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Welfare Implications of Leadership in a Resource Market under Bilateral Monopoly

Kenji Fujiwara

School of Economics, Kwansei Gakuin University

Ngo Van Long

Department of Economics, McGill University

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SCHOOL OF ECONOMICS

KWANSEI GAKUIN UNIVERSITY

1-155 Uegahara Ichiban-cho

Nishinomiya 662-8501, Japan

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Kenji Fujiwara · Ngo Van Long*

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Abstract

Formulating a dynamic game model of a world exhaustible resource market, this paper studies welfare implications of Stackelberg leaderships for an individual country and the world. We overcome the problem of time-inconsistency by imposing a "credibility condition" on the Markovian strategy of the Stackelberg leader. Under this condition, we show that the presence of a global Stackelberg leader leaves the follower worse off relative to the Nash equilibrium. Moreover, the world welfare is highest in the Nash equilibrium as compared with the two Stackelberg equilibria.

Keywords: Dynamic game, Exhaustible resource, Stackelberg leadership, Feedback equilibria.

*K. Fujiwara (Correspondence). Kwansei Gakuin University, Nishinomiya, Japan, e-mail: kenjifujiwara@kwansei.ac.jp. N. V. Long. McGill University, Montreal, Canada, e-mail: ngo.long@mcgill.ca.

1 Introduction

International trade in vital inputs such as oil and natural gas is a major concern for resource-poor and resource-rich economies. Reflecting this fact, World Trade Report of the WTO [31] that focuses on trade in natural resources points out that "natural resources represent a significant and growing share of world trade and amounted to some 24 per cent of total merchandise trade in 2008" (p. 40). It is obvious that fluctuations in prices and quantities of these resources can heavily affect the economic performance and welfare of individual countries as well as the global economy.[1] Considering the contemporary world market of natural resources, Karp and Newbery [10, p. 303] drew attention to two salient characteristics. First, a small group of buyers has a substantial share of the world demand, while a small group of sellers control much of the world supply, allowing them to exercise market power.[2] The world market for oil and gas is dominated by Russia and OPEC countries as major suppliers, while the United States, Japan and China account for much of the world imports. The second feature is that all natural resources are potentially exhaustible and therefore a careful analysis should take into account consideration of both flows and stocks.

This paper formulates a dynamic game model of trade in an exhaustible resource, paying special attention to the welfare implications of leaderships. There is a large theoretical literature on the exercise of market power in the trading relationship between a resource-poor country and a resource-rich country. Broadly, this literature consists of three groups of models. The first group is characterized by the assumption that the resource-exporting country exercises its market power while the importing country is passive.[3] The second one considers the opposite scenario: the importing country imposes

[1] Blanchard and Gali [5] empirically consider the macroeconomic effects of oil price shocks.

[2] According to the 2008 data of the U.S. Energy Information Administration, 67% of oil exports come from the OPEC countries while the United States and Japan account for 33% and 14% shares of oil imports, respectively.

[3] See Kemp and Long [13] and a survey by Long [18].

a tariff to shift resource rents away from passive foreign resource owners.[4] The third one deals with the case of bilateral monopoly: both the importing and exporting countries realize that they have market power and behave strategically.[5] This paper belongs to the third group, but we probe more deeply into the issue of leadership.

In modeling leaderships in a dynamic game, three solution concepts have been defined in the literature. The first is an open-loop Stackelberg equilibrium in which both the leader and follower use strategies that specify their actions as functions of time alone.[6] As shown by Kemp and Long [14], this solution concept is vulnerable to the problem of time inconsistency: the leader is tempted to deviate from the predetermined path strategy in later periods. The second is called a global Stackelberg equilibrium where the leader announces a stock-dependent (i.e. Markovian) decision rule at the beginning of the game and then the follower chooses a stock-dependent decision rule, taking the leader's rule as given. As is true of the open-loop solution, this equilibrium is also generally time inconsistent.[7] The third solution concept is a stagewise Stackelberg equilibrium in which no precommitment of any significant length is allowed for either player: the leader can only determines the stock-dependent decision rule just prior to the follower's choice in each period.[8] By definition, the solution is time consistent since no player precommits. Rubio [24] and Rubio and Escriche [25] compute the stagewise Stackelberg equilibrium in a set-up similar to ours, finding that the Stackelberg equilibrium coincides with the Nash equilibrium when the exporting

[4]See Kemp and Long [14], Bergstrom [4], Brander and Djajic [6], Karp [9], Maskin and Newbery [21], and Karp and Newbery [10,11,12].

[5]This group includes Karp [9], Wirl [29], Wirl and Dockner [30], Tahvonen [28], Rubio and Escriche [25], Liski and Tahvonen [17], Rubio [24], and Chou and Long [7].

[6]To adopt the terminology of Reinganum and Stokey [23], open-loop strategies are "path strategies," which they distinguish from "decision rule strategies" or Markovian strategies.

[7]Long and Sorger [20] discuss this issue. They point out that the global feedback Stackelberg equilibrium is "generically not time-consistent."

[8]The concepts of 'global Stackelberg equilibrium' and 'stagewise Stackelberg equilibrium' were discussed in Mehlmann [22] and Basar and Olsder [1]. For examples of these equilibria, see Long [18].

country is a leader.

In this paper, we consider global Stackelberg equilibria in a resource market, and impose a time-consistency requirement which effectively restricts the set of strategies that a leader can choose. We characterize a global Stackelberg equilibrium in linear strategies where the importing country leads, and one where the exporting country leads. We compare the resulting welfare levels with the Nash equilibrium welfare. In deriving these equilibria, we propose a condition called " credibility condition" that guarantees time consistency of the global Stackelberg equilibrium.

Our reasons for paying special attention to the global Stackelberg equilibrium are as follows. First, there is no compelling reason to prefer the stagewise Stackelberg equilibrium to the global one if time inconsistency is overcome. As mentioned above, we will show that the global Stackelberg equilibrium can be time consistent by imposing a time consistency condition. Thus, it makes sense to consider some implications of the global solution. Second, this solution concept has been successfully adopted in the literature, mainly in the field of taxation, e.g., Kemp, Long and Shimomura [15], Long and Shimomura [19], Benchekroun and Long [2], and Benchekroun et al. [3].[9] Therefore, it is of some interest to find out what one can infer from the global solution, in contrast to the stagewise solution. Finally, it has been argued that some degree of precommitment by the leader can be observed. Among others, OPEC serves as a precommitment device to extract oil rents.[10] In this respect, the case of the leader's precommitment is worth addressing. We will demonstrate that the coincidence of the Nash equilibrium and the Stackelberg equilibrium under the exporter's leadership is no longer valid under the global solution. And, by using numerical examples, we will establish that the world welfare is highest in the Nash equilibrium and lowest under the leadership of the importing country.

The paper is organized as follows. Section 2 presents a model and the

[9] Chapter 5 in Dockner et al. [8] provides both a theory and economic applications of the global Stackelberg equilibrium.

[10] See, for example, Kohl [16].

feedback Nash equilibrium as a reference point. Sections 3 and 4 derive the global Stackelberg equilibrium in linear strategies in which either of the importing and exporting countries is a leader. Based on the results, Section 5 seeks some interesting properties of the global Stackelberg equilibria. Section 6 concludes the paper.

2 The Basic Model

This section presents our basic model and the feedback Nash equilibrium as a benchmark for comparison with global Stackelberg equilibria.[11] There are two countries, a resource-importing country (Home) and a resource-exporting country (Foreign). All the Foreign variables are distinguished from the Home variables by attaching an asterisk (*). Foreign does not consume the resource good.[12] Home imposes a specific tariff on its imports. Foreign has a stock of resource $\overline{X}$. We assume that the extraction cost per unit increases as the stock dwindles. This can be easily pictured by thinking of a cylinder-shaped mine. The surface area of the mine is unity by normalization, so the depth at which the last unit of resource can be found is $\overline{X}$. The marginal cost of extraction increases with the depth of the mine. Denote by $q(t)$ the rate of extraction and by $S(t)$ the depth reached at time t, where : $\dot{S}(t) = q(t)$. We assume that at any time, the cost of extracting q is cSq, i.e., the marginal cost of extraction is cS.[13] Thus, the deeper one has to go down, the higher is the marginal cost.

Home's inverse demand function of the resource good is

$$p^c = a - q, \quad a > c, \tag{1}$$

where p^c is the price which the consumers have to pay per unit. The parameter a is called the 'choke price.' It is the marginal utility of consuming

[11] For a detailed derivation of the Nash equilibrium reported below, see Chou and Long [7].

[12] For a model where Foreign also consumes the resource good, see Brander and Djajic [6].

[13] In what follows, we suppress the time argument t unless confusion arises.

the first unit. Let $\overline{S}$ denote the depth at which the marginal extraction cost equals the choke price, i.e., $c\overline{S} = a$. We assume that $\overline{X}$ is larger than $\overline{S}$. Then, efficiency implies that the resource stock be abandoned as soon as the depth S reaches its critical level $\overline{S} = a/c$, i.e., before physical exhaustion of the stock.[14]

Let τ be a per unit tariff levied on imported resources. Then, the consumer price of Home is

$$p^c = p + \tau. \tag{2}$$

where $p(t)$ is the price posted at time t by the exporting country which uses a Markovian decision rule $p = p(S)$.[15] From (1) and (2), the Home demand is given by $q = a - p - \tau$, from which the resource dynamics is

$$\dot{S} = a - p(S) - \tau, \quad S(0) = S_0 : \text{ given.} \tag{3}$$

Taking equation (3) as a constraint, Home chooses a time profile of tariffs to maximize the discounted stream of the sum of consumer surplus and tariff revenue:

$$\max_{\tau} \quad \int_0^{\infty} e^{-rt} W dt = \int_0^{\infty} e^{-rt} \frac{[a - p(S) + \tau]\,[a - p(S) - \tau]}{2} dt, \tag{4}$$

where $r > 0$ is a constant rate of discount. Note that since this section deals with the Nash equilibrium, in solving this problem, we assume that Home takes Foreign's decision rule $p(S)$ as given. In a parallel way, Foreign chooses a time profile of producer prices to maximize the discounted stream of profits:

$$\max_{p} \quad \int_0^{\infty} e^{-rt} \pi dt = \int_0^{\infty} e^{-rt} \left(p - cS\right) \left[a - p - \tau(S)\right] dt, \tag{5}$$

where $\tau(S)$ is Home's decision rule for its tariff rate.

[14]This formulation was used in Karp [9]. It has been extended to the case of oligopoly by Salo and Tahvonen [26]. In a recent exposition of the state of the oil market, Smith [27, p. 147] pointed out that "*most of the oil in any given deposit will never be produced, and therefore does not count as proved reserves, because it would be too costly to effect complete recovery.*" This indicates that the "exhaustion" of a deposit should be interpreted as an "economic abandonment" of the deposit after the profitable part has been exploited.

[15]Note that at the moment $p(S)$ is in principle any arbitrary decision rule: it maps the state variable $S(t)$ to the posted price $p(t)$. Only after the equilibrium pair of decision rules is found can one use the equilibrium function $p(S)$ to predict the price.

Since this is a typical linear-quadratic game, it is straightforward to characterize the feedback Nash equilibrium. In particular, Chou and Long [7] find the feedback Nash equilibrium in linear strategies:

$$\begin{aligned}\tau(S) &= \left(\frac{a}{c} - S\right)\frac{\mu^2}{4r} \equiv \alpha S + \beta \\ p(S) &= \frac{2c+\mu}{6}S + \frac{a(r+\mu)\mu}{2rc} \equiv \alpha^* S + \beta\end{aligned}$$

where μ is the positive root of the quadratic equation $(3/4)\mu^2 + r\mu - cr = 0$, i.e., $\mu = 2\left[(r^2+3cr)^{1/2} - r\right]/3$. And, the value function of Home $V(S)$ is quadratic in S such that

$$V(S) = \frac{\mu^2}{8r}S^2 - \frac{a\mu^2}{4rc}S + \frac{1}{2r}\left(\frac{a\mu}{2c}\right)^2,$$

for all S in the interval $\left[0, \frac{a}{c}\right]$. Finally, in the Nash equilibrium, the value function of Foreign is $V^*(S) = 2V(S)$. Notice that the Nash equilibrium pair decision rules $(\tau(S), p(S))$ displays an attractive feature: as S approaches the abandonment level $\overline{S} = a/c$, (i) the tariff rate falls gradually to zero, and (ii) the posted price p rises gradually to the choke price a.

Remark 1 The time path of the stock is

$$S(t) = \left(S_0 - \frac{a}{c}\right)e^{-(\alpha+\alpha^*)t} + \frac{a}{c}$$

with $-(\alpha+\alpha^*) = \left(r - \sqrt{D}\right)/3 < 0$ and $D \equiv r^2 + 3rc > 0$. Then $V(S(t))$ is obtained from substituting $S(t) = \left(S_0 - \frac{a}{c}\right)e^{-(\alpha+\alpha^*)t} + \frac{a}{c}$ into $V(S)$.

The feedback Nash equilibrium gives a reference point in the comparison with Stackelberg equilibria. In particular, it is useful to find the welfare level of each country under $S = 0$:

$$V(0) = \frac{1}{2r}\left(\frac{a\mu}{2c}\right)^2 \tag{6}$$

$$V^*(0) = \frac{1}{r}\left(\frac{a\mu}{2c}\right)^2. \tag{7}$$

This completes the description of the Nash equilibrium. The subsequent sections derive the global Stackelberg equilibria in this model.

3 Global Stackelberg Equilibrium with the Importer's Leadership

To find the global Stackelberg equilibrium in which Home is a leader, we suppose that it announces a linear tariff rule $\tau(S) = \alpha S + \beta$ at the beginning of the game. To determine the leader optimal pair (α, β) we must first solve for the follower's reaction function: how does the follower's strategy depend on any arbitrary pair (α, β). Thus, taking (α, β) as given, Foreign's best reply must satisfy the following Hamilton-Jacobi-Bellman (HJB) equation:

$$rV^*(S) = \max_p \left\{ (p - cS)(a - p - \alpha S - \beta) + V_S^*(S)(a - p - \alpha S - \beta) \right\},$$

where $V^*(S)$ is Foreign's value function and $V_S^*(S) \equiv dV^*(S)/dS$. Inverting the first-order condition for maximizing the right-hand side yields Foreign's strategy:

$$p(S) = \frac{-V_S^*(S) + (-\alpha + c)S + a - \beta}{2}.$$

where $V_S^*(S)$ is to be determined. Given the linear-quadratic game, it is plausible to guess that $V^*(S)$ is quadratic:

$$V^*(S) = \frac{A^*}{2} S^2 + B^* S + C^* \quad \text{for} \quad S \in \left[0, \overline{S}\right], \tag{8}$$

where A^*, B^* and C^* are undetermined coefficients to be endogenously derived. Eq. (8) immediately leads to $V_S^*(S) = A^* S + B^*$ and the above strategy is rewritten as

$$p = \frac{(-A^* - \alpha + c)S - B^* + a - \beta}{2}. \tag{9}$$

Substituting these results into (8), we have an identity in S:

$$r\left(\frac{A^*}{2} S^2 + B^* S + C^*\right) = \left[\frac{(A^* - \alpha - c)S + B^* + a - \beta}{2}\right]^2.$$

Equating the coefficients of S^2 and S, and of the constant term on the left-hand side with those on the right-hand side, we have

$$\frac{rA^*}{2} = \left(\frac{A^* - \alpha - c}{2}\right)^2$$

$$
\begin{aligned}
rB^* &= \frac{(A^* - \alpha - c)(B^* + a - \beta)}{2} \\
rC^* &= \left(\frac{B^* + a - \beta}{2}\right)^2.
\end{aligned}
$$

Solving the first equation for A^* yields[16]

$$
A^* = \alpha + c + r \pm \sqrt{\Delta}, \quad \Delta \equiv r(2\alpha + 2c + r) > 0.
$$

Substituting (9) into the resource dynamics leads to

$$
\begin{aligned}
\dot{S} &= a - \alpha S - \beta - \frac{(-A^* - \alpha + c)S - B^* + a - \beta}{2} \\
&= \frac{(A^* - \alpha - c)}{2} S + \frac{B^* + a - \beta}{2}.
\end{aligned}
$$

Therefore, in order to guarantee asymptotic stability, we require that $(A^* - \alpha - c) < 0$. As a result, A^* is determined as

$$
A^* = \alpha + c + r - \sqrt{\Delta}. \tag{10}
$$

Using (10), we obtain

$$
B^* = \frac{\left(r - \sqrt{\Delta}\right)(a - \beta)}{r + \sqrt{\Delta}} = \frac{\left(-\alpha - c - r + \sqrt{\Delta}\right)(a - \beta)}{\alpha + c}. \tag{11}
$$

Substituting (11) into the equation for C^*, we get

$$
C^* = \frac{1}{4r} \left[\frac{\left(-r + \sqrt{\Delta}\right)(a - \beta)}{\alpha + c}\right]^2. \tag{12}
$$

Finally, substituting (10) and (11) into (9), the exporter's strategy takes a form

$$
p(S) = \frac{-2\alpha - r + \sqrt{\Delta}}{2} S + \frac{\left(2\alpha + 2c + r - \sqrt{\Delta}\right)(a - \beta)}{2(\alpha + c)} \equiv \alpha^* S + \beta^* \tag{13}
$$

We see from this equation that α^* depends on α and β^* depends on both α and β. In this sense, $p(S)$ is the follower's reaction function. Given $\tau(S)$, the

[16] Here, we assume that Home's choice of α is such that $2\alpha + 2c + r > 0$. This will be verified later.

function $p(S)$ is determined. The resulting price that consumers in Home face can then be expressed as a function of the state variable S :

$$p^c = p^c(S) = p(S) + \tau(S) = -\left(\frac{r-\sqrt{\Delta}}{2}\right)S + \left[a + \left(\frac{r-\sqrt{\Delta}}{2}\right)\left(\frac{a-\beta}{\alpha+c}\right)\right] \tag{14}$$

The function (14) has α and β as parameters. Now, as S approaches the threshold level $\overline{S} = a/c$ where economic efficiency would call for abandonment of the remaining stock $\overline{X} - \overline{S}$, intuitively in any sensible equilibrium the consumer's price should approach the choke price a. (If it did not, there would be an incentive for the leader, Home, to deviate from its tariff strategy when S is approaching $\overline{S}$.) We formalize this idea by making the following definition.

Definition 1 (credibility condition) *An equilibrium consumer's price function $p^c(S)$ is said to satisfy the credibility condition if and only if*

$$\lim_{S\to\overline{S}} p^c(S) = a. \tag{15}$$

Even though the above credibility condition has not been formalized in the literature, earlier authors such as Kemp and Long (1980), Karp (1984), and Karp and Newbery (1991a,b, 1992) have alluded to the desirability of requiring that when the importing country stops importing, consumer's price should be equal to the choke price, because otherwise there would exist scope for achieving gains to consumers (at a negligible loss of tariff revenue) by adjusting the tariff rate near the end of the importing phase. The following result immediately follows.

Lemma 1 *When Home is the leader, the credibility condition (15) is satisfied if and only if its choice of (α, β) satisfies the condition that*

$$\beta = -\frac{\alpha a}{c}. \tag{16}$$

Having described the follower's behavior, let us turn to the leader's problem. To this end, substituting (13) into (3), the resource dynamics under linear strategies is

$$\dot{S} = -(\alpha + \alpha^*)S + a - \beta - \beta^*,$$

the solution of which is

$$S(t) = e^{-(\alpha+\alpha^*)t}\left(S_0 - \frac{a-\beta-\beta^*}{\alpha+\alpha^*}\right) + \frac{a-\beta-\beta^*}{\alpha+\alpha^*}.$$

The instantaneous welfare of Home under linear strategies $\tau(S) = \alpha S + \beta$ and $p(S) = \alpha^* S + \beta^*$ is

$$2W = \left(\alpha^{*2} - \alpha^2\right) S^2 - 2\left[\alpha\beta + \alpha^*\left(a - \beta^*\right)\right] S + \left(a - \beta^{*2}\right)^2 - \beta^2.$$

Substituting the above solution of S, and α^* and β^* in (13) into this felicity function and rearranging terms, we obtain

$$\begin{aligned} 2W &= \frac{r\left(3\alpha + c + r\right) - (2\alpha + r)\sqrt{\Delta}}{2} e^{\left(r-\sqrt{\Delta}\right)t}\left(S_0 - \frac{a-\beta}{\alpha+c}\right)^2 \\ &\quad + \frac{\left(r - \sqrt{\Delta}\right)\left(\alpha a + \beta c\right)}{\alpha + c} e^{\frac{r-\sqrt{\Delta}}{2}t}\left(S_0 - \frac{a-\beta}{\alpha+c}\right). \end{aligned}$$

Taking the integral of this function, Home's payoff from any state-date pair (S', t') is finally obtained as

$$\begin{aligned} \int_{t'}^{\infty} e^{-r(t-t')} W dt &= \frac{r(3\alpha + c + r) - (2\alpha + r)\sqrt{\Delta}}{4\sqrt{\Delta}}\left(S' - \frac{a-\beta}{\alpha+c}\right)^2 \\ &\quad + \frac{\left(r - \sqrt{\Delta}\right)\left(\alpha a + \beta c\right)}{\left(r + \sqrt{\Delta}\right)(\alpha + c)}\left(S' - \frac{a-\beta}{\alpha+c}\right). \qquad (17) \end{aligned}$$

At time $t = 0$ Home chooses α and β to maximize (17) with $(S', t') = (S_0, 0)$. Therefore, α and β are obtained by solving the first-order conditions by differentiating the right-hand side of (17)- evaluated at $(S', t') = (S_0, 0)$- with respect to α and β. However, the resulting solutions for α and β inevitably depend on S_0. This implies that if Home is allowed to reoptimize at any time $t_1 > 0$, the optimal value of α and β becomes a function of $S(t_1)$ which is generally different from α and β that depend on S_0. In other words, α and β determined at time 0 are no longer optimal at time t_1, i.e., they are time inconsistent.

One way to overcome this difficulty is to impose the restriction that $\alpha a + \beta c = 0$. This restriction will ensure that the derivative of the equilibrium payoff function (17) with respect to the parameters of the tariff function be independent of stock levels, for all non-negative stock levels. We will call this condition a "time consistency" condition. The economic meaning of this restriction is that when $S' = \overline{S}$, Home's payoff is zero, as the term inside the square brackets in (17) is then zero. Interestingly, from Lemma 1, we can see that this time consistency condition is satisfied if and only if the "credibility condition" in Definition 1 is.

So, what is the relationship between the credibility condition and time consistency? In our linear quadratic formulation, they turn out to be mathematically equivalent conditions, even though they are formulated differently. The credibility condition seems weaker, because it is only a condition on the limiting behavior of the equilibrium consumer's price function, and as such, it relates only to values of stock levels near $\overline{S}$. On the other hand, the time-consistency condition is the requirement that the derivative of the equilibrium payoff function (17) with respect to the parameters of the tariff function be independent of stock levels, for all non-negative stock levels. We conjecture that for non-linear-quadratic models, the latter requirement is a stricter requirement than the credibility condition.

Under this restriction, the above maximization problem of Home amounts to

$$\max_{\alpha} \quad \frac{r(3\alpha + c + r) - (2\alpha + r)\sqrt{\Delta}}{4\sqrt{\Delta}} \left(S' - \frac{a}{c}\right)^2.$$

The first-order condition is

$$r^{\frac{1}{2}} \left[\frac{3}{2}(2\alpha + 2c + r) + 2c + \frac{r}{2}\right] = 2(2\alpha + 2c + r)^{\frac{3}{2}}.$$

While it is impossible to obtain an explicit solution of α for this equation, we can prove the existence of the solution. Since we want $\Delta \equiv r(2\alpha + 2c + r) > 0$, let us define $\lambda \equiv 2\alpha + 2c + r$ and rewrite the above equation as

$$\frac{3r^{\frac{1}{2}}}{4}\lambda + \frac{r^{\frac{1}{2}}}{2}\left(2c + \frac{r}{2}\right) = \lambda^{\frac{3}{2}}.$$

Squaring both sides, we have

$$\frac{9r}{16}\lambda^2 + \frac{3r}{4}\left(2c + \frac{r}{2}\right)\lambda + \frac{r}{4}\left(2c + \frac{r}{2}\right)^2 = \lambda^3.$$

Let us define

$$f(\lambda) = \lambda^3 - \frac{9r}{16}\lambda^2 - \frac{3r}{4}\left(2c + \frac{r}{2}\right)\lambda.$$

The rest of our task is to find $\lambda > 0$ that satisfies $f(\lambda) = \frac{r}{4}\left(2c + \frac{r}{2}\right)^2$. The function $f(\lambda)$ has the properties that $f(0) = 0$ and $f'(0) = -\frac{3r}{4}\left(2c + \frac{r}{2}\right) < 0$. Noting that $f(-\infty) = -\infty$ and $f(\infty) = \infty$, we conclude that $f(\lambda) = 0$ at three values, $\lambda_1 = 0$, $\lambda_2 < 0$, and $\lambda_3 > 0$, and that there exists a unique positive λ^* which satisfies $f(\lambda^*) = \frac{r}{4}\left(2c + \frac{r}{2}\right)^2$. This implies that there exists a unique value of α which maximizes Home's objective function. Finally, β is derived as $\beta = -\alpha a/c$.

This result is summarized as:

Proposition 1 *There exists a unique global Stackelberg equilibrium in linear strategies where Home (the importing country) is a leader. As S approaches $\overline{S}$, the tariff rate τ approaches zero, and the price approaches the choke price a.*

Proof. The second sentence of Proposition 1 is proved as follows. Substituting $\overline{S} = a/c$ and $\beta = -\alpha a/c$ into $\tau(S) = \alpha S + \beta$, we have $\tau\left(\overline{S}\right) = \alpha a/c - \alpha a/c = 0$. Substituting the same values of $\overline{S}$ and β into (13) yields

$$p\left(\overline{S}\right) = \frac{-2\alpha - r + \sqrt{\Delta}}{2} \cdot \frac{a}{c} + \frac{2\alpha + 2c + r - \sqrt{\Delta}}{2(\alpha + c)}\left(a + \frac{\alpha a}{c}\right) = a,$$

as is to be proved. ||

Remark 2 Using $\alpha a + \beta c = 0$, we obtain from (17) the welfare of the Home as the leader when the stock is S' :

$$V(S') = \frac{r(3\alpha + c + r) - (2\alpha + r)\sqrt{\Delta}}{4\sqrt{\Delta}} \left(S' - \frac{a}{c}\right)^2$$

The time path of the leader's welfare is then

$$V(S(t)) = \frac{r(3\alpha + c + r) - (2\alpha + r)\sqrt{\Delta}}{4\sqrt{\Delta}} \left(S(t) - \frac{a}{c}\right)^2$$

with

$$S(t) = \left(S_0 - \frac{a}{c}\right) e^{-(\alpha+\alpha^*)t} + \frac{a}{c}$$

and $-(\alpha + \alpha^*) = \left(r - \sqrt{\Delta}\right)/2 < 0$.

4 Feedback Stackelberg Equilibrium with the Exporter's Leadership

This section turns to the case in which Foreign is a leader. The detailed steps for computing the equilibrium made as brief as possible because the same derivation as that in the previous section applies to this case as well. Supposing that Foreign chooses a feedback price rule $p(S) = \alpha^* S + \beta^*$, Home's problem is

$$\begin{array}{ll} \max\limits_{\tau} & \displaystyle\int_0^\infty e^{-rt} \frac{(a - \alpha^* S - \beta^* + \tau)(a - \alpha^* S - \beta^* - \tau)}{2} dt \\ \text{s.t.} & \dot{S} = a - \alpha^* S - \beta^* - \tau. \end{array}$$

The HJB equation associated with this problem is

$$\begin{aligned} rV(S) \quad = \quad & \max_{\tau} \left\{ \frac{(a - \alpha^* S - \beta^* + \tau)(a - \alpha^* S - \beta^* - \tau)}{2} \right. \\ & \left. + V_S(S) \left(a - \alpha^* S - \beta^* - \tau\right) \right\}, \end{aligned}$$

where $V(S)$ is Home's value function and $V_S(S) \equiv dV(S)/dS$. The first-order condition for maximizing the right-hand side yields Home's strategy

$$\tau(S) = -V_S(S) = -AS - B \equiv \alpha S + \beta \qquad (18)$$

by assuming $V(S) = AS^2/2 + BS + C$. Substituting this into the HJB equation, we have an identity in S:

$$r\left(\frac{A}{2}S^2 + BS + C\right) = \frac{\left[(A-\alpha^*)S + B + a - \beta^*\right]^2}{2}.$$

Using the method of undetermined coefficients as in the last section, the three parameters can be determined:

$$\begin{aligned}
A &= \frac{2\alpha^* + r - \sqrt{\Gamma}}{2} && (19)\\
B &= \frac{-\left(2\alpha^* + r - \sqrt{\Gamma}\right)(a-\beta^*)}{2\alpha^*} && (20)\\
C &= \frac{1}{2r}\left[\frac{\left(-r + \sqrt{\Gamma}\right)(a-\beta^*)}{2\alpha^*}\right]^2 && (21)\\
\Gamma &\equiv r\left(4\alpha^* + r\right) > 0.
\end{aligned}$$

Substituting these into (18), the follower's strategy is

$$\tau(S) = \frac{-2\alpha^* - r + \sqrt{\Gamma}}{2}S + \frac{\left(2\alpha^* + r - \sqrt{\Gamma}\right)(a-\beta^*)}{2\alpha^*} \equiv \alpha S + \beta. \tag{22}$$

We see from this equation that α depends on α^* and β depends on both α^* and β^*. In this sense, $\tau(S)$ is the follower's reaction function. Given $p(S)$, the function $\tau(S)$ is determined. The resulting price that consumers in Home face can then be expressed as a function of the state variable S :

$$p^c = p^c(S) = p(S) + \tau(S) = \left(\frac{-r + \sqrt{\Gamma}}{2}\right)S + \left[a + \left(\frac{r - \sqrt{\Gamma}}{2}\right)\left(\frac{a-\beta^*}{\alpha^*}\right)\right] \tag{23}$$

The function (23) has α^* and β^* as parameters. Now, as S approaches the threshold level $\overline{S} = a/c$ where economic efficiency would call for abandonment of the remaining stock $\overline{X} - \overline{S}$, intuitively in any sensible equilibrium the consumer's price should approach the choke price a. So definition 1 in the preceding section also applies here. We can now state:

Lemma 2 *When Foreign is the leader, the credibility condition (15) is satisfied if and only if its choice of* (α^*, β^*) *satisfies the condition that*

$$\frac{a}{c} = \frac{a - \beta^*}{\alpha^*}. \tag{24}$$

Invoking that the dynamics of S with the linear strategies is

$$\dot{S} = a - \alpha^* S - \beta^* + AS + B,$$

the solution is obtained as

$$\begin{aligned} S(t) &= e^{(A-\alpha^*)t}\left(S_0 - \frac{a - \beta^* + B}{\alpha^* - A}\right) + \frac{a - \beta^* + B}{\alpha^* - A} \\ &= e^{\frac{r-\sqrt{\Gamma}}{2}t}\left(S_0 - \frac{a - \beta^*}{\alpha^*}\right) + \frac{a - \beta^*}{\alpha^*}. \end{aligned}$$

Based on these preparations, we now consider the exporting firm's problem. The instantaneous profit is

$$\pi = (p - cS)(a - p - \tau) = (\alpha^* S + \beta^* - cS)(a - \alpha^* S - \beta^* + AS + B).$$

Substituting A, B and the solution of S into this expression and making some arrangements yield

$$\begin{aligned} \pi &= \frac{(\alpha^* - c)\left(r - \sqrt{\Gamma}\right)}{2} e^{\left(r-\sqrt{\Gamma}\right)t}\left(S_0 - \frac{a - \beta^*}{\alpha^*}\right)^2 \\ &\quad + \frac{[a\alpha^* - c(a - \beta^*)]\left(r - \sqrt{\Gamma}\right)}{2\alpha^*} e^{\frac{r-\sqrt{\Gamma}}{2}t}\left(S_0 - \frac{a - \beta^*}{\alpha^*}\right). \end{aligned}$$

Taking the integral at any (state, date) pair (S', t') we have

$$\begin{aligned} \int_{t'}^{\infty} e^{-r(t-t')}\pi dt &= \frac{(\alpha^* - c)\left(-4\alpha^* - r + \sqrt{\Gamma}\right)}{8\alpha^* + 2r}\left(S' - \frac{a - \beta^*}{\alpha^*}\right)^2 \\ &\quad - \frac{[a\alpha^* - c(a - \beta^*)]\left(2\alpha^* + r - \sqrt{\Gamma}\right)}{2\alpha^{*2}}\left(S' - \frac{a - \beta^*}{\alpha^*}\right), \end{aligned} \tag{25}$$

which Foreign seeks to maximize by choosing α^* and β^*.

Recalling the argument in the previous section, the optimal pair (α^*, β^*) that is derived by partially differentiating (25) is vulnerable to time inconsistency; the pair determined at $t = t_1$ deviates from the pair precommited at $t = 0$. Following the previous section, let us make the time consistency condition: $a\alpha^* - c(a - \beta^*) = 0$ to ensure time consistency. Interestingly, from Lemma 2, we can see that this time consistency condition is satisfied if and only if the "credibility condition" in Definition 1 is.

Then, Foreign's problem at hand reduces to

$$\max_{\alpha^*} \quad \frac{(\alpha^* - c)\left(-4\alpha^* - r + \sqrt{\Gamma}\right)}{8\alpha^* + 2r}\left(S' - \frac{a}{c}\right)^2.$$

The first-order condition is

$$(2\alpha^* + 2c + r)\left[r(4\alpha^* + r)\right]^{\frac{1}{2}} = (4\alpha^* + r)^2,$$

which can not yield an explicit solution for α^*. However, we can prove the unique existence of the solution by a transformation of variables.

Let us define $\gamma = 4\alpha^* + r$ and square the above equation. Then, we have

$$r\left(\frac{\gamma}{2} + 2c + \frac{r}{2}\right)^2 \gamma = \gamma^4,$$

which is equivalent to a cubic equation of γ:

$$r\left[\gamma^2 + (4c + r)^2 + 2(4c + r)\gamma\right] = 4\gamma^3.$$

We must find $\gamma > 0$ that satisfies this condition. Defining

$$g(\gamma) = 4\gamma^3 - r\gamma^2 - 2r(4c + r)\gamma,$$

the rest of our task to find a positive γ which satisfies $g(\gamma^*) = r(r + 4c)^2$.

Since $g(0) = 0$, $g'(0) < 0$, $\lim_{\gamma\to\infty} g(\gamma) = \infty$ and $\lim_{\gamma\to-\infty} g(\gamma) = -\infty$, we find three solutions to $g(\gamma) = 0$: $\gamma = 0, \gamma_1 < 0$ and $\gamma_2 > 0$. Therefore, we have arrived at:

Proposition 2 *There exists a unique global Stackelberg equilibrium in linear* *strategies where Foreign (the exporting country) is a leader. As S approaches $\overline{S}$, the tariff rate τ approaches zero, and the price approaches the choke price a.*

Proof. We prove the second sentence in Proposition 2. Substituting the time consistency condition $\overline{S} = a/c$ and $\beta^* = (c - \alpha^*)\, a/c$ into the leader's strategy leads to $p\left(\overline{S}\right) = \alpha^* a/c + (c - \alpha^*)\, a/c = a$. Moreover, substituting the same values of $\overline{S}$ and β^* into (22), we have

$$\begin{aligned}
\tau\left(\overline{S}\right) &= \frac{-2\alpha^* + r - \sqrt{\Gamma}}{2} \cdot \frac{a}{c} + \frac{2\alpha^* + r - \sqrt{\Gamma}}{2\alpha^*}\left[a - \frac{(c - \alpha^*)\, a}{c}\right] \\
&= \frac{2\alpha^* + r - \sqrt{\Gamma}}{2}\left(-\frac{a}{c} + \frac{a}{c}\right) = 0.
\end{aligned}$$

Thus, we have arrived at Proposition 2. ||

Before moving to the next section, a useful result is stated and proved.

Lemma 3 *The undiscounted sum of imports over time equals $\overline{S} - S_0$.*

Proof. Under the linear strategies $\tau(S) = \alpha S + \beta$ and $p(S) = \alpha^* S + \beta^*$, the undiscounted sum of imports is

$$\begin{aligned}
\int_0^\infty (a - p - \tau)dt &= \int_0^\infty [-(\alpha + \alpha^*)S + a - \beta - \beta^*] \\
&= -(\alpha + \alpha^*)\int_0^\infty S(t)dt + \lim_{t\to\infty}(a - \beta - \beta^*)t \\
&= -(\alpha + \alpha^*)\int_0^\infty \left[e^{-(\alpha+\alpha^*)t}\left(S_0 - \overline{S}\right) + \overline{S}\right]dt + \lim_{t\to\infty}(a - \beta - \beta^*)t \\
&= -(\alpha + \alpha^*)\left[\frac{-e^{-(\alpha+\alpha^*)t}}{\alpha + \alpha^*}\left(S_0 - \overline{S}\right) + \overline{S}t\right]_0^\infty + \lim_{t\to\infty}(a - \beta - \beta^*)t \\
&= -(\alpha + \alpha^*)\frac{S_0 - \overline{S}}{\alpha + \alpha^*} = \overline{S} - S_0,
\end{aligned}$$

where the last equality follows from the definition of $\overline{S}$: $\overline{S} = (a - \beta - \beta^*)/(\alpha + \alpha^*)$. ||

Remark 3 Using the time consistency condition: $a\alpha^* - c(a - \beta^*) = 0$, we obtain from (25) the welfare of Foreign as the leader when the stock is S' :

$$V^*(S') = \frac{(\alpha^* - c)\left(-4\alpha^* - r + \sqrt{\Gamma}\right)}{8\alpha^* + 2r}\left(S' - \frac{a}{c}\right)^2$$

The time path of the exporting leader's welfare is then

$$V^*(S(t)) = \frac{(\alpha^* - c)\left(-4\alpha^* - r + \sqrt{\Gamma}\right)}{8\alpha^* + 2r}\left[S(t) - \frac{a}{c}\right]^2$$

with

$$S(t) = \left(S_0 - \frac{a}{c}\right)e^{-(\alpha+\alpha^*)t} + \frac{a}{c}$$

where $-(\alpha + \alpha^*) = \left(r - \sqrt{\Gamma}\right)/2 < 0$.

5 Numerical Results

Based on the results in the previous sections, this section seeks some implications of global Stackelberg equilibria for strategies and welfare in a comparison with the feedback Nash equilibrium. One difficulty is that the first-order condition for the optimization problem of leaders involves a cubic polynomial and hence we must resort to a numerical analysis. Tables 1 and 2 reports the equilibrium strategies in the Nash and two Stackelberg equilibria, and Tables 3 summarizes a welfare comparison.[17]

Notice that, in all cases, the total sum of imports over time (in quantity terms, and undiscounted) is always $\overline{S}$, which is just a confirmation of Lemma 3. So, policies only affect the time profile of imports and the time path of the consumer price p^c but not the total imported stock.

5.1 Comparison of α and α^* (Table 1)

(Table 1 around here)

Table 1 tells us that α is negative while α^* is positive in all cases. The reason for this is as follows. If S increases, marginal cost and price rise, which

[17]We have checked robustness of the results in these tables for other sets of parameter values.

reduces the importing country's welfare because both consumer surplus and tariff revenue decrease. In order to deal with this welfare loss, the importing country will lower a tariff for import expansion, i.e., α is negative. On the other hand, a rise in marginal cost induced by an increase in S lowers the exporting country's profit. Hence, the exporting country will raise price for securing its profit, which makes α^* positive.

When the importing country leads, it is bound by the time-consistent constraint $\beta = -\alpha a/c$. It precommits to a faster rate of fall in tariff; α under its leadership is more negative than that in the Nash case (the absolute value of α increases). Observing this choice of the importer, the exporter optimally responds by setting a lower price earlier on (when S is still small), i.e., α^* becomes higher while β^* becomes lower. The leader thus manages to tilt the consumption path toward the present.

If, on the other hand, the exporting country is a leader, it is bound by the time-consistent constraint $\alpha^* a = c(a - \beta^*)$. It chooses a lower α^*, and this raises β^*. Thus, its posted price is higher earlier on. Such a choice induces the follower (the importing country) to tax less and hence import demand and profits that accrue to the exporting country become larger.

5.2 Comparison of β and β^* (Table 2)

(Table 2 around here)

Table 2 is concerned with the time-invariant term of feedback strategies. A first glance at them allows us to find that each country behaves more aggressively when it is a leader, i.e., the importing (resp. exporting) country chooses a higher tariff (resp. price) under its leadership. This is a natural consequence since each party aims for more resource rents by using a higher tariff or a higher price. As a result, the follower also takes a more aggressive response to the leader's precommitment. That is, β and β^* of the leader are larger than those in the Nash case.

5.3 Welfare Comparison (Table 3)

(Table 3 around here)

We now compare welfare levels of each individual country and the world. From the definition of the Stackelberg equilibrium, it is trivial that the leader improves its payoff relative to the feedback Nash equilibrium. On the other hand, the follower loses regardless of whether it is an exporting country or an importing country. The follower's welfare loss is large enough to dominate the leader's welfare gain, leading to a net welfare loss for the world. In other words, the presence of leadership leaves the world worse off than the Nash equilibrium. This result has a strong policy implication. As mentioned in the introduction, there is some evidence that supports the hypothesis that OPEC serves as a commitment device. Given this evidence and our result, such an oil cartel should be eliminated from the point of view of the world welfare. The same is true of the importing country. Although we have no empirics at hand that shows the precommitment behavior of the importing countries, such a behavior is harmful from the viewpoint of world welfare. For this purpose, some kind of international organization or agreement that can play such a role may be called for.[18]

5.4 Comparison between Global and Stagewise Solutions (Table 4)

(Table 4 around here)

While we have focused on the global Stackelberg equilibrium in which the leader precommits, it is interesting to compare our result with that under the stagewise Stackelberg equilibrium. We omit the derivation of the stagewise Stackelberg equilibrium since it is in detail provided by Rubio and Escriche [25]. Here, we just offer numerical values of welfare by choosing the same

[18]One may claim that the WTO can serve as an international organization for eliminating precommitment to trade-distorting actions. At present, 11 members of 12 OPEC participating countries belong to the WTO.

parameters as Table 3. One notable insight of the stagewise Stackelberg equilibrium is that the Nash and Stackelberg equilibria coincide when the exporting country leads.

Comparing Tables 3 and 4, and paying special attention to the case in which Home is a leader, it gains more in the global solution than in the stagewise solution, starting from the Nash payoff. The reason is that the leader can attain a higher payoff by precommiting to its rule of strategies α and β.

5.5 Time Path of $S, \tau(S)$ and $p(S)$

(Figure 1 around here)

It is useful to compare, across different scenarios, the time paths of $S, \tau(S)$ and $p(S)$. Under linear feedback strategies $\tau(S) = \alpha S + \beta$ and $p(S) = \alpha^* S + \beta^*$, the law of motion of S is $\dot{S} = -(\alpha + \alpha^*)S + a - \beta - \beta^*$, and hence we have

$$S(t) = e^{-(\alpha+\alpha^*)t}\left(S_0 - \overline{S}\right) + \overline{S}, \quad \overline{S} \equiv \frac{a}{c}.$$

Therefore, the time path of $\tau(S)$ is

$$\begin{aligned}
\tau(S) &= \alpha S + \beta \\
&= \alpha\left[e^{-(\alpha+\alpha^*)t}\left(S_0 - \overline{S}\right) + \overline{S}\right] + \beta \\
&= \alpha e^{-(\alpha+\alpha^*)t}\left(S_0 - \overline{S}\right) + \alpha\overline{S} + \beta \\
&= \alpha e^{-(\alpha+\alpha^*)t}\left(S_0 - \overline{S}\right),
\end{aligned}$$

where the last equality follows from Propositions 1 and 2 that assert that the tariff becomes zero in the steady state, i.e., $\alpha\overline{S} + \beta = 0$. In a similar way, the path of $p(S)$ becomes

$$\begin{aligned}
p(S) &= \alpha^* S + \beta^* \\
&= \alpha^*\left[e^{-(\alpha+\alpha^*)t}\left(S_0 - \overline{S}\right) + \overline{S}\right] + \beta^* \\
&= \alpha^* e^{-(\alpha+\alpha^*)t}\left(S_0 - \overline{S}\right) + \alpha^*\overline{S} + \beta^* \\
&= \alpha^* e^{-(\alpha+\alpha^*)t}\left(S_0 - \overline{S}\right) + a,
\end{aligned}$$

where the last equality uses $\alpha^* \overline{S} + \beta^* = a$ in Propositions 1 and 2.

Figure 1 shows the time path of $S, \tau(S)$ and $p(S)$ under the three scenarios with parameter values $r = 0.05, c = 1$ and $S_0 = 0$. We briefly comment on this figure.

The middle panel of Figure 1 shows the time path of the tariff rate τ under the three scenarios. Not surprisingly, when Home is the leader, the tariff rate is higher than that under the Nash equilibrium. With such high tariff rate, Home is able to pay less to Foreign per unit, as shown in the bottom panel of Figure 1. Conversely, when Foreign is the leader, it is able to charge a higher price than under the Nash equilibrium. This is shown as the dotted curve in the bottom panel of Figure 1. Consequently, Home, being a follower in this scenario, responds by imposing a lower tariff rate to ensure that consumers surplus is not too low. This is shown as the dotted path in the middle panel.

The quantity purchased is the slope of the time path of S. This slope is decreasing with time, as imports fall over time. Under Home's leadership, consumers buy relatively less (compared to Nash equilibrium imports) earlier on, and buy relatively more later on. This is reflected in the slope of the dotted curve for S in the top panel being less steep than the slope of the solid curve for S. Under Foreign leadership, such tilting (relative to the path under Nash equilibrium) is less sharp. While the long-run cumulative import is the same (it is equal to $\overline{S} - S_0$ in all cases), the short-run cumulative import $(S_t - S_0)$ is lowest under Home's leadership.

5.6 Time Path of $V(S), V^*(S)$ and $V(S) + V^*(S)$

(Figure 2 around here)

The top panel 1 of Figure 2 depicts the time path of welfare for Home under each of the three scenarios. What is worth noting is that being a global Stackelberg leader improves welfare substantially: the corresponding welfare path lies above the other two paths. A similar remarks applies to the middle panel which refers to Foreign. In the bottom panel, world welfare is depicted.

Generally, the paths of welfare intersect. This is not surprising because at the time when the intersection occurs, the stock levels are not the same.

6 Concluding Remarks

We have developed a dynamic Stackelberg game model of a world market of an exhaustible resource to consider some welfare implications of leaderships. After characterizing the two global Stackelberg equilibria in which either of the importing and exporting countries leads, we have shown that the world welfare is highest in the Nash equilibrium, namely, the presence of leaderships imparts a welfare loss to the world. This, in turn, implies that some kind of world organization or forum may be necessary to prevent the precommitment behavior of either party from the world welfare viewpoint.

While this paper offers some novel results, our model should admittedly be extended to relax a number of simplifying assumptions, e.g., linear demand, and a price-setting firm. It is part of our future research agenda to closely look at how our results are sensitive to the underlying assumptions.

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References 1. Basar T, Olsder GJ (1982) Dynamic noncooperative game theory. Academic Press, London

2. Benchekroun H, Long NV (1998) Efficiency inducing taxation for pollut-

ing oligopolists. J Public Econ 70: 325-342

3. Benchekroun H, Long NV, Tian H (1999) Learning-by-doing and strategic trade policy. Rev Int Econ 7: 493-508

4. Bergstrom TC (1982) On capturing oil rents with a national excise tax. Amer Econ Rev 72: 194-201

5. Blanchard OJ, Gali J (2010) The macroeconomic effects of oil price shocks: why are the 2000s so different from the 1970s?. In: Gali J, Gertler M (eds), International dimensions of monetary policy. University of Chicago Press, Chicago, pp. 373-428

6. Brander J, Djajic S (1983) Rent extracting tariffs and the management of exhaustible resources. Can J Econ 16: 288-298

7. Chou S, Long NV (2009) Optimal tariffs on exhaustible resources in the presence of cartel behavior. Asia-Pacific J Acc Econ 16: 239-254

8. Dockner E, Jorgensen S, Long NV, Sorger G (2000) Differential games in economics and management science. Cambridge University Press, Cambridge

9. Karp L (1984) Optimality and consistency in a differential game with non-renewable resources. J Econ Dynam Control 8: 73-97

10. Karp L, Newbery DM (1991a) OPEC and the U.S. oil import tariff. Econ J 101: 303-313

11. Karp L, Newbery DM (1991b) Optimal tariffs on exhaustible resources. J Int Econ 30: 285-299

12. Karp L, Newbery DM (1992) Dynamically consistent oil import tariffs, Can J Econ 25: 1-21

13. Kemp MC, Long NV (1979) The interaction between resource-poor and resource-rich economies. Australian Econ Pap 18: 258-267

14. Kemp MC, Long NV (1980), Optimal tariffs on exhaustible resources. In: Kemp MC, Long NV (eds), Exhaustible resources, optimality, and trade. North Holland, Amsterdam, pp. 183-186

15. Kemp MC, Long NV, Shimomura K (1993) Cyclical and noncyclical redistributive taxation. Int Econ Rev 34: 415-429

16. Kohl WL (2002) OPEC behavior, 1998-2001, Quart Rev Econ Finance 42: 209-233

17. Liski M, Tahvonen O (2004) Can carbon tax eat OPEC's rents? J Environ Econ Manage 47: 1-12

18. Long NV (2010) A survey of dynamic games in economics. World Scientific

19. Long NV, Shimomura K (2002) Redistributive taxation in closed and open economies. In: Woodland A (ed), Economic theory and international trade: essays in honour of Murray C. Kemp, Edward Elgard, Cheltenham, U.K., pp. 104-123

20. Long NV, Sorger G (2010) A dynamic principal-agent problem as a feedback Stackelberg differential game. Central Europ J Operations Res 18: 491-509

21. Maskin E, Newbery D (1990) Disadvantageous oil tariffs and dynamic consistency. Amer Econ Rev 80: 143-156

22. Mehlmann A (1988), Applied differential games. Kluwer Academic Publishers, New York

23. Reinganum JF, Stokey NL (1985) Oligopoly extraction of a common property natural resource: the importance of the period of commitment in dynamic games. Int Econ Rev 26: 161-173

24. Rubio S (2005) Tariff agreements and non-renewable resource international monopolies: prices versus quantity, Working Paper WP-AD-2005-10, University of Valencia

25. Rubio S, Escriche L (2001) Strategic Pigouvian taxation, stock externalities and polluting non-renewable resources. J Public Econ 79: 297-313

26. Salo S, Tahvonen O (2001) Oligopoly equilibria in non-renewable resource markets. J Econ Dynam Control 25: 671-702

27. Smith JL (2009) World oil: market or mayhem? J Econ Perspect 23: 145-164

28. Tahvonen O (1996) Trade with polluting non-renewable resources. J Environ Econ Manage 30: 1-17

29. Wirl F (1995) The exploitation of fossil fuels under the threat of global warming and carbon taxes: a dynamic game approach. Environ Resource Econ 5: 333-352

30. Wirl F, Dockner E (1995) Leviathan governments and carbon taxes: costs and potential benefits. Europ Econ Rev 39: 1215-1236

31. World Trade Organization (2010), World Trade Report 2010

	α	α^*
Nash	-0.257663891	0.371168053
Stackelberg (Home is leader)	-0.8	0.849999983
Stackelberg (Foreign is leader)	-0.085096394	0.150325373

Table 1: α and α^* under $S_0 = 0, r = 0.05, c = 1$

	β	β^*
Nash	$0.257663891a$	$0.628831943a$
Stackelberg (Home is leader)	$0.8a$	$0.15a$
Stackelberg (Foreign is leader)	$0.085096394a$	$0.849674627a$

Table 2: β and β^* under $S_0 = 0, r = 0.05, c = 1$

	Home	Foreign	Total
Nash	$0.128831946a^2$	$0.257663892a^2$	$0.386495838a^2$
Stackelberg (Home is leader)	$0.275a^2$	$0.05a^2$	$0.325a^2$
Stackelberg (Foreign is leader)	$0.042548195a^2$	$0.307126431a^2$	$0.349674626a^2$

Table 3: Payoffs under $S_0 = 0, r = 0.05$ and $c = 1$

	Home	Foreign	Total
Nash & Foreign is leader	$0.128831946a^2$	$0.257663892a^2$	$0.386495838a^2$
Stackelberg (Home is leader)	$0.222493132a^2$	$0.148328754a^2$	$0.370821885a^2$

Table 4: Payoffs under $S_0 = 0, r = 0.05$ and $c = 1$: Stagewise Stackelberg Equilibriua

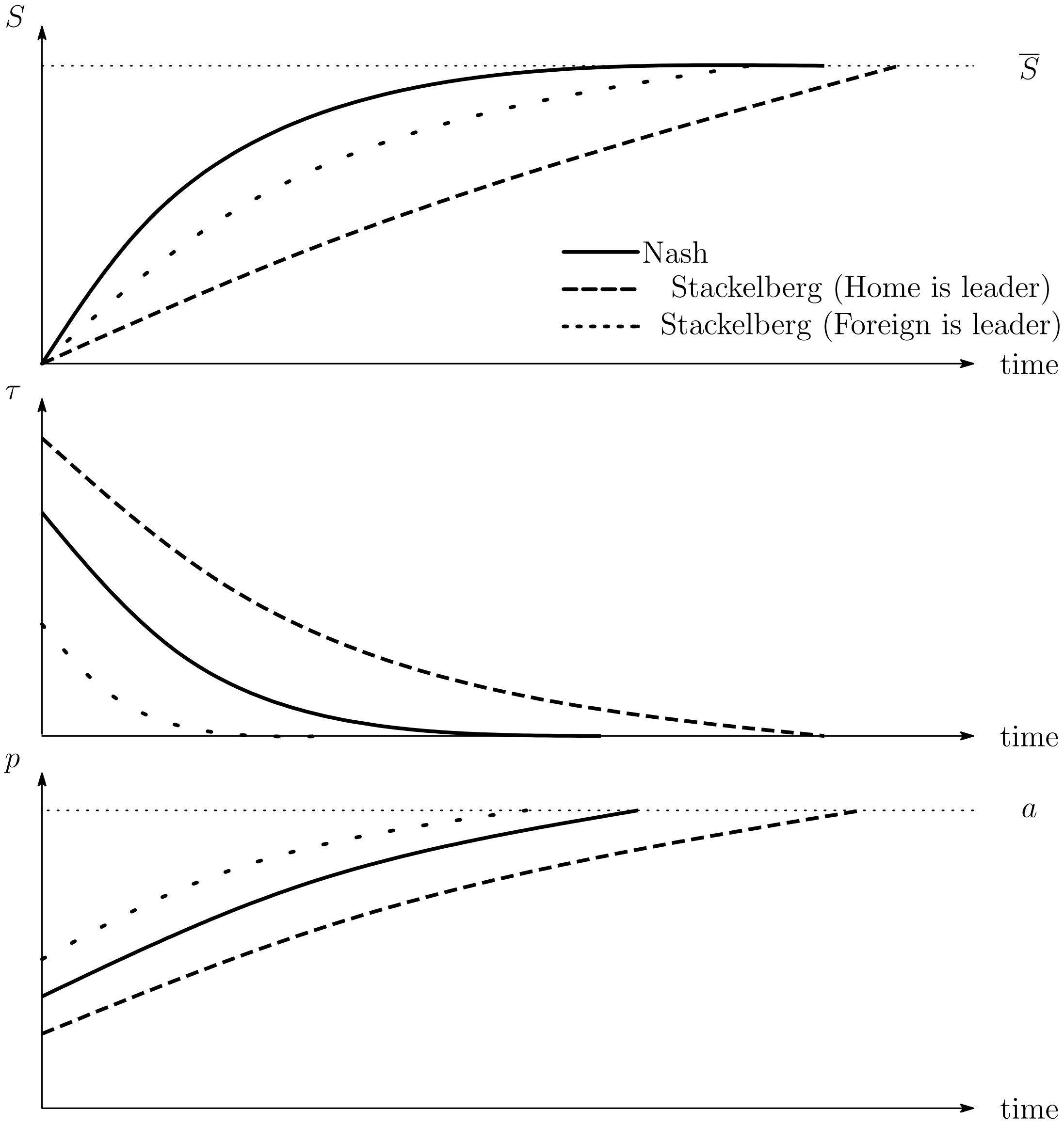

Figure 1: Time Paths of $S, \tau(S)$ and $p(S)$

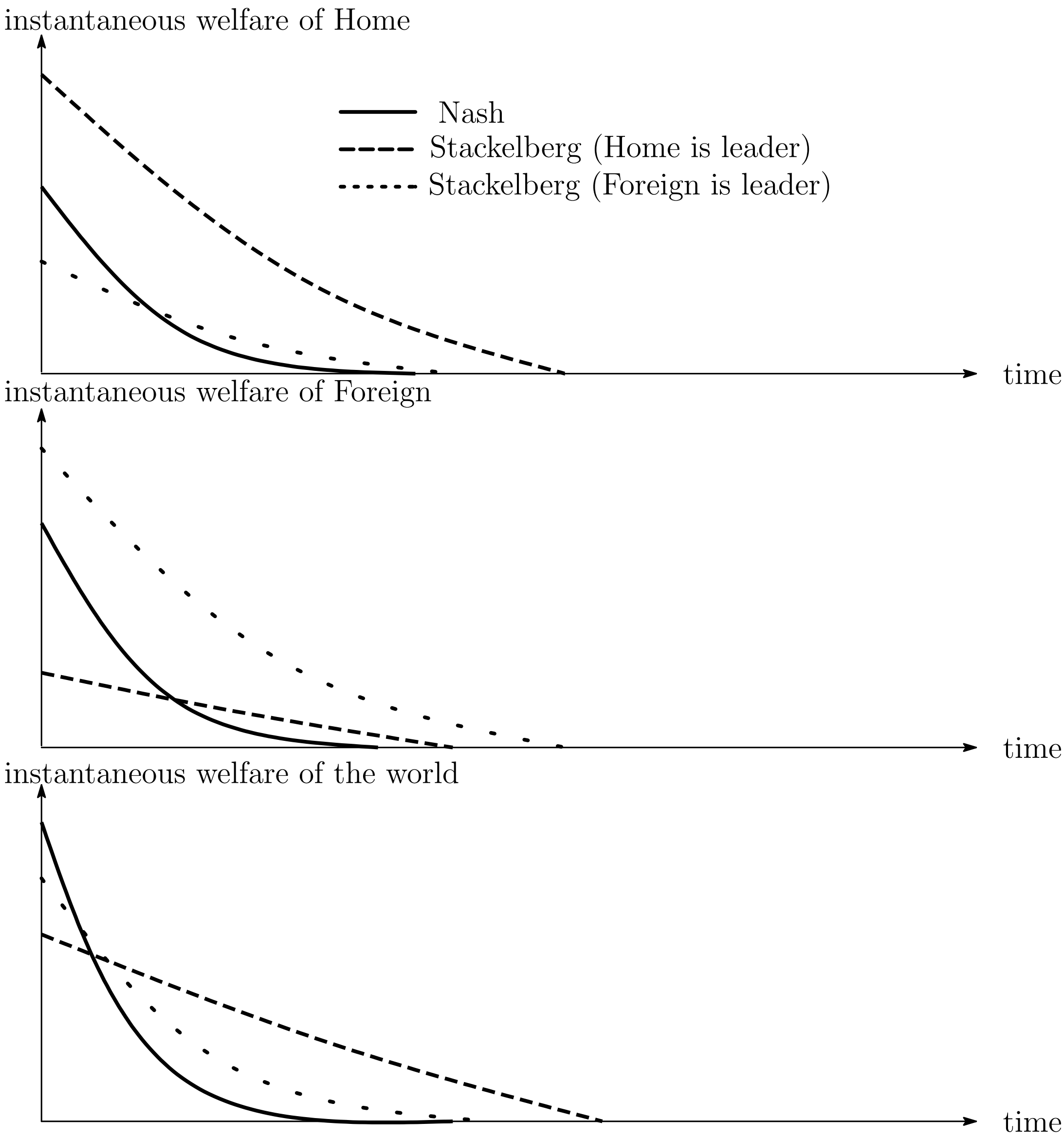

Figure 2: Time Paths of Welfare