governments do not enjoy a strategic advantage to set

1. The idea that rent can be extracted from a foreign monopolist was presented for the first time by Katrak (1977) and Svedberg (1979).

2. Most major exporters of non-renewable resources consume a negligible portion of their production, so the assumption is not too great a departure from reality.

a tariff on imports is advantageous for the consumers of the importing countries [3]. The optimality of the tariff is explained by the existence of an indirect strategic relationship that is not present in the static setting. For the case of a non-renewable resource we can distinguish two types of strategic relationship between an importing country government and the monopolist, one direct or intratemporal and another indirect or intertemporal. The direct strategic interdependence, that characterizes the static model, appears because the consumer's welfare depends on the monopolist price and the monopolist profits depend on the tariff, whereas the indirect strategic relationship appears because through the tariff the governments of the importing countries can influence the dynamics of the accumulated extractions and hence the extractions costs and the evolution of the monopolist price. For this reason, in this case the importing countries governments can use strategically a tariff to capture a part of the monopolist rent.

In section 5 we analyze the effects on the optimal tariff of a wider international market, i.e., a market with a large number of importing countries. Our analysis allows us to conclude that the optimal tariff decreases when the number of importing countries increases, at least during an initial stage of the exploitation period of the resource. Thus we find, as it can be expected, that the greater is the number of countries, the lower is the capacity of importing countries to use strategically a tariff against a monopolist. A numerical example suggests that this capacity decreases quickly as the number of importing countries increases. For our numerical example the initial tariff goes down from 25.767 to 3.895, a reduction of almost 85%, when there is two importing countries instead of one. This result is explained by the combination of two facts. The first is that in our model besides the strategic interdependence between the importing countries governments and the monopolist there also exists an indirect strategic interdependence among the importing countries governments that appears because the extraction rate, and consequently the dynamics of the accumulated extractions, depends on the decision about the tariff of every one of the importing countries governments. The second is that the optimal tariff reflects the user cost of the resource for the importing countries. Then given the tariff of one country if another

3. As it is well known in a static setting if the monopolist chooses the price, the Nash equilibrium tariff of the game is zero and there is no place to use strategically a tariff. See Alepuz and Rubio (2005) for a study of the strategical use of a tariff against a monopolist under an integrated international market in a static framework. In a dynamic framework this result was already suggested by Bergstrom (1982) but for the case of a monopolist that extracts the resource costlessly.

country increases its tariff, the extraction rate is going to decrease which means as well a decrease in the variation rate of the resource and hence a lower user cost for all the importing countries. The consequence is then that the greater is the number of importing countries, the lower is the optimal tariff for a given level of the accumulated extractions which finally explains why the tariff is going to be lower at least during an initial stage of the exploitation period of the resource.

The issue of using an import tariff to reap a part of the non-renewable resource rent has been also addressed by Kemp and Long (1980), Bergstrom (1982), Brander and Djajic (1983), Karp (1984, 1991), Maskin and Newbery (1990), Karp and Newbery (1991, 1992) and more recently by Rubio (2005). Among them only Bergstrom (1982), Brander and Djajic (1983), Karp (1984) and Rubio (2005) have focused on the case of a non-renewable resource monopolist [4]. Bergstrom (1982) briefly discusses, in the framework of a partial equilibrium model where consumption takes place only in the importing countries and extraction costs are zero, the case in which all importing countries choose the same constant ad valorem tariff against a monopolist that sets the price. He argues that almost all the monopolist rent can be taxed away by the importing countries if they choose a sufficiently high tariff rate. On the other hand, Brander and Djajic (1983) develop their analysis in the context of a simple two-country general equilibrium model of trade in exhaustible resources where it is assumed that the resource is extracted costlessly and used by the two countries as an essential input in the production of a homogeneous consumption good. They find that the country without resource has an incentive to impose a tariff so as to extract at least some of the available rent. The magnitude of the optimal tariff is found to be an increasing function of the relative size of the importing country and approaches the confiscatory level as the resource importing country becomes very large. In Karp (1984) the interaction between a monopolist and a single buyer is modeled as a Stackelberg game where the extraction cost is inversely related to the stock and the buyer is the leader of the game. The buyer chooses a tariff and the monopolist the rate of extraction. He shows that the open-loop tariff is temporally inconsistent because of the stock-dependence of extraction costs. Besides, he proposes a method of obtaining temporally consistent strategies and concludes that the consistent tariff against the monopolist is in general not identically zero which implies that the consistent tariff allows the buyer to improve his position. Rubio (2005) completes Karp's (1984) analysis studying the

4. In the rest of papers it is assumed that producers are competitive.

interaction between a coalition of importing countries governments and a resource monopolist when the monopolist chooses the price. In this paper it is showed that when the monopolist chooses the price a tariff is advantageous for the single buyer even when this does not enjoy a first movement advantage as it occurs in Karp's (1984) model. Thus our paper can be seen as an extension of Bergstrom (1982) and Rubio's (2005) papers although it differs from these in several respects. As regards Bergstrom's paper we assume that extraction costs rise with cumulative extractions and we investigate the game theoretic aspects of the problem more completely. Moreover, we do not assume as Bergstrom does that the importing countries choose a constant tariff throughout the exploitation period of the resource. In fact, we find that this is not the optimal path for the tariff when there are depletion effects. In this case, the tariff must be decreasing since the rent converges to zero in the long run because of the economic exhaustion of the resource. Nevertheless, our analysis supports his conclusion that a tariff can be used to capture a part of the monopolist's rent but not almost all the rent as was suggested by Bergstrom (1982). In fact, our analysis shows that the part of the rent that can be reaped by the importing countries through a tariff decreases with the number of importing countries. As regards Rubio's (2005) paper we propose a model where n importing countries act in a non-cooperative way against a monopolist. Thus this paper can be seen a generalization for $n > 1$ of the results obtained in Rubio's (2005) paper for $n = 1$. So that our main contribution in comparison with his paper is that we show that even without any kind of cooperation or coordination among the importing countries governments to set a tariff on resource imports is advantageous for the consumers of the importing countries.

2. The Model

AS in Bergstrom's (1982) analysis, we shall confine ourselves to a partial equilibrium model. Assuming that the representative consumer of an importing country acts as a price-taker agent, we can write the consumer's welfare function as $aq_i(t) - (1/2)q_i(t)^2 - (p(t) + \theta_i(t))q_i(t) + R_i(t)$, where $aq_i(t) - (1/2)q_i(t)^2$ is the consumer's gross surplus, $q_i(t)$ the amount of the resource bought by the representative consumer of the importing country i, $p(t)$ the international price of the resource, $\theta_i(t)$ the *per unit tariff* on the resource imports fixed by the government of the importing country i, and $R_i(t)$ a lump-sum transfer that the consumer receives from the government. Thus, the resource demand depends only on the consumer price: $q_i(t) = a - p(t) - \theta_i(t)$ and consequently the aggregate demand function can be written as $Q = \sum_{i=1}^{n}(a - p(t) - \theta_i(t))$ where n is the number of importing countries [5]. We also assume for simplifying the analysis that the importing countries are not endowed with the resource.

The governments set the tariff with the aim of maximizing the discounted present value of the representative consumer's welfare. They reimburse tariff revenues as *lump-sum transfers*, so that finally the consumer's welfare does not depend on tariff revenue. The optimal time path for the tariff is thus given by the solution of the following optimal control problem

$$\max_{\{\theta_i(t)\}} \int_0^\infty e^{-rt} \left(a(a - p(t) - \theta_i(t)) - \frac{1}{2}(a - p(t) - \theta_i(t))^2 - p(t)(a - p(t) - \theta_i(t)) \right) dt$$

where r is the discount rate.

Simplifying, this problem can be written as [6]

$$\max_{\{\theta_i(t)\}} \int_0^\infty e^{-rt} \frac{1}{2} \left((a - p(t))^2 - \theta_i(t)^2 \right) dt, \quad i = 1, ..., n \tag{2.1}$$

5. We assume as in Bergstrom's (1982) analysis an integrated international market so that all the importing countries pay the same price for the resource.

6. Notice that in a static simultaneous game with a payoff function equal to $(a - p)^2 - \theta^2$ the optimal tariff of the Nash equilibrium is zero when the monopolist chooses the price. As we will see in section 4 this is not the case for the dynamic game analyzed in this paper.

On the other side of the market we have a monopolist extracting the resource at a cost equal to $c(x)Q$, where $c(x) = cx$ is the marginal extraction cost, x stands for the accumulated extractions and Q for the current extraction rate of the resource. Observe that given the price and the tariffs, the extraction rate is determined by the aggregate demand function and consequently is equal to the resource bought by the representative consumers of the importing countries. The objective of the monopolist is to define a price strategy that maximizes the present value of profits

$$\max_{\{p(t)\}} \int_0^\infty e^{-rt} \left((p(t) - cx(t)) \sum_{i=1}^{n} (a - p(t) - \theta_i(t)) \right) dt \tag{2.2}$$

Finally, the dynamics of the accumulated extractions is given by the following differential equation

$$\dot{x} = Q = \sum_{i=1}^{n} \left(a - p(t) - \theta_i(t)\right), \quad x(0) = x_0 \geq 0 \tag{2.3}$$

Both types of players face the same dynamic constraint and the optimal time paths for the tariffs and the price are given by the solution of the *differential game* among the monopolist and the governments of the importing countries defined by (2.1)-(2.3).

3. The Markov-perfect Nash Equilibrium

THIS section solves the differential game through the computation of a Markov-perfect Nash equilibrium. We use Markov strategies because these kinds of strategies, which capture essential strategic interactions, provide a subgame perfect equilibrium that is dynamically consistent.

Markov strategies must satisfy the following system of Hamilton-Jacobi-Bellman (HJB) equations

$$rW_i = \max_{\{\theta_i\}} \left\{ \frac{1}{2}\left((a-p)^2 - \theta_i^2\right) + W_i' \sum_{j=1}^{n}(a-p-\theta_j) \right\},\ i = 1, ..., n \quad (3.1)$$

$$rW_M = \max_{\{p\}} \left\{ (p-cx)\sum_{j=1}^{n}(a-p-\theta_j) + W_M' \sum_{j=1}^{n}(a-p-\theta_j) \right\} \quad (3.2)$$

where $W_M(x)$ stands for the optimal current value function associated with dynamic optimization problem for the monopolist (2.2) and $W_i(x)$ for the optimal current value function associated with dynamic optimization problem for the importing country i (2.1), i.e., they denote the maxima of the objectives (2.1) and (2.2) subject to (2.3) for the current value of the state variable [7].

From the first-order conditions for the maximization of the right-hand sides of the HJB equations, we get the instantaneous reaction functions of the importing countries and the monopolist

7. Time arguments and the argument of the value function will be eliminated when no confusion arises.

$$\theta_i = -W_i', \; i = 1, ..., n \tag{3.3}$$

$$p = \frac{1}{2}\left(a + cx - W_M' - \frac{1}{n}\sum_{j=1}^{n}\theta_j\right) \tag{3.4}$$

These expressions establish that the optimal tariff is independent of the monopolist price and equal to the user cost of the resource for the importing countries, and that the price and the tariffs are *strategic substitutes* for the monopolist for a given value of the state variable.

By substitution of (3.3) in (3.4), we get the solution of the price as a function of the first derivatives of the value functions

$$p = \frac{1}{2}\left(a + cx - W_M' + \frac{1}{n}\sum_{j=1}^{n}W_j'\right) \tag{3.5}$$

Next, by incorporating optimal strategies (3.3) and (3.5) into HJB equations (3.1) and (3.2), we eliminate the maximization and obtain the following system of $n+1$ nonlinear differential equations

$$\begin{aligned}
rW_i &= \frac{1}{2}\left(\frac{1}{4}\left(a - cx + W_M' - \frac{1}{n}\sum_{j=1}^{n}W_j'\right)^2 - (W_i')^2\right) + \\
&\quad + W_i'\sum_{k=1}^{n}\left(\frac{1}{2}\left(a - cx + W_M' - \frac{1}{n}\sum_{j=1}^{n}W_j'\right) + W_k'\right), \quad i = 1, ..., n \\
rW_M &= \sum_{i=1}^{n}\frac{1}{2}\left(\frac{1}{2}\left(a - cx + W_M' - \frac{1}{n}\sum_{j=1}^{n}W_j'\right) + W_i'\right) \\
&\quad \left(a - cx + W_M' - \frac{1}{n}\sum_{j=1}^{n}W_j'\right)
\end{aligned}$$

This system seems analytically intractable so that we will focus on the symmetric case: $W_1' = ... = W_n' = W_I'$.

$$\begin{aligned} rW_I &= \frac{1}{4}\left(\frac{1}{2}\left(a-cx+W_M'\right)^2+(2n-1)\left(a-cx+W_M'\right)W_I'+\right. \\ &\quad \left.+\frac{4n-3}{2}(W_I')^2\right) && (3.6) \\ rW_M &= \frac{n}{4}(a-cx+W_M'+W_I')^2 && (3.7) \end{aligned}$$

In order to derive the solution to this system of differential equations, we guess quadratic representations for the value functions W_I and W_M

$$W_I(x)=\frac{1}{2}\alpha_I x^2+\beta_I x+\mu_I,\ W_M(x)=\frac{1}{2}\alpha_M x^2+\beta_M x+\mu_M \qquad (3.8)$$

Substituting W_I, W_M, W_I' and W_M' in (3.6) and (3.7), we obtain the following system of coupled Riccati equations:

$$\begin{aligned} 4r\alpha_I &= (c-\alpha_M)^2-2(2n-1)(c-\alpha_M)\alpha_I+(4n-3)\alpha_I^2 && (3.9) \\ 2r\alpha_M &= n(c-\alpha_I-\alpha_M)^2 && (3.10) \\ 4r\beta_I &= -(a+\beta_M)(c-\alpha_M)+(2n-1)((a+\beta_M)\alpha_I- && (3.11) \\ &\quad -(c-\alpha_M)\beta_I)+(4n-3)\alpha_I\beta_I \\ 2r\beta_M &= -n(a+\beta_I+\beta_M)(c-\alpha_I-\alpha_M) && (3.12) \\ 8r\mu_I &= (a+\beta_M)^2+2(2n-1)(a+\beta_M)\beta_I+(4n-3)\beta_I^2 && (3.13) \\ 4r\mu_M &= n(a+\beta_I+\beta_M)^2 && (3.14) \end{aligned}$$

If this system has a solution, the linear Markov-perfect Nash equilibrium strategies for the tariff and the price are given by the following expressions

$$\begin{aligned} \theta &= -\alpha_I x-\beta_I && (3.15) \\ p &= \frac{1}{2}\left(a+\beta_I-\beta_M+(c+\alpha_I-\alpha_M)x\right) && (3.16) \end{aligned}$$

which are obtained from (3.3) and (3.5). Then the consumer price can be calculated as $p+\theta$

$$\pi=p+\theta=\frac{1}{2}\left(a-\beta_I-\beta_M+(c-\alpha_I-\alpha_M)x\right) \qquad (3.17)$$

Finally, we obtain the dynamics of the state variable in terms of the coefficients of the value functions using this expression in (2.3)

$$\dot{x} = \frac{n}{2}\left(a + \beta_I + \beta_M - (c - \alpha_I - \alpha_M)x\right) \tag{3.18}$$

Thus, if we look for a stable solution the following condition should be satisfied by the coefficients of the value functions

$$\frac{d\dot{x}}{dx} < 0 \ \rightarrow \ \frac{d\dot{x}}{dx} = -\frac{n}{2}(c - \alpha_I - \alpha_M) < 0 \rightarrow c - \alpha_I - \alpha_M > 0 \tag{3.19}$$

Next, we show that the system of Riccati equations has at least one stable solution.

4. An Advantageous Tariff

THE system (3.9)-(3.14) has not an analytical solution for $n > 1$ *. However, it can be shown that it has at least one stable solution. Reordering terms in (3.9) and (3.10) we obtain the following system of equations for α_I and α_M

$$(4n-3)\alpha_I^2 - 2((2n-1)(c-\alpha_M)+2r)\alpha_I + (c-\alpha_M)^2 = 0 \quad (4.1)$$
$$n\alpha_I^2 - 2n(c-\alpha_M)\alpha_I + n(c-\alpha_M)^2 - 2r\alpha_M = 0 \quad (4.2)$$

Adding and subtracting $2rc$ in the second equation and doing the following change of variable $\hat{\alpha}_M = c - \alpha_M$ this system can be rewritten as

$$(4n-3)\alpha_I^2 - 2((2n-1)\hat{\alpha}_M + 2r)\alpha_I + \hat{\alpha}_M^2 = 0 \quad (4.3)$$
$$n\alpha_I^2 - 2n\hat{\alpha}_M\alpha_I + n\hat{\alpha}_M^2 - 2r(c-\hat{\alpha}_M) = 0 \quad (4.4)$$

and the following result can be established:

Lemma 1. *The system (4.3)-(4.4) has at least one solution that satisfies the stability condition. For this solution* α_I *and* α_M *belong to interval* $(0, c)$ *and* $c - \alpha_I - \alpha_M > 0$.
Proof: See appendix A.1.

Showed that system (4.3)-(4.4) has at least one real solution it is easy to check that the complete system of Riccati equations has at least one real solution and it can showed that [8]

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* This is not the case for $n = 1$. See Rubio (2005) for an analytical solution of this differential game when there is only one importing country or a coalition of importing countries.

8. For the numerical example that we present in section 5 we also find that the solution that belongs to interval $(0, c)$ is the unique stable solution.

Proposition 1. *A tariff is advantageous for the consumers of the importing countries, i.e.* $\theta = -\alpha_I x - \beta_I$ *is positive in interval* $[0, a/c)$ *where* a/c *is the steady-state value of the accumulated extractions.*

Proof: See appendix A.2.

This analysis establishes that for the case of a non-renewable resource there exist two types of strategic relationship, one direct and another indirect. The direct strategic relationship appears because the consumer's welfare depends on the monopolist price, see (2.1), and the monopolist profits depend on the tariff, see (2.2), whereas the indirect strategic relationship appears because through the tariff the governments of the importing countries can influence the dynamics of the accumulated extractions and hence the extraction costs and the optimal policy of the monopolist. In the model this indirect strategic relationship operates through differential equation (2.3). Thus given the price, an increase in the tariff reduces the extraction rate which determines the accumulation rate of the stock yielding finally a reduction of the marginal extraction cost which has a positive influence in the evolution of the price. For this reason, it is advantageous for the importing countries to set up a tariff on the resource imports since the governments can influence the dynamics of the price through their influence on the dynamics of the stock using the tariff. Thus the profitability of the tariff for the importing countries is explained by the existence of this indirect strategic relationship [9].

In appendix A.2 we have obtained that $\beta_I = -a\alpha_I/c$ and that $\beta_M = -a\alpha_M/c$ so that the equilibrium strategy for the tariff given by (3.15) can be rewritten as

$$\theta = -\alpha_I x + a\alpha_I/c = \alpha_I(a/c - x) \tag{4.5}$$

which establishes that the optimal tariff is decreasing with respect to the accumulated extractions and is zero for $x^\infty = a/c$. Moreover, using the above expressions for β_I and β_M, we obtain that the intersection point

9. Notice that when there are more than one importing country there also exists an indirect strategic interdependence among the importing countries since the dynamics of the accumulated extractions depends, according to (2.3), on the decision about the tariff of every one of the importing countries. As we show in section 5 this strategic interdependence reduces the capacity of one importing country to use strategically the tariff.

with the vertical axis for the monopolist price equilibrium strategy given by (3.16) is positive an equal to [10]

$$\frac{1}{2}(a+\beta_I-\beta_M)=\frac{1}{2}\left(a-\alpha_I\frac{a}{c}+\alpha_M\frac{a}{c}\right)=\frac{a}{2c}(c-\alpha_I+\alpha_M)>0$$

so that equilibrium strategy for the monopolist price (3.16) can be rewritten as [11]

$$p=\frac{1}{2}\left(\frac{a}{c}(c-\alpha_I+\alpha_M)+(c+\alpha_I-\alpha_M)x\right) \tag{4.6}$$

which establishes that the monopolist price is increasing with respect to the accumulated extractions and equal to a for $x^{\infty}=a/c$. We obtain the same kind of results for the consumer price whose equilibrium strategy is given by

$$\pi=\frac{1}{2}\left(\frac{a}{c}(c+\alpha_I+\alpha_M)+(c-\alpha_I-\alpha_M)x\right) \tag{4.7}$$

where

$$a-\beta_I-\beta_M=\frac{a}{c}(c+\alpha_I+\alpha_M)>0$$

in (3.17).

Finally, for extraction rate (3.18) we get that

$$a+\beta_I+\beta_M=a-\alpha_I\frac{a}{c}-\alpha_M\frac{a}{c}=\frac{a}{c}(c-\alpha_I-\alpha_M)>0$$

and the equilibrium strategy for the rate of extraction can be rewritten as

$$\dot{x}=Q=\frac{n}{2}\left(\frac{a}{c}(c-\alpha_I-\alpha_M)-(c-\alpha_I-\alpha_M)x\right)=\frac{n}{2}(c-\alpha_I-\alpha_M)\left(\frac{a}{c}-x\right) \tag{4.8}$$

which establishes that the rate of extraction is decreasing with respect to the accumulated extractions and is zero for $x^{\infty}=a/c$.

Next, we calculate the optimal path of the model variables. To obtain these paths we need to solve differential equation (4.8). The solution to this equation for $x_0=0$ is [12]

10. Notice that as $\alpha_I,\alpha_M\in(0,c)$, the difference $c-\alpha_I+\alpha_M$ cannot be negative or zero.

11. Again $c+\alpha_I-\alpha_M$ is positive because α_I,α_M belong to the interval $(0,c)$.

12. In order to simplify the presentation we assume that $x_0=0$. This does not change the sign of the dynamics of the model variables. In any case, in this kind of non-renewable resources models it must be assumed that $x_0<a/c$ since $\dot{x}=Q\geq 0$.

$$x = \frac{a}{c}\left(1 - \exp\left\{-\frac{n}{2}\left(c - \alpha_I - \alpha_M\right)t\right\}\right) \tag{4.9}$$

Then substituting x in (4.5) and (4.6) we get

$$\theta = \alpha_I \frac{a}{c}\exp\left\{-\frac{n}{2}\left(c - \alpha_I - \alpha_M\right)t\right\} \tag{4.10}$$

$$p = a\left(1 - \frac{c + \alpha_I - \alpha_M}{c}\exp\left\{-\frac{n}{2}\left(c - \alpha_I - \alpha_M\right)t\right\}\right) \tag{4.11}$$

Finally, the consumer price can be simply calculated by the addition of the monopolist price and the tariff

$$\pi = p + \theta = a\left(1 - \frac{c - \alpha_I - \alpha_M}{2c}\exp\left\{-\frac{n}{2}\left(c - \alpha_I - \alpha_M\right)t\right\}\right) \tag{4.12}$$

so we can summarize these results as

Remark 1. *The Markov-perfect Nash equilibrium tariff decreases throughout the exploitation period of the resource and converges to zero in the long run. Moreover, the monopolist and consumer prices are increasing and converge to the backstop price.*

5. The Effects of a Wider International Market

IN this section we want to analyze the effects on the optimal tariff of a wider international market, i.e., a market with a large number of importing countries. The aim is to show that the conjecture that the greater is the number of countries, the lower is the capacity of importing countries to use strategically a tariff is true.

Our analysis allows us to conclude that

Lemma 2. *The greater is the number of importing countries, the lower is the optimal tariff for a given level of the accumulated extractions and the greater is the monopolist and consumer prices provided that* c *is not very low.*

Proof: See appendix A.3.

In the appendix we obtain that for instance for $r = 0.05$ and $n \geq 4$, c must be greater than 0.0275 to get the results presented in the previous lemma [13]. This gives us an idea that the condition that appears in this proposition is not very restrictive.

However, to evaluate the effect of an increase in the number of importing countries on the optimal path of the tariff we need to evaluate the effect on the optimal path of the accumulated extractions since the optimal tariff depends, according to (4.5), on the accumulated extractions. Using (4.9) we find that the sign of difference $x(t; n+1) - x(t; n)$ is determined by the sign of the following expression

13. These results hold for the tariff and the monopolist price when $n \geq 2$. However, for the consumer price we have been able to show this effect only for $n \geq 4$. Nevertheless, the fact that $n \geq 4$ is a sufficient condition to get these results and that the numerical example developed in this section shows that this effect also occurs when n changes from 1 to 2 leads us to think that it also holds for $n \geq 2$.

$$(n+1)(c-\alpha_I(n+1)-\alpha_M(n+1))-n(c-\alpha_I(n)-\alpha_M(n))=$$

$$=(c-\alpha_I(n+1)-\alpha_M(n+1))-n\left(\alpha_I(n+1)-\alpha_I(n)+\alpha_M(n+1)-\alpha_M(n)\right) \tag{5.1}$$

The problem is that we cannot determined the sign of this expression without knowing the values of α_I and α_M [14]. Nevertheless, it is straightforward that

Proposition 2. *The greater is the number of importing countries, the lower is the optimal tariff for a given level of the accumulated extractions and the greater is The optimal tariff decreases when the number of importing countries increases, at least during an initial stage of the exploitation period of the resource.*

Proof: From lemma 2 we know that $\theta(x_0;n) > \theta(x_0;n+1)$ which implies necessarily that $\theta(x(t);n)$ must be greater than $\theta(x(t);n+1)$ at least during an initial stage of the exploitation period given the continuity of the accumulated extractions dynamics defined by function (4.9).

Obviously this relationship can hold for the entire exploitation period of the resource although our analysis cannot allow us to conclude this since the sign of (5.1) is undetermined. Nevertheless, as the sign of (5.1) does not depend on time, a change in the number of importing countries moves up or down the optimal path of the accumulated extractions so that for all t the accumulated extractions are greater or lower depending on the number of importing countries. This means that if the accumulated extractions increase with the number of importing countries for all t, the optimal tariff must decrease also for all t given that the equilibrium strategy for the tariff moves down in that case as it has been established in lemma 2 [15].The following numerical example illustrates this possibility.

For $a = 100,\ c = 1$ and $r = 0.05$ we obtain that the optimal path for the accumulated extractions is given by [16]

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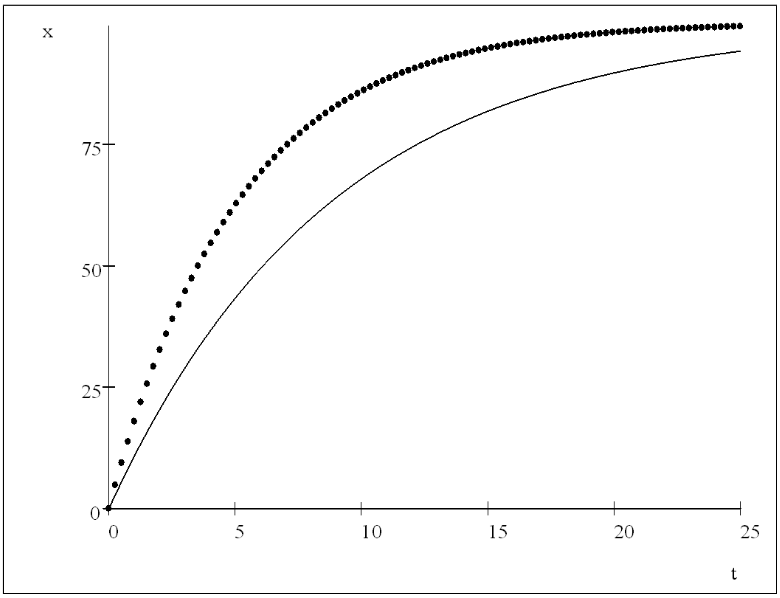
14. In appendix A.3 has been established that α_I increases with the number of importers but that α_M decreases which leaves difference (5.1) undetermined.

15. Remember that the slope of the equilibrium strategy for the tariff given by (4.5) is negative. The same result would be obtained if (5.1) were zero.

16. The dot-line stands for $n = 2$. These are the same figures used in the numerical illustration of appendix A.3. For these figures we find that the solution to system (4.3)-(4.4) that belong to interval $(0, c)$ is the unique stable solution of the system.

GRAPHIC 5.1: The accumulated extractions



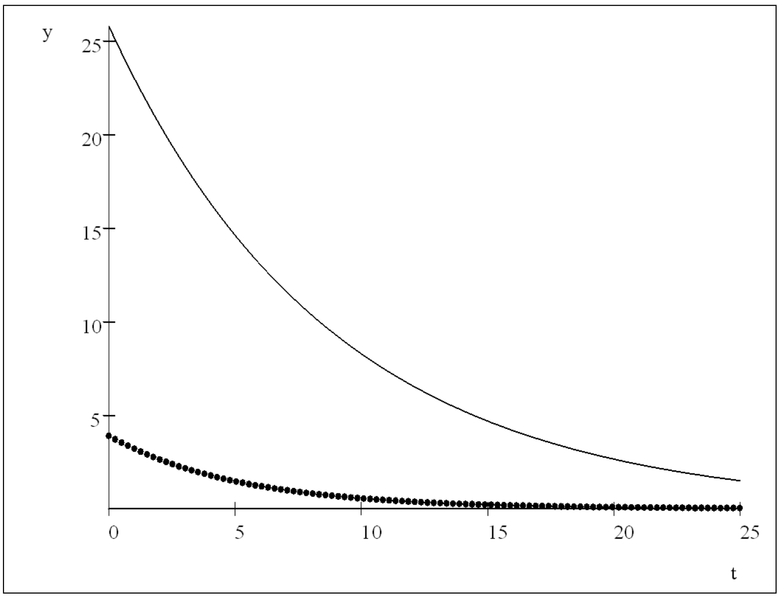
$$x(t) = 100\,(1 - \exp\{-0.11350t\}) \quad \text{for } n = 1$$
$$x(t) = 100\,(1 - \exp\{-0.19563t\}) \quad \text{for } n = 2$$

and the optimal path for the tariff by [17]

$$\theta(t) = 25.767\exp\{-0.11350t\} \quad \text{for } n = 1$$
$$\theta(t) = 3.8\,95\exp\{-0.195\,63t\} \quad \text{for } n = 2$$

17. Where y stands for the optimal tariff.

GRAPHIC 5.2: The optimal tariff



From the previous functions it is easy to check that $\theta(t; n = 1) > \theta(t; n = 2)$ for all $t \geq 0$. Moreover, it is evident from graphic 5.2 that a change in the number of importing countries have a substantial effect on the capacity of to use strategically a tariff to capture part of the monopolist rent. Thus, for this numerical exercise, the initial tariff goes down from 25.767 to 3.895, a reduction of almost 85%, when there is two importing countries instead of one, and it is lower than 1 for $t \geq 7$.

6. Conclusions

IN this paper we have revisited the issue, first tackled by Bergstrom (1982), of using a tariff on non-renewable resource imports in order to appropriate part of the monopolist rent. We extend his analysis taking into account that the exploitation of non-renewable resources is characterized by the presence of depletion effects, i.e., the marginal extraction cost increases for the same extraction rate as the accumulated extractions increase. Moreover, we investigate the game theoretic aspects of the problem more completely using the differential games theory.

Our results establish that a tariff is advantageous for the consumers of the importing countries even when there is no commitment to the trade policy. This is an interesting result that does not appear in a static setting. The optimality of the tariff in our dynamic game is explained by the fact that through the tariff the governments of the importing countries can influence the dynamics of the accumulated extractions and hence the extraction costs and the evolution of the monopolist price.

Our paper also generalizes the results obtained by Rubio (2005) for the case of a coalition of importing countries or a single buyer. Thus we establish in this paper that it is not necessary any kind of cooperation or coordination among the importing countries governments to use strategically a tariff to capture a part of the monopolist rent as occurs in Rubio's (2005) analysis. However, our results suggest that the part of the rent that can be captured decreases substantially with the number of importing countries.

Appendices

Appendix A.1. Proof of lemma 1

THE system (4.3)-(4.4) can be written in an explicit way as

$$\alpha_{I1} = \frac{1}{4n-3}\left((2n-1)\hat{\alpha}_M + 2r + 2\left((n-1)^2\hat{\alpha}_M^2 + (2n-1)r\hat{\alpha}_M + r^2\right)^{1/2}\right) \tag{A.1.1}$$

$$\alpha_{I2} = \frac{1}{4n-3}\left((2n-1)\hat{\alpha}_M + 2r - 2\left((n-1)^2\hat{\alpha}_M^2 + (2n-1)r\hat{\alpha}_M + r^2\right)^{1/2}\right) \tag{A.1.2}$$

for equation (4.3) and

$$\alpha_{I3} = \hat{\alpha}_M + \frac{1}{2n}\left(8nr(c-\hat{\alpha}_M)\right)^{1/2} \tag{A.1.3}$$

$$\alpha_{I4} = \hat{\alpha}_M - \frac{1}{2n}\left(8nr(c-\hat{\alpha}_M)\right)^{1/2} \tag{A.1.4}$$

for equation (4.4). Thus the solutions could be calculated from the following system of equations only for $\hat{\alpha}_M$: $\alpha_{I1} = \alpha_{I3}$, $\alpha_{I1} = \alpha_{I4}$, $\alpha_{I2} = \alpha_{I3}$ and $\alpha_{I2} = \alpha_{I4}$.

First we will see that if $\alpha_{I1} = \alpha_{I3}$ and $\alpha_{I2} = \alpha_{I3}$ have a solution, this is not stable. Let us suppose that there exists a value $\hat{\alpha}'_M \in R$ such that $\hat{\alpha}'_M \leq c$ that satisfies $\alpha_{I1} = \alpha_{I3}$ or $\alpha_{I2} = \alpha_{I3}$. In this case α'_I is given by (A.1.3): $\alpha'_I = \hat{\alpha}'_M + \frac{1}{2n}\left(8nr(c-\hat{\alpha}'_M)\right)^{1/2}$ that taking into account that $\hat{\alpha}'_M = c - \alpha'_M$ yields

$$c - \alpha'_I - \alpha'_M = -\frac{1}{2n}\left(8nr\alpha'_M\right)^{1/2} \leq 0$$

which implies that stability condition (3.19) is not satisfied.

Next, we show that $\alpha_{I1} = \alpha_{I4}$ cannot have a real solution. This equation can be written as

$$\alpha_{I1} = \frac{1}{4n-3}\left((2n-1)\hat{\alpha}_M + 2r + 2\left((n-1)^2\hat{\alpha}_M^2 + (2n-1)r\hat{\alpha}_M + r^2\right)^{1/2}\right) =$$

$$= \hat{\alpha}_M - \frac{1}{2n}\left(8nr(c-\hat{\alpha}_M)\right)^{1/2} = \alpha_{I4}$$

that reordering terms yields

$$4n\left((n-1)^2\hat{\alpha}_M^2 + (2n-1)r\hat{\alpha}_M + r^2\right)^{1/2} =$$
$$= 4n(n-1)\hat{\alpha}_M - 4nr - (4n-3)\left(8nr(c-\hat{\alpha}_M)\right)^{1/2}$$

Now we study the functions defined by the two sides of the equation that we call

$$f(\hat{\alpha}_M) = 4n\left((n-1)^2\hat{\alpha}_M^2 + (2n-1)r\hat{\alpha}_M + r^2\right)^{1/2} \quad \text{(A.1.5)}$$

$$g(\hat{\alpha}_M) = 4n(n-1)\hat{\alpha}_M - 4nr - (4n-3)\left(8nr(c-\hat{\alpha}_M)\right)^{1/2} \quad \text{(A.1.6)}$$

to know whether they intersect.

First, we study for which values of $\hat{\alpha}_M$, $f(\hat{\alpha}_M)$ takes real values. This will occur when the quadratic function $(n-1)^2\hat{\alpha}_M^2 + (2n-1)r\hat{\alpha}_M + r^2$ is positive or zero. This function is strictly convex and presents a unique minimum for $\hat{\alpha}_M^* = -(2n-1)r/2(n-1)^2$ which yields a minimum value for the function equal to

$$f(\hat{\alpha}_M^*) = r^2\left(1 - \frac{(2n-1)^2}{4(n-1)^2}\right) < 0 \quad \text{(A.1.7)}$$

since $(2n-1)^2/4(n-1)^2$ is a decreasing function that converges to the unity when n tends to plus infinite. This means that equation $(n-1)^2\hat{\alpha}_M^2 + (2n-1)r\hat{\alpha}_M + r^2 = 0$ presents two negative solutions, since the intersection point with the vertical axis is positive, given by

$$\hat{\alpha}_M^1 = -\frac{2n-1+r((2n-1)^2-4(n-1)^2r^2)^{1/2}}{2(n-1)^2} < 0$$
$$\hat{\alpha}_M^2 = \frac{-(2n-1)+r((2n-1)^2-4(n-1)^2r^2)^{1/2}}{2(n-1)^2} < 0$$

So that function $f(\hat{\alpha}_M)$ takes positive real values when $\hat{\alpha}_M < \hat{\alpha}_M^1$ or $\hat{\alpha}_M > \hat{\alpha}_M^2$ and is zero when $\hat{\alpha}_M = \hat{\alpha}_M^1$ and $\hat{\alpha}_M = \hat{\alpha}_M^2$.

Now, we focus on the behavior of function $f(\hat{\alpha}_M)$. Its first derivative is

$$f'(\hat{\alpha}_M) = \frac{2n(2(n-1)^2\hat{\alpha}_M + (2n-1)r)}{\left((n-1)^2\hat{\alpha}_M^2 + (2n-1)r\hat{\alpha}_M + r^2\right)^{1/2}}$$

where the sign of the numerator is determined by the following relationship:

$$\text{If } \hat{\alpha}_M \left\{ \begin{array}{c} > \\ = \\ < \end{array} \right\} - \frac{(2n-1)r}{2(n-1)^2} \text{ then } 2(n-1)^2\hat{\alpha}_M + (2n-1)r \left\{ \begin{array}{c} > \\ = \\ < \end{array} \right\} 0$$

Notice that the value that determines the sign of the numerator is the same that minimizes function $f(\hat{\alpha}_M)$ and the radicand of the denominator of $f'(\hat{\alpha}_M)$. Thus we can conclude that if $\hat{\alpha}_M \leq \hat{\alpha}_M^1$ then $\hat{\alpha}_M$ is also lower than $-(2n-1)r/2(n-1)^2$ and the numerator is negative so that the first derivative is negative as well which implies that $f(\hat{\alpha}_M)$ is decreasing. Moreover, we know that in this case the function is non-negative. On the other hand, if $\hat{\alpha}_M \geq \hat{\alpha}_M^2$ then $\hat{\alpha}_M$ is also higher than $-(2n-1)r/2(n-1)^2$ and the numerator is positive so that the first derivative is positive as well which implies that $f(\hat{\alpha}_M)$ is increasing. Moreover, we also know that in this case the function is non-negative.

Next, we focus on the behavior of function $g(\hat{\alpha}_M)$ for $\hat{\alpha}_M \leq c$. In this domain it is easy to show that $g(\hat{\alpha}_M)$ is a strictly convex increasing function with a negative value for $\hat{\alpha}_M = 0$. This implies that $g(\hat{\alpha}_M)$ is negative for $\hat{\alpha}_M \leq 0$. Thus we can conclude that $g(\hat{\alpha}_M) = f(\hat{\alpha}_M)$ has no solution for $\hat{\alpha}_M \leq 0$ since $f(\hat{\alpha}_M)$ is positive or zero in this domain.

For $(0, c]$ we continue the analysis using the following function

$$\begin{aligned} h(\hat{\alpha}_M) &= f(\hat{\alpha}_M) - g(\hat{\alpha}_M) = 4n\left((n-1)^2\hat{\alpha}_M^2 + (2n-1)r\hat{\alpha}_M + r^2\right)^{1/2} - \\ &\quad -4n(n-1)\hat{\alpha}_M + 4nr + (4n-3)\left(8nr(c-\hat{\alpha}_M)\right)^{1/2} \end{aligned}$$

that is built from (A.1.5) and (A.1.6). For this function $\hat{\alpha}_M = 0$ and $\hat{\alpha}_M = c$ yield

$$\begin{aligned} h(0) &= 8nr + (4n-3)(8nrc)^{1/2} > 0 \\ h(c) &= 4n\left(\left((n-1)^2c^2 + (2n-1)rc + r^2\right)^{1/2} - (n-1)c + r\right) \end{aligned}$$

with $h(c)$ positive for $c = 0$. Next, we calculate the first derivative of $h(c)$ with respect to c and we find that is positive so that we can conclude that $h(c)$ is positive also for $c > 0$. The first derivative is

$$h'(c) = 4n\left(\frac{2(n-1)^2c + (2n-1)r}{2\left((n-1)^2c^2 + (2n-1)rc + r^2\right)^{1/2}} - (n-1)\right)$$

Let us suppose that $h'(c) \leq 0$. This implies that

$$2(n-1)^2c + (2n-1)r \leq 2(n-1)\left((n-1)^2c^2 + (2n-1)rc + r^2\right)^{1/2}$$

that squaring and simplifying terms can be written as

$$r^2\left(\frac{(2n-1)^2}{4(n-1)^2} - 1\right) \leq 0$$

but this is a contradiction according to (A.1.7). Thus we can conclude that $h'(c)$ is positive and given that $h(c=0)$ is also positive that $h(c)$ is positive for all $c > 0$.

Now we investigate the behavior of $h(\hat{\alpha}_M)$ in interval $(0, c]$. First, we calculate the first derivative

$$h'(\hat{\alpha}_M) = f'(\hat{\alpha}_M) - g'(\hat{\alpha}_M)$$

that can be positive, negative or zero since $f'(\hat{\alpha}_M)$ is positive for $\hat{\alpha}_M \geq 0$, according to what we have obtained above, and $g'(\hat{\alpha}_M)$ is also positive since $g(\hat{\alpha}_M)$ is increasing. Then if $h'(\hat{\alpha}_M)$ is positive in interval $(0, c]$, $h(\hat{\alpha}_M)$ is also positive in this interval since $h(0)$ is positive, and if $h'(\hat{\alpha}_M)$ is negative $h(\hat{\alpha}_M)$ is also positive since $h(c)$ is positive. However, for $h'(\hat{\alpha}_M) = 0$ we need to know the sign of the second derivative to find out whether $h(\hat{\alpha}_M)$ intersects the horizontal axis in interval $(0, c]$.

The second derivative, $h''(\hat{\alpha}_M) = f''(\hat{\alpha}_M) - g''(\hat{\alpha}_M)$, is negative with

$$f''(\hat{\alpha}_M) = -\frac{(4n-3)r^2}{2\left((n-1)^2c^2 + (2n-1)rc + r^2\right)^{3/2}} < 0 \text{ for } \hat{\alpha}_M \in (0, c]$$

and

$$g''(\hat{\alpha}_M) = \frac{8(4n-3)r^2}{(8nr(c-\hat{\alpha}_M))^{3/2}} > 0 \text{ for } \hat{\alpha}_M \in (0, c]$$

which established that $h(\hat{\alpha}_M)$ is a strictly concave function in the domain $(0, c]$ so that $h(\hat{\alpha}_M) = 0$ defines a maximum for the function. Then $h(\hat{\alpha}_M)$ is also positive in this case since both $h(0)$ and $h(c)$ are positive. For the same reason, $h(\hat{\alpha}_M)$ would be also positive if $h'(\hat{\alpha}_M) = 0$ for all $\hat{\alpha}_M$ in interval $(0, c]$. Obviously, it this were the case $h(0)$ should be equal to $h(c)$.

Summarizing we have obtained that there does not exist any value of $\hat{\alpha}_M \leq c$ that satisfies $f(\hat{\alpha}_M) = g(\hat{\alpha}_M)$ so that we can conclude that equation $\alpha_{I1} = \alpha_{I4}$ has no a real solution.

Finally, we study equation $\alpha_{I2} = \alpha_{I4}$ in the interval $[0, c]$. This equation can be written as

$$\alpha_{I2} = \frac{1}{4n-3}\left((2n-1)\hat{\alpha}_M + 2r - 2\left((n-1)^2\hat{\alpha}_M^2 + (2n-1)r\hat{\alpha}_M + r^2\right)^{1/2}\right) =$$

$$= \hat{\alpha}_M - \frac{1}{2n}\left(8nr(c-\hat{\alpha}_M)\right)^{1/2} = \alpha_{I4} \qquad \text{(A.1.8)}$$

The first derivative of function α_{I2} with respect to $\hat{\alpha}_M$ is

$$\alpha'_{I2} = \frac{1}{4n-3}\left(2n-1-\frac{2(n-1)^2\hat{\alpha}_M + r(2n-1)}{\left((n-1)^2\hat{\alpha}_M^2 + (2n-1)r\hat{\alpha}_M + r^2\right)^{1/2}}\right)$$

Let us suppose that $\alpha'_{I2} \leq 0$. This implies that

$$(2n-1)\left((n-1)^2\hat{\alpha}_M^2 + (2n-1)r\hat{\alpha}_M + r^2\right)^{1/2} \leq 2(n-1)^2\hat{\alpha}_M + r(2n-1)$$

then squaring, reordering terms and taking common factor we obtain

$$(4n^3 - 11n^2 + 10n - 3)\hat{\alpha}_M^2 + r(8n^2 - 10n + 3)\hat{\alpha}_M \leq 0$$

but the left-hand side of this inequality is positive for $\hat{\alpha}_M > 0$ and $n \geq 2$ so that we can conclude that $\alpha'_{I2} > 0$. Now we calculate the second derivative

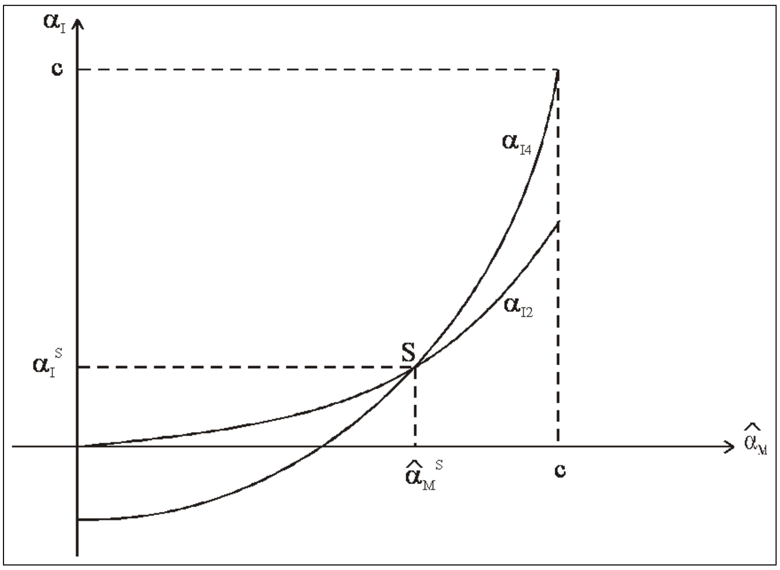
$$\alpha''_{I2} = \frac{r^2}{2\left((n-1)^2\hat{\alpha}_M^2 + (2n-1)r\hat{\alpha}_M + r^2\right)^{3/2}} > 0$$

This establishes that α_{I2} is a strictly convex increasing function of $\hat{\alpha}_M$ in interval $[0, c]$ that takes positive values for $\hat{\alpha}_M > 0$ since $\alpha_{I2} = 0$ for $\hat{\alpha}_M = 0$.

On the other hand, α_{I4} is also a strictly convex increasing function of $\hat{\alpha}_M$ in interval $[0, c]$ according to the following signs

$$\begin{aligned}
\alpha'_{I4} &= 1 + \frac{2r}{(8nr(c-\hat{\alpha}_M))^{1/2}} > 0 \\
\alpha''_{I4} &= \frac{8nr^2}{(8nr(c-\hat{\alpha}_M))^{3/2}} > 0
\end{aligned}$$

GRAPHIC A.1.1: Graphical representation of the solution to equation A.1.8



and it takes the following values in the extremes of the interval

$$\alpha_{I4}(\hat{\alpha}_M = 0) = -\frac{(8cnr)^{1/2}}{2n}, \ \alpha_{I4}(\hat{\alpha}_M = c) = c$$

Then given the behavior of these two functions in interval $[0, c]$ there will exist a unique intersection point if $\alpha_{I2}(\hat{\alpha}_M = c) < c = \alpha_{I4}(\hat{\alpha}_M = c)$.

Let us suppose the contrary. In that case, we have that

$$\alpha_{I2}(\hat{\alpha}_M = c) = \frac{1}{4n-3}\left((2n-1)c + 2r - 2\left((n-1)^2c^2 + (2n-1)rc + r^2\right)^{1/2}\right) \geq c$$

that can be written as

$$r - (n-1)c \geq \left((n-1)^2c^2 + (2n-1)rc + r^2\right)^{1/2}$$

squaring and simplifying terms the following contradiction is obtained for $c > 0$

$$0 \geq cr(4n-3)$$

and we can conclude that $\alpha_{I2}(\hat{\alpha}_M = c) < c$ which implies that equation (A.1.8) has a unique solution in interval $[0, c]$ as it is illustrated in graphic A.1.1.

For this solution $\alpha_I, \hat{\alpha}_M \in (0, c)$ and the same happens for α_M since $\hat{\alpha}_M$ has been defined as $c - \alpha_M$. Moreover, this solution is stable since it is a point of function α_{I4}. In this case α_I can be written as

$$\alpha_I = \alpha_{I4}(\hat{\alpha}_M) = \hat{\alpha}_M - \frac{1}{2n}\left(8nr(c - \hat{\alpha}_M)\right)^{1/2}$$

that substituting $\hat{\alpha}_M$ by $c - \alpha_M$ yields

$$c - \alpha_I - \alpha_M = \frac{(8nr\alpha_M)^{1/2}}{2n} > 0 \text{ since } \alpha_M \in (0, c)$$

which means that the solution to equation (A.1.8) satisfies stability condition (3.19).

Appendix A.2. Proof of proposition 1

ACCORDING to lemma 1 α_I is positive then we need to show that β_I is negative and that (3.15) is positive in interval $[0, x^\infty)$ where x^∞ is the steady-state value of the accumulated extractions to conclude that a tariff is advantageous for the consumer. Thus we begin this proof calculating x^∞. According to differential equation (3.18)

$$x^\infty = \frac{a + \beta_I + \beta_M}{c - \alpha_I - \alpha_M}$$

that using (3.10) and (3.12) yields

$$x^\infty = -\beta_M / \alpha_M \tag{A.2.1}$$

which establishes that

$$\beta_M + \alpha_M x^\infty = 0 \tag{A.2.2}$$

Now we calculate β_M from (3.11) and (3.12)

$$\beta_M = -\frac{a(c - \alpha_I - \alpha_M)\left(4rn + 2(n-1)n(c - \alpha_I - \alpha_M)\right)}{N}$$

where

$$N = 8r^2 + 2r(2n-1)(c - \alpha_M) - 2r(4n-3)\alpha_I + 4rn(c - \alpha_I - \alpha_M) +$$
$$+ 2(n-1)n(c - \alpha_I - \alpha_M)^2$$

that allows us to write (A.2.1) as

$$x^\infty = \frac{a(c - \alpha_I - \alpha_M)\left(4rn + 2(n-1)n(c - \alpha_I - \alpha_M)\right)}{N\alpha_M}$$

According to (3.10) we can substitute $2r\alpha_M$ in the denominator by $n(c - \alpha_I - \alpha_M)^2$ obtaining after some simplifications

$$x^{\infty} = \frac{a\,(4r + 2(n-1)(c - \alpha_I - \alpha_M))}{(c - \alpha_I - \alpha_M)(4r + (2n-1)(c - \alpha_M) - (4n-3)\alpha_I + 2(n-1)\alpha_M) + 4r\alpha_M} \tag{A.2.3}$$

Now developing the denominator, the following expression is obtained

$$-4r\alpha_I + 4r(c - \alpha_M) - (2n-1)(c - \alpha_M)\alpha_I + 2n(c - \alpha_M)^2 -$$
$$-(c - \alpha_M)^2 + (4n-3)\alpha_I^2 - (4n-3)(c - \alpha_M)\alpha_I +$$
$$+4r\alpha_M + 2(n-1)(c - \alpha_I - \alpha_M)\alpha_M$$

where $-4r\alpha_I$ can be substituted by

$$(c - \alpha_M)^2 - 2(2n-1)(c - \alpha_M)\alpha_I + (4n-3)\alpha_I^2$$

according to (3.9) yielding the following expression for the denominator after simplifying terms

$$2(n-1)(c - \alpha_M)^2 + (2n-1)(c - \alpha_M)\alpha_I + 4rc - (4n-3)(c - \alpha_M)\alpha_I +$$
$$+2(n-1)(c - \alpha_I - \alpha_M)\alpha_M$$

Developing this expression we obtain finally that the numerator of (A.2.3) is equal to

$$c(4r + 2(n-1)(c - \alpha_I - \alpha_M))$$

and, consequently, that $x^{\infty} = a/c$. This establishes according to (A.2.1) that $\beta_M = -a\alpha_M/c < 0$ since according to lemma 1 α_M is positive.

Now we use differential equation (3.18) to end the proof. The steady-state value of the accumulated extractions must satisfied

$$\dot{x} = 0 = \frac{n}{2}\,(a + \beta_I + \beta_M - (c - \alpha_I - \alpha_M)x^{\infty})$$

where $\beta_M + \alpha_M x^{\infty} = 0$ according to (A.2.2) so that $a + \beta_I - (c - \alpha_I)x^{\infty}$ must be equal to zero. As $x^{\infty} = a/c$ we obtain that $\beta_I + \alpha_I(a/c) = 0$ which implies that $\beta_I = -a\alpha_I/c < 0$ since according to lemma 1 α_I is positive. This concludes the proof.

Appendix A.3. Proof of lemma 2

TO evaluate the effect of a change in the number of importing countries first we study which is the effect on the values of α_I and α_M that satisfy equation (A.1.8). With this aim we calculate the sign of the following derivatives $\partial\alpha_{I2}/\partial n$ and $\partial\alpha_{I4}/\partial n$ to find out how the two sides of equation (A.1.8) change [18].

$$\frac{\partial\alpha_{I2}}{\partial n} = -\frac{2\hat{\alpha}_M + 8r}{(4n-3)^2} +$$
$$+\frac{((n-1)^2\hat{\alpha}_M^2 + (2n-1)r\hat{\alpha}_M + r^2)^{-1/2}(-2(n-1)\hat{\alpha}_M^2 + 2(4n-1)r\hat{\alpha}_M + 8r^2)}{(4n-3)^2} \tag{A.3.1}$$

$$\frac{\partial\alpha_{I4}}{\partial n} = \frac{(8nr(c-\hat{\alpha}_M))^{1/2}}{4n^2} > 0, \quad \text{for } \hat{\alpha}_M < c \text{ and } n \geq 1 \tag{A.3.2}$$

This means that the curve that stands for the right-hand side of (A.1.8) in graphic A.1.1 moves up for any value of $\hat{\alpha}_M$ or, in other words, that for any value of $\hat{\alpha}_M$, the greater is n, the greater is the corresponding value of α_{I4}. See graphic A.3.1. However, the sign of $\partial\alpha_{I2}/\partial n$ is ambiguous. Let us suppose that this sign is positive or zero. This implies that

$$-2(n-1)\hat{\alpha}_M^2 + 2(4n-1)r\hat{\alpha}_M + 8r^2 \geq$$
$$\geq ((n-1)^2\hat{\alpha}_M^2 + (2n-1)r\hat{\alpha}_M + r^2)^{1/2}(2\hat{\alpha}_M + 8r)$$

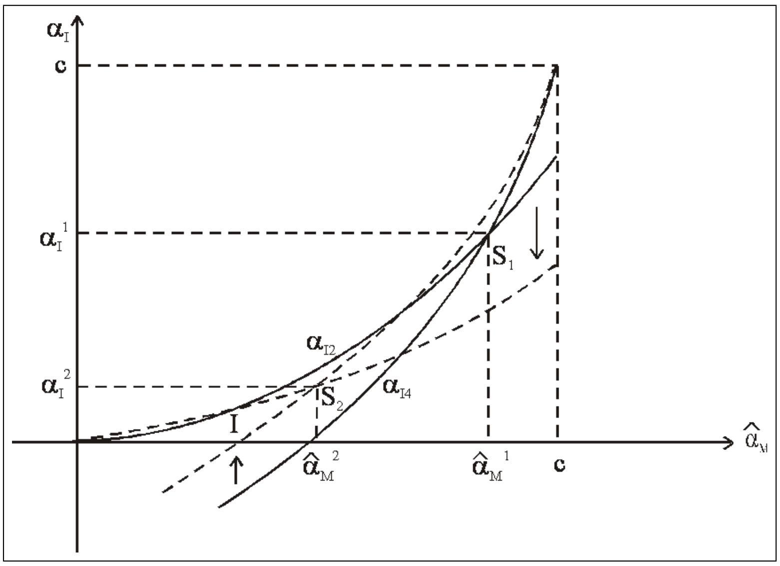
that squaring, simplifying terms and taking common factor yields

$$4r\hat{\alpha}_M^2\left(8(2n-1)r - (4n-3)^2\hat{\alpha}_M\right) \geq 0$$

so that for $\hat{\alpha}_M > 8(2n-1)r/(4n-3)^2$ we get a contradiction which allows us to conclude that $\partial\alpha_{I2}/\partial n$ is negative in this case. This implies that the

18. In order to study the behavior of α_{I2} and α_{I4} with respect to n we assume now that n is a real number and once we know the sign of the derivatives then we can investigate the effect of a change in n but now with n restricted to be a natural number. For instance, as $\partial\alpha_{I4}/\partial n$ is positive for all real numbers $n \geq 1$ and $\hat{\alpha}_M < c$, we can conclude that the difference $\alpha_{I4}(n+1) - \alpha_{I4}(n)$ is also positive for all natural numbers $n \geq 1$ and for any value of $\hat{\alpha}_M$ less than c.

GRAPHIC A.3.1: The effects of a change in n on curves α_{I2} and α_{I4}



left-hand side of (A.1.8) moves down for $\hat{\alpha}_M > 8(2n-1)r/(4n-3)^2$ and up in the other case. Then if the value for $\hat{\alpha}_M$ given by equation (A.1.8) is greater than $8(2n-1)r/(4n-3)^2$ we can conclude that both $\hat{\alpha}_M$ and α_I decrease with the number of countries since curve α_{I2} moves down whereas curve α_{I4} moves up so that the intersection point has to move down-left. See again graphic A.3.1. In the graphic, intersection point I corresponds with the critical value $8(2n-1)r/(4n-3)^2$ for $\hat{\alpha}_M$ [19].

Next, we investigate under what conditions this is true. We know that the solution to equation (A.1.8) is given by the intersection of α_{I2} and α_{I4} when α_{I4} is positive, which implies that the value for $\hat{\alpha}_M$ must be greater than

$$-\frac{1}{n}(r-(r^2+2nrc)^{1/2}) > 0 \tag{A.3.3}$$

where the left-hand side of this inequality is given by the solution of equation $\alpha_{I4}=0$. Then our conclusion holds necessarily when

$$\frac{8(2n-1)r}{(4n-3)^2} < -\frac{1}{n}(r-(r^2+2nrc)^{1/2})$$

since this condition guarantees that $\partial\alpha_{I2}/\partial n$ is negative at the intersection

19. The arrows indicate the movement of the curves.

point S_1 defined by curves α_{I2} and α_{I4} in graphic A.3.1. Or in other words, this condition guarantees that S_1 is on the right of I.

This condition implies that

$$\frac{8r(48n^3 - 80n^2 + 46n - 9)}{(4n-3)^4} < c \tag{A.3.4}$$

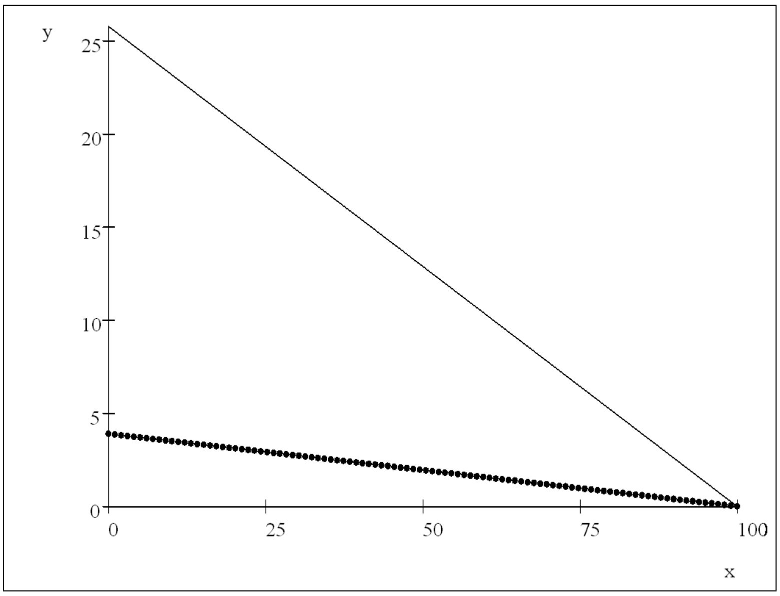
where $48n^3 - 80n^2 + 46n - 9 > 0$ for $n \geq 1$. This is a sufficient condition that guarantees that α_I and $\hat{\alpha}_M$ decrease when the number of importing countries increase. In other words, if we evaluate the signs of derivatives (A.3.1) and (A.3.2) at the intersection point of the two curves which gives us the solution to equation (A.1.8), at that point $(A.3.1)$ is negative and (A.3.2) is positive for all n that satisfies (A.3.4) that if c is high enough means for all $n \geq 1$. Then if we consider an increase in the number of importing countries, as the natural numbers are a subset of the real numbers $n \geq 1$, we are going to obtain the same result and consequently we can conclude that the values of $\hat{\alpha}_M$ and α_I decrease with respect to the number of importing countries and that the one of α_M increases [20]. Graphically, the key point of our argument is that condition (A.3.4) guarantees that intersection point S_1 in graphic A.3.1 is on the right of intersection point I so that an increase in n necessarily reduces the values of $\hat{\alpha}_M$ and α_I that satisfy equation (A.1.8).

This lower bound on c is not very restrictive since $8(48n^3 - 80n^2 + 46n - 9)/(4n-3)^4$ decreases very quick with n and r must be lower than the unity. For instance, for $n = 2$ and $r = 0.05$, c must be bigger than 0.0941 according to (A.3.4) but for $n = 4$, only bigger than 0.0275.

Basing on this result, it is easy to establish that the greater is the number of importing countries, the lower is the optimal tariff for the same level of accumulated extractions since the steady state level of accumulated extractions is independent of the number of countries. The argument is the following: as $\theta = \alpha_I(a/c - x)$, according to (4.5), a reduction in α_I, as a consequence of an increment in the number of importing countries, reduces both the intersection point with the horizontal axis and the slope of the equilibrium strategy for the tariff, and consequently the line that represents the equilibrium strategy for the tariff moves down as it is shown in graphic A.3.2a. The result is that the greater is the number of importing countries, the lower is the optimal tariff for the same level of accumulated extractions.

20. Remember that $\alpha_M = c - \hat{\alpha}_M$.

GRAPHIC A.3.2a: The equilibrium strategies for the tariff



Graphic A.3.2a represents the movement of the equilibrium strategy for a change in the number of countries of 1 to 2 and for the following values of the rest of parameters: $a = 100,\ c = 1$ and $r = 0.05$ **. For these figures, the equilibrium strategies are

$$\begin{aligned}\theta &= 25.766 - 0.25767x \quad \text{for } n = 1\\ \theta &= 3.8953 - 0.03895x \quad \text{for } n = 2\end{aligned}$$

The effect on the equilibrium strategy for the monopolist price is also easy to establish. The effect of a change in n on the intersection point with the vertical axis and the slope of equilibrium strategy (4.6) can be derived from the sign of the following expressions [21]

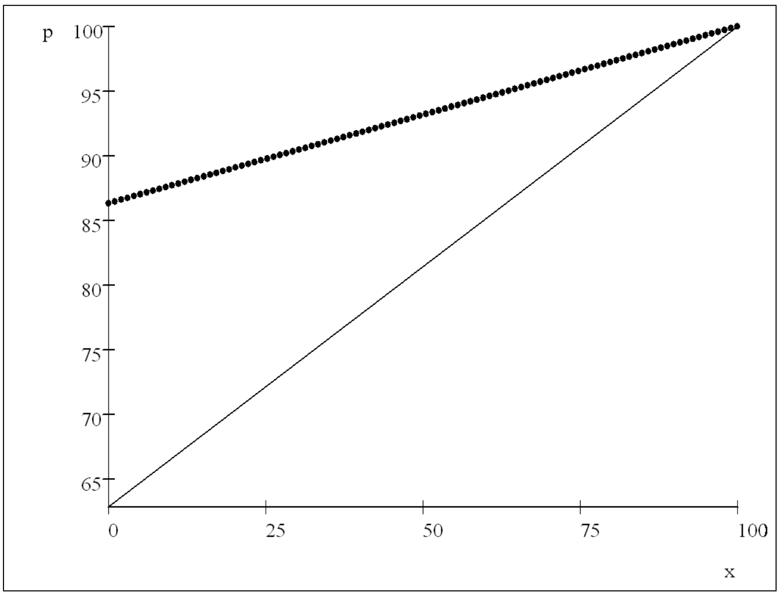
$$c - \alpha_I(n+1) + \alpha_M(n+1) - (c - \alpha_I(n) + \alpha_M(n)) =$$

$$= -(\alpha_I(n+1) - \alpha_I(n)) + \alpha_M(n+1) - \alpha_M(n) > 0$$

** In the graphic y stands for the optimal tariff and the plot-line for the case of $n = 2$.

21. Notice that we have established above that α_I increases with the number of importers but that α_M decreases.

GRAPHIC A.3.2b: The equilibrium strategies for the monopolist price



$$c + \alpha_I(n+1) - \alpha_M(n+1) - (c + \alpha_I(n) - \alpha_M(n)) =$$
$$= \alpha_I(n+1) - \alpha_I(n) - (\alpha_M(n+1) - \alpha_M(n)) < 0$$

for all natural numbers $n \geq 1$ provided that (A.3.4) is satisfied. The first expression says us that the intersection point with the vertical axis of (4.6) increases with the number of importing countries, and the second that the slope decreases. Thus the combination of a lower slope and a greater intersection point with the vertical axis moves up the line that represents the equilibrium strategy for the monopolist price. The result is that the greater is the number of countries, the greater is the price in the international market for the same level of accumulated extractions as it is shown in graphic A.3.2b.

$$\begin{aligned} p &= 62.883 + 0.37117x \quad \text{for } n = 1 \\ p &= 86.323 + 0.13677x \quad \text{for } n = 2 \end{aligned}$$

The evaluation of the effect of a variation in the number of importing countries on the consumer price is more complicated of deriving since in this case the effect of a change in n on the intersection point with the vertical axis and the slope of equilibrium strategy (4.7) cannot be determined without having an explicit expression for α_I and

α_M. Observe that for (4.7) the sign of the following expressions is ambiguous

$$\begin{aligned} & c+\alpha_I(n+1)+\alpha_M(n+1)-(c+\alpha_I(n)+\alpha_M(n)) \\ = \;& \alpha_I(n+1)-\alpha_I(n)+\alpha_M(n+1)-\alpha_M(n) \end{aligned} \tag{A.3.5}$$

$$\begin{aligned} & c-\alpha_I(n+1)-\alpha_M(n+1)-(c-\alpha_I(n)-\alpha_M(n)) \\ = \;& -(\alpha_I(n+1)-\alpha_I(n)+\alpha_M(n+1)-\alpha_M(n)) \end{aligned} \tag{A.3.6}$$

since α_I decreases with the number of importing countries whereas α_M increases.

With the objective of solving this ambiguity we calculate derivatives $\partial\alpha_I/\partial n$ and $\partial\alpha_M/\partial n$ applying the implicit function theorem to system (4.1) and (4.2) [22]. The result is given by the following system of equations written in matrix form

$$\begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix} \begin{pmatrix} \frac{\partial\alpha_I}{\partial n} \\ \frac{\partial\alpha_M}{\partial n} \end{pmatrix} = \begin{pmatrix} b_1 \\ b_2 \end{pmatrix}$$

where

$$\begin{aligned} a_{11} &= (4n-3)\alpha_I-(2n-1)(c-\alpha_M)-2r \\ a_{12} &= (2n-1)\alpha_I-(c-\alpha_M) \\ a_{21} &= 2n(c-\alpha_I-\alpha_M)>0 \\ a_{22} &= 2n(c-\alpha_I-\alpha_M)+2r>0 \\ b_1 &= 2\alpha_I(c-\alpha_I-\alpha_M)>0 \\ b_2 &= (c-\alpha_I-\alpha_M)^2>0 \end{aligned}$$

Now applying Cramer's rule we get

$$\frac{\partial\alpha_I}{\partial n}=\frac{(c-\alpha_I-\alpha_M)\left((2n+1)(c-\alpha_I-\alpha_M)+4r\alpha_I+(c-\alpha_M)(c-\alpha_I-\alpha_M)\right)}{2r\left(3(3n-1)\alpha_I-4(n-1)\alpha_M-(4n-1)(c-\alpha_M)-2r\right)} \tag{A.3.7}$$

where (4.2) has been used to simplify the denominator, and

22. Again we assume the n is a real number to see if we are able to find out the sign of differences (A.3.5) and (A.3.6) from the sign of derivatives $\partial\alpha_I/\partial n$ and $\partial\alpha_M/\partial n$.

$$\frac{\partial \alpha_M}{\partial n} = -\frac{(c-\alpha_I-\alpha_M)\left((n-2)(c-\alpha_M)^2+(3n-2)\alpha_I^2+2rc\right)}{2r\left(3(3n-1)\alpha_I-4(n-1)\alpha_M-(4n-1)(c-\alpha_M)-2r\right)} \qquad \text{(A.3.8)}$$

where (4.1) and (4.2) have been use to simplify the numerator. In both cases the sign of the numerator is positive but the sign of the denominator is ambiguous [23]. However, as we have established above that $\partial \alpha_I/\partial n$ is negative and $\partial \alpha_M/\partial n$ is positive when they are evaluated at the solution given by equation (A.1.8), we can conclude that this denominator must be negative for this solution. Then we can calculate the sign of $\partial \alpha_I/\partial n + \partial \alpha_M/\partial n$ using (A.3.7) and (A.3.8)

$$\frac{\partial \alpha_I}{\partial n} + \frac{\partial \alpha_M}{\partial n} =$$

$$= -\frac{(c-\alpha_I-\alpha_M)\left((n+2)^2\alpha_I^2+2(n-1)(c-\alpha_M)\alpha_I+(n-4)(c-\alpha_M)^2+2rc\right)}{2r\left(3(3n-1)\alpha_I-4(n-1)\alpha_M-(4n-1)(c-\alpha_M)-2r\right)}$$

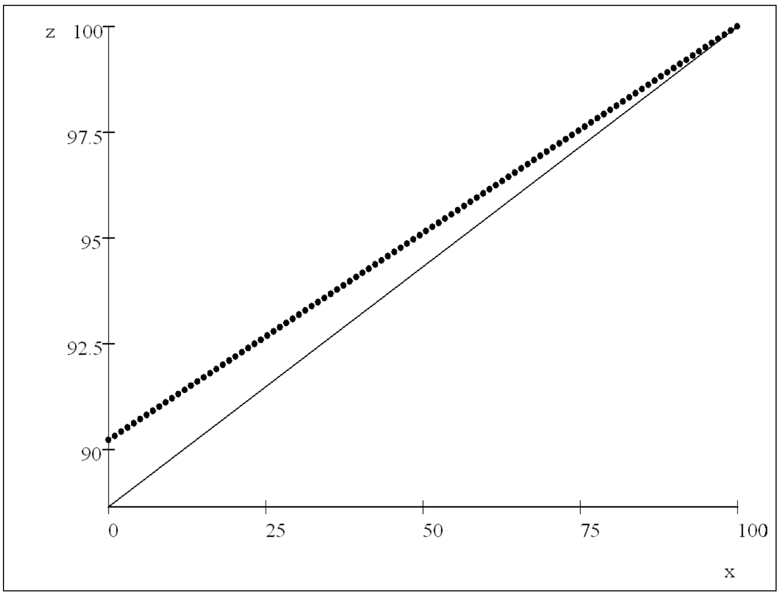
where (4.1) has been used to simplify the numerator. This expression is positive for $n \geq 4$. Thus for all natural numbers $n \geq 4$ (A.3.5) is positive and (A.3.6) negative. Then, as in the case of the monopolist price, an increase in the number of importing countries increases the intersection point with the vertical axis and decreases the slope of equilibrium strategy (4.7). The result is that the greater is the number of countries, the greater is the national price paid by the consumer as it is illustrated in graphic A.3.2c [***].

$$\begin{aligned} \pi &= 88.649 + 0.1135x \quad \text{for } n = 1 \\ \pi &= 90.218 + 0.09782x \quad \text{for } n = 2 \end{aligned}$$

23. Notice that α_I, $c-\alpha_M$ and $c-\alpha_I-\alpha_M$ are positive according to lemma 1.

*** This result is a little less general than the two previous since we need to be sure of the sign that $n \geq 4$. z stands for the consumers' price in the graphic.

GRAPHIC A.3.2c: The equilibrium strategies for the consumer price



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