COORDINATION OF TAXATION AND INNOVATION FOR THE PROTECTION OF THE INTERNATIONAL ENVIRONMENT

by

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REAL 01-T-8 August, 2001

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First version : July 1998
This version : March 2001

Abstract

Two regulators face an international environmental problem because of the transfrontier polluting activity of their domestic firm. These firms can adopt a new and less polluting production technology by incurring an actualized investment cost. When the cost of immediate adoption of the cleaner technology is relatively high and the environmental taxation is well chosen, firms will adopt it at finite but different dates even though the model is symmetric and there is no informational asymmetry. The optimal emission tax parameter is greater under cooperation which induce firms to adopt the friendly technology earlier than in the non-cooperative regime. Consequently, residual emissions are lower under cooperation and intertemporal individual social welfare is greater. However, the private diffusion is the same in the two regimes.

Keywords : International environment ; Taxation; Innovation; Diffusion; Cooperation.

JEL classification : D62 ; H32 ; H77 ; O31

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1. Introduction

The environmental problems of international dimension have the specificity that they are generated by some types of pollution emissions of all countries which are almost all affected. Examples of such problems are the ozone layer depletion and climate change. The first problem has a negative effect on all countries. However, the effects of the second vary from one region to another, with a negative and catastrophic expected global effect. Because of their international dimension, these problems cannot be solved unilaterally by positive actions of some countries. To avoid free-riding behavior, they need the adherence to environmental international agreements of all polluting countries. Such agreements may consist of the introduction of an environmental tax which may induce the adoption of less polluting technologies.

For an international protection of the environment, Carraro and Siniscalco (1993) show that theoretically stable[1] environmental coalitions may exist under reasonable conditions, although they are of small extent. They recommend linking environmental and economic negotiations in order to form sufficiently large and stable environmental coalitions. In addition, Chander and Tulkens (1992), Ben Youssef and Mansouri (2000) and Pallage (2000) have been interested in the transborder environmental externalities.

Some authors have tried to investigate the link between international environmental externalities and innovation. Ulph, A. and D. Ulph (1995) have studied the effects of cooperation and non-cooperation between countries on the taxes imposed and the environmental R&D. Nevertheless, they have ignored consumer surplus.

At the national level, Milliman and Prince (1989) have evaluated the incentive effects of five environmental policy tools (emission taxes, subsidies, auctioned

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[1] An environmental coalition is a set of countries committed to comply with environmental agreements once they have been negotiated. It is said to be stable when no country decides to join it or to leave it.

permits, issued marketable permits and performance standards) to encourage the development and adoption of advanced pollution abatement technology. They support the view that taxes and auctioned permits are the most effective policy instruments. Jung, Krutilla and Boyd (1996) have extended this comparative approach to the industry level. See also Dosi and Moretto (1997, 2000), Stranlund (1997) and Farzin and Kort (2000).

Reinganum (1981) has analyzed the diffusion of a new technology in an industry where firms can adopt a cost reducing technology within a time t. Even if there is full information and firms are identical, she shows that there is a diffusion of innovation as one firm innovates earlier than the other and gains more. Nevertheless, she supposes that the payoff functions of firms are globally concave in their arguments. In addition, these functions are not differentiable when innovation is simultaneous (i.e. in $T_1 = T_2$, see Reinganum (1981) page 397). Fudenberg and Tirole (1985) set a less strong condition on the payoffs of firms to get quasiconcavity. They show that, depending on certain conditions, there is diffusion or not. Hoppe (2000) extends the work of Fudenberg and Tirole to include uncertainty concerning the profitability of a new technology and shows that there may be second-mover advantages because of informational spillovers. Dutta et al. (1995) highlight a similar result in a context where the later innovator continues to develop the technology and eventually offers a higher-quality good.

In Ben Youssef (2001), which is an extension of the work of Carraro and Topa (1991), a regulator faces an environmental problem because of the polluting activity of firms. The latter can adopt a new and less polluting technology by spending an actualized investment cost, decreasing exponentially with the adoption date. When firms adopt the cleaner technology, they produce more, pollute less, pay fewer emission taxes and, consequently, have greater profit and higher social welfare. If the cost of immediate adoption of the cleaner technology is relatively high and the environmental taxation is adequate, firms will adopt it at finite but different dates even though the model is symmetric and there is no informational asymmetry. Moreover, we show that technological diffusion is socially optimal. The social adoption date of the first innovator is earlier than the private one and the contrary happens for the second innovator. Subsidies may be used to induce the socially optimal adoption dates.

This paper is an extension of the one of Carraro and Topa (1993). It stands out from the existing literature by studying the diffusion of a cleaner technology in two countries facing an international environmental problem and taxing their respective firms, which compete in the common market. It also enables us to compare the diffusion process under the cooperative and non-cooperative regimes.

The most important differences of this model from that of Carraro and Topa (1993) are : *i)*the function $\rho(t)$ representing the actualized cost of adopting a less polluting technology by a firm at time t; *ii)*the intertemporal payoffs of firms and regulators ; *iii)*the consumer welfare of each country in the non-cooperative regime. This function ρ makes the intertemporal objective functions of firms and regulators locally concave with respect to their arguments (i.e. supposes a weaker condition).

The symmetric model we consider in this paper consists of two firms, each of which is located in one country. Firms produce the same good sold in both countries. A byproduct of the production process is pollution (e.g. CO_2) which negatively affects the two countries. These firms can adopt a new and less polluting technology at time t by spending an actualized investment cost $\rho(t)$ which decreases exponentially. In order to induce their respective firms to adopt the cleaner technology, because it enables them to produce more while polluting less, each regulator imposes a pollution tax to his domestic firm. Regulators and firms maximize their intertemporal objective functions which take into account the investment cost of innovation. We compare the effects of environmental taxation under two regimes. In the first, countries agree to adopt an environmental taxation scheme, tax rates are set by a central authority, so that the environmental policy is fully coordinated. In the second regime, countries still agree to introduce an environmental taxation; however, according to the subsidiary principle, each country sets its own tax rate non-cooperatively. Our main interest is the case where the cost of immediate innovation (i.e. at date 0) is relatively high.

We find that environmental tax competition between regulators ends up to an optimal emission tax parameter, which is lower than the one of cooperation.

Consequently, private adoption dates, which are chosen by firms, are postponed in the non-cooperative regime with respect to the cooperative ones. Moreover, total emissions and firms profits are higher, but total abatements and total (and individual) intertemporal social welfare are lower than with cooperation. We show that even though the model is symmetric and there is no uncertainty, firms innovate at different dates and this private diffusion is the same in the two regimes[2]

The model is introduced in section 2, and section 3 analyzes the innovating reaction of firms to the taxation scheme introduced in each country. Section 4 studies the cooperative regime and section 5 the non-cooperative one. Section 6 compares the two regimes and section 7 contains some conclusions.

2. The model

Two identical firms compete by quantities on the same product market where they offer a single homogeneous good. A byproduct of the production process is pollution. Firms are located in different but symmetric countries. These countries have agreed to tax emissions in order to protect the international environment. However, the tax parameters can be set either cooperatively, in such case the optimal tax parameter is jointly chosen by the two regulators, or non-cooperatively when, according to the subsidiary principle, each regulator chooses the optimal domestic tax parameter. The variable time is assumed to be continuous.

Before any environmental regulation is introduced, firms produce output using a single-product technology D characterized by a fixed emission/output ratio k. Polluting emissions x_i are a linear function of firm i's output q_i: $x_i = \mathrm{k} q_i$, k>0. If no environmental taxation is introduced, firms use technology D.

The marginal cost of production is c>0. No pollution abatement is possible with the old technology D: firms can reduce pollution only by reducing output. Nevertheless, firms can adopt a new and more flexible technology F characterized by abatement possibilities and a lower emission/output ratio.

[2] This last result is different from the one established by Carraro and Topa (1993, Theorem 9).

The new technology F is a multiple-product one that enables firms to produce an abatement good a_i jointly with output q_i. Firm i's residual emissions are: $x_i = kq_i - a_i$. Therefore, the new emission/output ratio k' is : $k'_i = (kq_i - a_i) / q_i \leq k$. The unit abatement cost d' is set equal to d/k>0 (i.e. d=kd'>0). Due to this unit cost, pollution is not automatically totally absorbed. Total abatement and emissions are respectively $A = a_1 + a_2$ and $X = x_1 + x_2$.

Pollution causes damages M(X) to both countries, which are a convex function of total emissions X :

$$M(X) = lX^2$$

λ>0 is greater as consumers give more importance to the environment protection.

When the regulators introduce an emission tax, firms could be induced to invest in R&D in order to adopt the cleaner technology. In such a case, each firm chooses the time at which the innovation will be available and in each period of time determines the abatement level and output. Generally speaking, we suppose that regulators announce the emission tax parameters at time 0. If the taxation scheme is adequately designed, firms react by being engaged in the innovation game, in which, each decides whether to innovate or not, and at which date.

Firm i, located in country i, is asked to pay a tax t_i(X) per unit of residual emission to regulator i. Notice that both in the cooperative and non-cooperative regimes, the tax rate is positively correlated to the total emissions because the damages in each country depend on the total emissions since we are dealing with an international environmental problem. Therefore, t_i(X)=$v_i X$, where the parameter v_i > 0 is chosen by regulator i, and the tax paid by firm i is $T_i(x_i, X) = v_i X x_i$.

The good produced has the following inverse demand function[3]:

$$P(Q) = \alpha - \beta Q \text{ with } Q = q_1 + q_2, \alpha > c + 3d \text{ and } \beta > 0 \qquad (1)$$

Firms can adopt the new technology within a period t from the beginning of the game by spending an actualized monetary amount ρ(t). This investment cost could comprise the R&D cost and/or the cost of purchasing and installing the new

[3] The restriction α>c+3d is necessary to make the tax parameter inferior to a positive value (see (A2) in Appendix 1).

technology. Thus, we will use the terms innovation and adoption interchangeably. Function ρ is decreasing due to the existence of freely-available scientific research permitting firms to reduce the cost of innovation as they delay its adoption, and it is convex because the innovation cost increases more rapidly when firms try to accelerate the adoption date.

The actualized cost at date 0 of adopting the cleaner technology at date t is[4] :

$$\rho(t) = be^{-mrt}, b > 0,\ m > 1,\ r > 0 \text{ is the discount rate} \tag{2}$$

For any v satisfying conditions (A1) and (A2) (see Appendix 1), we need b, m and r verify :

$$\frac{f^t_{FD} - f^t_{DD}}{mr} \leq b \tag{3}$$

where f^t_{FD} (resp. f^t_{DD}) is the profit of a firm when it has innovated while the other still uses the old technology (resp. no firm has innovated) in the presence of an emission tax. Since the tax parameter v, verifying conditions (A1) and (A2), is minored and majored by strictly positive numbers, then $f^t_{FD} - f^t_{DD}$ (given by (A8) in Appendix 2) is majored by a strictly positive number independent of v. Consequently, by choosing mr sufficiently high, inequality (3) is feasible.

Inequality (3) means that the cost of immediate innovation (ρ(0)=b) is relatively high. For it to be fulfilled when we decrease r to zero, we increase m so that mr remains constant. In so doing, the function ρ(t) does not change. The cost of innovation decreases more rapidly when m is greater.

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[4] Carraro and Topa (1993) impose a strong condition on the function ρ making the intertemporal objective functions of firms globally concave with respect to their arguments. This too strong condition is expressed in A.C (d) of page 14 and does not make it possible to prove the adoption by firms of the new technology within a finite time, unless the calculated limit (see proof of Theorem 1 that we can find in page 20 of Carraro and Topa (1991), and page 22 of the one of 1993) is incorrect. They also assume, but do not prove, that firms adopt the new technology at different dates (this critic is valid for the private optimal adoption dates and the socially optimal ones) as shown by their expressions defining the intertemporal objective functions of firms and regulators, which are not differentiable in $t_1 = t_2$ (expressions (9),(10a),(10b), (16), (25) and (26)). More precisely, they have ignored our expression (11). Our function ρ makes the intertemporal objective functions of firms locally concave with respect to their argument (i.e. we suppose a less strong condition).

The two firms autonomously decide on their own date of adoption of the new technology at the beginning of the innovation game (date 0), and there is nothing (such as informational spillover) that can induce them to change their strategy later (i.e. open-loop strategies).

When both firms use technology D, even in the presence of the emission tax , we have :

$$\Pi_i = \left[a - b(q_i + q_j)\right]q_i - (c + v_i kX)q_i = \left[a - (b + v_i k^2)(q_i + q_j) - c\right]q_i \tag{4}$$

$$i \neq j\ ,\ i\ ,\ j = 1\ ,\ 2$$

In the absence of the emission tax, the above expression is still valid by setting $v_i = 0$.

When both firms adopt the cleaner technology after the introduction of the tax, we have:

$$\begin{aligned}\Pi_i &= \left[a - b(q_i + q_j)\right]q_i - v_i X(kq_i - a_i) - cq_i - d/k.a_i \\ &= \left[a - (b + v_i k^2)(q_i + q_j) + v_i k(a_i + a_j) - c\right]q_i + \left[v_i k(q_i + q_j) - v_i(a_i + a_j) - d/k\right]a_i\end{aligned} \tag{5}$$

$$i \neq j\ ,\ i\ ,\ j = 1\ ,2$$

Lastly, we consider the case in which one of the two firms (for instance, firm 2) has innovated, whereas the other still produces using the old technology :

$$\Pi_1 = \left[a - b(q_1 + q_2)\right]q_1 - cq_1 - v_1 kXq_1 = \left[a - (b + v_1 k^2)(q_1 + q_2) + v_1 ka_2 - c\right]q_1 \tag{6}$$

$$\begin{aligned}\Pi_2 &= \left[a - b(q_1 + q_2)\right]q_2 - v_2 X(kq_2 - a_2) - cq_2 - d/k.a_2 \\ &= \left[a - (b + v_2 k^2)(q_1 + q_2) + v_2 ka_2 - c\right]q_2 + \left[v_2 k(q_1 + q_2) - v_2 a_2 - d/k\right]a_2\end{aligned} \tag{7}$$

In the cooperative regime, $v_c = v_1^c = v_2^c$ is the tax parameter set by the two regulators by maximizing their intertemporal joint social welfare. In the non-cooperative regime, each regulator i sets the domestic tax parameter v_i^{nc} by maximizing his intertemporal social welfare. However, having assumed symmetric model, we will prove in section 5 that the non-cooperative tax parameters are equals ($v_1^{nc} = v_2^{nc} = v_{nc}$).

Using the background induction principle, we solve the game between firms in the second stage, given a certain tax parameter. Then, we analyze the game between regulators which determines the optimal tax parameters under both regimes.

3. Innovating reactions of firms

Given the taxes imposed by regulators in the first stage, firms engage in a dynamic game of innovation, deciding whether to adopt the new technology or not, and if so at which date. Whether regulators cooperate or not is not relevant at this stage because symmetry implies that tax parameters are identical in each regime (we will prove it in section 5 for the non-cooperative regime). Therefore, we study the reactions of firms to a given tax parameter v.

We denote by f_{DD} and f^t_{DD} the firm profits when both use technology D without pollution tax and after the introduction of it, respectively. Once again, f^t_{FF} is the profit of a firm after both have innovated and f^t_{FD} is its profit when it has innovated while the other still uses the old technology. Lastly, f^t_{DF} is its profit when it still uses technology D, while the other has innovated. We designate by Φ the total profits.

At each period of time, equilibrium quantities are determined by computing the equilibrium of the production game between firms (see Appendix 1). Production levels -and abatement levels when the cleaner technology is used- are the optimal strategies of a Nash-Cournot duopoly game between firms.

We can rank all quantities, prices, emission/output ratios and profits in the four technological cases by using conditions (A1) and (A2) in Appendix 1 :

Output : $q_{DD} \geq q^t_{FD} > q^t_{FF} > q^t_{DF} = q^t_{DD} > 0 \qquad Q_{DD} > Q^t_{FF} > Q^t_{FD} > Q^t_{DD} > 0$

Price : $p^t_{DD} > p^t_{FD} > p^t_{FF} > p_{DD} > 0$

Abatement : $a^t_{FD} > a^t_{FF} > a^t_{DF} = a^t_{DD} = a_{DD} = 0 \qquad A^t_{FF} > A^t_{FD} > A^t_{DD} = A_{DD} = 0$

Emissions : $x_{DD} > x^t_{DD} = x^t_{DF} > x^t_{FF} > x^t_{FD} \geq 0 \qquad X_{DD} > X^t_{DD} > X^t_{FD} > X^t_{FF} > 0$

Emission/output ratios : $(x/q)_{DD} = (x/q)^t_{DD} = (x/q)^t_{DF} = k > (x/q)^t_{FF} > (x/q)^t_{FD} \geq 0$

Profits : $f_{DD} \geq f^t_{FD} > f^t_{FF} > f^t_{DF} = f^t_{DD} > 0 \qquad \Phi_{DD} > \Phi^t_{FD} > \Phi^t_{FF} > \Phi^t_{DD} > 0$

Production is highest without taxation (DD), and is lowest when regulators tax emissions and firms don't innovate. When innovation spreads within the industry, the impact of emission taxes is less serious because total emissions are lower and that is why total production increases. The profit squeeze induced by the emission taxes is much lower when firms adopt the cleaner technology.

To understand the innovation game, we analyze the situation where only one firm innovates (the FD/t case). The firm that adopts first gains substantially from innovation, exploiting the fact that the other must reduce production in order to limit the burden of the pollution tax. Residual emissions and the emission/output ratio are lower than in all other cases for the firm that innovates first. Consequently, production q_{FD}^{t} is higher than all the other cases and individual profit f_{FD}^{t} is relatively very high making the total profit Φ_{FD}^{t} higher than in the FF/t case, even if the profit of the non-innovating firm remains at the $f_{DF}^{t} = f_{DD}^{t}$ level. These reasons incite each firm to innovate first, but they should be compared to the cost of innovating sooner.

Firm 1's intertemporal objective function, when t_1 and t_2 are the adoption dates of respectively firm 1 and 2, is :

$$V_1(t_1,t_2) = \begin{cases} g_1^1(t_1,t_2) & if\ t_1 < t_2 \\ g_1^2(t_1,t_2) & if\ t_1 > t_2 \\ g(t) & if\ t_1 = t_2 \end{cases} \tag{8}$$

with,

$$g_1^1(t_1,t_2) = \int_0^{t_1} f_{DD}^{t} e^{-rt}\,dt + \int_{t_1}^{t_2} f_{FD}^{t} e^{-rt}\,dt + \int_{t_2}^{+\infty} f_{FF}^{t} e^{-rt}\,dt - r(t_1) \tag{9}$$

$$g_1^2(t_1,t_2) = \int_0^{t_2} f_{DD}^{t} e^{-rt}\,dt + \int_{t_2}^{t_1} f_{DF}^{t} e^{-rt}\,dt + \int_{t_1}^{+\infty} f_{FF}^{t} e^{-rt}\,dt - r(t_1) \tag{10}$$

$$g(t) = \int_0^{t} f_{DD}^{t} e^{-rt}\,dt + \int_{t}^{+\infty} f_{FF}^{t} e^{-rt}\,dt - r(t) \tag{11}$$

The payoff of firm 1 is $g_1^1(t_1,t_2)$ if it adopts first and $g_1^2(t_1,t_2)$ if firm 2 adopts first. Each firm receives g(τ) if they adopt simultaneously at $t = t_1 = t_2$. Theorem 1 shows that firms decide not to innovate simultaneously. Notice that $t_i = +\infty$ means that firm i never innovates.

Theorem 1. *Assume conditions (A1),(A2) and v£2l, then there exists two Nash equilibria of the innovation game between firms :*

$$(t_1^*, t_2^*) = (\hat{t}, \bar{t}) \text{ and } (t_1^*, t_2^*) = (\bar{t}, \hat{t}),\ 0 \le \hat{t} < \bar{t} < +\infty$$

These optimal adoption dates are accelerated by a higher taxation parameter.

Proof. See Appendix 2.

The innovation game is characterized by diffusion in adoption dates even if the model is symmetric and there is no uncertainty. Indeed, both firms have an incentive to adopt first with respect to the cases where they innovate simultaneously or do not innovate because $f_{FD}^t > f_{FF}^t > f_{DF}^t = f_{DD}^t$. This is because the first innovator has a lower emission/output ratio which enables it to produce more while polluting less and paying fewer emission taxes. Moreover, it exploits the fact that the non-innovating firm has to produce less for not paying important emission taxes. Nevertheless, the first will support higher R&D cost and, therefore, has to compare the competitive advantage from being first to the higher investment cost. Our comparison shows that it is profitable to adopt this cleaner technology first.

In what follows, the optimal adoption dates will be $t_1^* = \hat{t}$ and $t_2^* = \bar{t}$ where the subscripts 1 and 2 refer respectively to the firm that adopts first and second.

4. The cooperative regime

Using the Nash-perfect equilibrium concept, we derive the regulators optimal strategy that induces firms to adopt the cleaner technology at different dates.

By maximizing a joint intertemporal social welfare function, the two regulators decide whether to set a positive tax parameter or not, and if so, the optimal one. Regulators are supposed to be committed to carry on the agreed environmental policy[5].

The cooperating regulators joint social welfare at date t is the sum of the consumer welfare and firms profits in both countries :

$$\mathrm{W} = \mathrm{CS} + \Phi \tag{12}$$

[5] The problem of stability of such international environmental agreements is studied in Carraro and Siniscalco (1993) and Botteon and Carraro (1996).

Consumer welfare is defined as the sum of consumer surplus derived from the consumption of Q and of taxes, minus damages from the total pollution :

$$CS = \int_0^{Q^*} p(Q)\,dQ - p(Q^*)Q^* + t(X^*)X^* - M(X^*) \tag{13}$$

where Q^* and X^* are the optimal total output and emissions computed in stage two of the game.

Consequently, we have[6] :

$$W = \int_0^{Q^*} p(Q)dQ - cQ^* - \frac{d}{k}A^* - M(X^*) \tag{14}$$

We remark that taxes do not appear in the above expression as they are pure transfers from firms to consumers.

Total social welfare in the four technological cases are denoted by :

$$W(t=0) = W_{DD}\,,\ W(DD/t) = W_{DD}^t\ ,W(FF/t) = W_{FF}^t\,, W(FD/t) = W_{FD}^t\ = W_{DF}^t$$

The intertemporal total social welfare is :

$$\begin{cases} W^t \ \ if \ \ the\ \ two\ \ regulators\, set\ \ a\ \ tax \\ W^0\ if\ \ there\ is\ no\ tax \end{cases} \tag{15}$$

where,

$$W^t = W^t(t_1^*, t_2^*) = \int_0^{t_1^*} W_{DD}^t e^{-rt}\,dt + \int_{t_1^*}^{t_2^*} W_{FD}^t e^{-rt}\,dt + \int_{t_2^*}^{+\infty} W_{FF}^t e^{-rt}\,dt - r(t_1^*) - r(t_2^*) \tag{16}$$

$$W^0 = \int_0^{+\infty} W_{DD} e^{-rt}\ dt \tag{17}$$

Let's recall that t_1^* and t_2^* are the adoption dates of the first and second innovator, respectively.

Theorem 2. *Assume that the discount rate is sufficiently close to zero and* $l \in \left]l_1^c, l_{A2}^c\right]$, *then the optimal cooperative tax parameter is* $\overline{v}_c = \dfrac{4}{3}l$.

Proof. See Appendix 3.

[6] This general formulation comprises the (DD/t) configuration where the optimal abatement level A^* is zero.

It appears that cooperating regulators find it optimal to tax emissions if and only if consumers' sensitivity to the environment is sufficiently high. The upper bound l^{c}_{A2} implies non-negative residual emissions. Conditions (A1) and (A2) are satisfied by $\overline{v}_c$ when λ belongs to $\left]l^c_1, l^c_{A2}\right]$.

5. The non-cooperative regime

The social welfare of country i at date t is the sum of consumer welfare of the domestic residents and the profit of the domestic firm:

$$W_i = CS_i + f_i \tag{18}$$

The consumer surplus obtained by the consumption of Q is equally split between the two symmetric countries having the same market size. Since we deal with an international environmental problem, damages from total pollution are also equally split between the two symmetric countries. Thus, consumer welfare of country i at date t is defined as[7]:

$$CS_i = \frac{1}{2}\left[\int_0^{Q^*} p(Q)dQ - p(Q^*)Q^*\right] + t_i(X^*)x_i^* - \frac{1}{2}M(X^*) \tag{19}$$

We can then re-write country i's social welfare at date t as:

$$W_i = \frac{1}{2}\int_0^{Q^*} p(Q)\,dQ + \frac{1}{2}p(Q^*)\left[q_i^* - q_j^*\right] - cq_i^* - \frac{d}{k}a_i^* - \frac{1}{2}M(X^*) \tag{20}$$

We denote by W^t_{1i} the country i's intertemporal social welfare given that the domestic firm has innovated first, by W^t_{2i} when the domestic firm has innovated second and by W^0_i when there is no tax. Moreover, the instantaneous social welfare of country i in the different technological configurations is denoted by :

$$W_i(DD/t) = W^t_{DDi}, W_i(FF/t) = W^t_{FFi}, W_i(FD/t) = W^t_{FDi}, W_i(DF/t) = W^t_{DFi}, W_i(0) = W_{DDi}$$

[7] Expression (23) in Carraro and Topa (1993), defining the consumer welfare of each country, depends only on the domestic polluting emissions, which is in contradiction with the fact that we deal with an international environmental problem. Moreover, this equation is in contradiction with the hypothesis of symmetric countries having the same product market, because joint consumer surplus is not equally divided between the two countries.

Then, we have :

$$W_{1i}^t = \int_0^{t_1^*} W_{DDi}^t e^{-rt}\, dt + \int_{t_1^*}^{t_2^*} W_{FDi}^t e^{-rt}\, dt + \int_{t_2^*}^{+\infty} W_{FFi}^t e^{-rt}\, dt - r(t_1^*) \tag{21}$$

$$W_{2i}^t = \int_0^{t_1^*} W_{DDi}^t e^{-rt}\, dt + \int_{t_1^*}^{t_2^*} W_{DFi}^t e^{-rt}\, dt + \int_{t_2^*}^{+\infty} W_{FFi}^t e^{-rt}\, dt - r(t_2^*) \tag{22}$$

$$W_i^0 = \int_0^{+\infty} W_{DDi}\, e^{-rt}\, dt \tag{23}$$

In Appendix 4, we compute the equilibrium of the Nash-Cournot duopoly game on the product market, FF/t case, when competing regulators set their tax parameters separately. We choose the study of the FF/t case because if the taxes are well designed, firms will adopt the new technology and this situation will characterize the behavior of firms and regulators since it takes place for the longest and infinite period of time. In this non-cooperation case, ex-ante v_i may differ from v_j. It is easy to check that the equilibrium values are those calculated in Appendix 1 if $v_i = v_j = v$.

Proposition 1. *Suppose that firms adopt the new technology and (A11) is verified, then :*

· *Ex-ante total emissions of firms decrease with each tax parameter.*

· *Ex-ante profit of each firm decreases with the domestic tax parameter and increases with the foreign tax parameter.*

· *Ex-ante social welfare of each country decreases with the domestic tax parameter if* $v_i \geq l / 3$, *" i=1,2, and increases with the foreign tax parameter.*

Proof. See Appendix 4.

Proposition 1 shows that in the FF/t case, when a regulator raises his tax parameter, imposes a supplementary charge on the domestic firm inducing a loss of competitiveness, and therefore reduces his own social welfare. Moreover, when the foreign regulator increases his tax parameter, then total emissions decrease while the profit of the domestic firm and the home welfare increase. These results incite each regulator to reduce his own tax parameter and this competition, as we will prove it later, leads competing regulators to impose the same tax parameter, which is lower than the one obtained by cooperation.

Theorem 3. *Suppose that the discount rate is enough close to zero, then there exists a non-empty interval in* l *so that the optimal non-cooperative tax parameter is a symmetric one* $\overline{v}_{nc} = \frac{l}{3}$.

Proof. See Appendix 5.

We notice that the non-empty interval in λ ensure that conditions (A1) and (A2) are satisfied by $\overline{v}_{nc}$.

6. Cooperation versus non-cooperation

Before comparing the optimal tax parameters in the two regimes, it is necessary to verify that the comparison is actually feasible: there must exists a non-empty interval in λ so that regulators strictly prefer the optimal positive tax parameters previously determined in each regime.

Proposition 2. *If the discount rate is sufficiently close to zero,* $3d < a - c < 9d$ *and* $l \in L = \left] l^{nc}_{A1}, l^{c}_{A2} \right]$*, we have* $\overline{v}_c = \frac{4}{3} l$ *and* $\overline{v}_{nc} = \frac{l}{3}$.

Proof. See Appendix 6.

Notice that the lower and upper bound in λ are higher for the non-cooperative regime (see Appendix 6). Thus, in the non-cooperative regime, consumers valuation of environmental quality must be higher than under cooperation so that the two competing regulators find it profitable to tax emissions. This constitutes a free-riding behavior.

Proposition 2 shows that the optimal non-cooperative tax parameter is lower than the cooperative one. The intuition is the following: In the FF/t technological configuration, both the domestic profit and social welfare decrease when the domestic tax parameter is raised. Thus, a competing regulator does not want to penalize his firm nor decrease his social welfare. In addition, each competing regulator wants to free-ride on the tax imposed by the other because a higher foreign tax parameter reduces the environmental problem, increases the domestic profit and, as a global result, increases the domestic social welfare (see Proposition 1). These reasons yield a lower tax parameter than in the cooperative regime.

Proposition 3. *If the discount rate is enough near zero, $3d<a-c<9d$ and l Î L, then, in the cooperative regime, total abatement in the two countries and intertemporal total (and individual) social welfare are higher than under non-cooperation, whereas total residual emissions are lower.*

Proof: By calculating the partial derivatives of total abatement and total emissions with respect to v in the DD/t , FD/t and FF/t technological configurations, and using $\bar{v}_{nc} < \bar{v}_c$, the proof is easy for total abatement and emissions. Intertemporal total (and individual) welfare is higher under cooperation because Theorem 2 shows that $\bar{v}_c$ is the unique maximum of $W^t_{FF} = 2W^t_{FFi}$ (since $v_i = v_j$).

Let t_i^{*c} and t_i^{*nc} be respectively the private optimal adoption dates of cooperation and non-cooperation.

Proposition 4. *If the discount rate is sufficiently close to zero, $3d < a - c < 9d$, l Î L and the tax parameters set at $\bar{v}_c$ and $\bar{v}_{nc}$, then we have :*

$$t_1^{*nc} > t_1^{*c} \;,\; t_2^{*nc} > t_2^{*c}$$

Proof : Results of Theorem 1 make the proof immediate since $\bar{v}_c > \bar{v}_{nc}$.

Therefore, the lower optimal tax parameter in the non-cooperative regime has the further effect of delaying the adoption dates of firms because the gain from adopting the cleaner technology (in terms of lower taxes on residual emissions) is smaller compared to the cost of innovating earlier.

By using (A5), (A7) and (A8), we establish that :

$$t_2^{*c} - t_1^{*c} = t_2^{*nc} - t_1^{*nc} = \frac{\ln(4/9)}{(1-m)r}$$

Private diffusion is independent of the tax parameter and is, therefore, the same in the two regimes[8] . We think that this result is due to the specificity of the function ρ. However, it's lower when the cost of adopting the new technology decreases more rapidly (i.e. when m increases).

If competing regulators prefer to accelerate the adoption of the new technology, they can increase their tax parameters, particularly by setting them equal to $\bar{v}_c$ and so fully cooperate. They can also subsidize their firms in order to innovate sooner.

7. Conclusion

We study coordination of taxation and innovation by regulators for the protection of the international environment. We consider a symmetric model comprising two countries and two firms each located in one country. Firms by-produce pollution along with the same good sold in both countries, and can adopt a less polluting technology within a time t by incurring an actualized investment cost ρ(t). Damages in a country are brought about by total pollution of firms. We suppose that the cost of immediate adoption is relatively too high and the discount rate is enough low. An adequate environmental taxation induces firms to adopt the cleaner technology. We compare the effects of environmental taxation under the cooperative and non-cooperative regimes.

We find that environmental tax competition between regulators leads to an optimal tax parameter, which is lower than the one obtained through cooperation. This induces firms to adopt the friendly technology later than under cooperation. Consequently, residual emissions are higher and intertemporal individual social

[8] Carraro and Topa (1993, Theorem 9) have established a different result as they have shown that private diffusion is greater under cooperation.

welfare are lower without cooperation. We have established that there is diffusion of the less polluting innovation between firms. Furthermore, this private diffusion is independent of the regime.

Even though we dealt with an infinite horizon, thus avoiding more difficult computations, our conclusions remain valid for a sufficiently long finite horizon.

We have used a taxation scheme for each regulator depending on domestic and total emissions. A possible extension of this work is to consider the case where each taxation scheme depends only on domestic emissions. We think that this expresses a greater free-riding behavior of competing regulators. Another possible extension is to consider that damages caused to the environment are due to the stock of pollution rather than the flow of pollution. It is also interesting to know if the current results are robust to increasing the number of regulators and firms.

Acknowledgements

A previous version of this paper has been presented at the Warwick/IFS/ESRC conference on ''Theoretical Environmental Economics and Economies in Transition'' held at Warwick University on May 27-29, 1999. I gratefully acknowledge financial support from the Warwick University to participate at the conference. I am also very grateful to John Conley, Drew Fudenberg, Faysal Mansouri, and Myrna Wooders as well as participants at the conference for their useful suggestions. All remaining mistakes are mine.

Appendix 1

Case DD without taxation

$$q_1^* = q_2^* = \frac{a-c}{3b} = q_{DD} \quad , \quad Q^* = \frac{2(a-c)}{3b} = Q_{DD} \quad , \quad p^* = p(Q^*) = \frac{a+2c}{3} = p_{DD}$$

$$a_1^* = a_2^* = 0 = a_{DD} \quad , \quad x_1^* = x_2^* = \frac{k(a-c)}{3b} = x_{DD} \quad , \quad X^* = \frac{2k(a-c)}{3b} = X_{DD}$$

$$\Pi_1^* = \Pi_2^* = \frac{(a-c)^2}{9b} = f_{DD} \quad , \quad \Phi_{DD} = 2f_{DD} = \frac{2(a-c)^2}{9b}$$

The emission/output ratio is $(x / q)_{DD} = k$.

Case DD with taxation

We define β′=β+vk^2, then :

$$q_1^* = q_2^* = \frac{a-c}{3b'} = q_{DD}^t \quad , \quad Q^* = \frac{2(a-c)}{3b'} = Q_{DD}^t \quad , \quad p^* = p(Q^*) = \frac{a\,(b+3vk^2)+2bc}{3b'} = p_{DD}^t$$

$$a_1^* = a_2^* = 0 = a_{DD}^t \quad , \quad x_1^* = x_2^* = \frac{k(a-c)}{3b'} = x_{DD}^t \quad , \quad X^* = \frac{2k(a-c)}{3b'} = X_{DD}^t$$

$$\Pi_1^* = \Pi_2^* = \frac{(a-c)^2}{9b'} = f_{DD}^t \quad , \quad \Phi_{DD}^t = 2f_{DD}^t = \frac{2(a-c)^2}{9b'}$$

The emission/output ratio is $(x/q)_{DD}^t = k$.

Case FF with taxation

$$q_1^* = q_2^* = \frac{a-c-d}{3b} = q_{FF}^t \quad , \quad Q^* = \frac{2(a-c-d)}{3b} = Q_{FF}^t \, , \quad p^* = p(Q^*) = \frac{a+2(c+d)}{3b} = p_{FF}^t$$

$$a_1^* = a_2^* = \frac{vk^2(a-c)-b'd}{3bvk} = a_{FF}^t \quad , \quad A^* = \frac{2\left[vk^2(a-c)-b'd\right]}{3bvk} = A_{FF}^t$$

$$x_1^* = x_2^* = \frac{d}{3vk} = x_{FF}^t \quad , \quad X^* = \frac{2d}{3vk} = X_{FF}^t$$

$$\Pi_1^* = \Pi_2^* = \frac{(a-c-d)^2}{9b} + \frac{d^2}{9vk^2} = f_{FF}^t \quad , \quad \Phi_{FF}^t = 2f_{FF}^t = \frac{2(a-c-d)^2}{9b} + \frac{2d^2}{9vk^2}$$

The emission/output ratio is $(x/q)_{FF}^t = \dfrac{bd}{vk(a-c-d)} < k$.

$$a_{FF}^t > 0 \;\; iff \;\; vk^2(a-c) > b'd \quad i.e. \quad v > v_{A1} = \frac{bd}{k^2(a-c-d)} \tag{A1}$$

Therefore, to induce firms to abate a strictly positive amount of emissions, the tax parameter must be high enough. The minimum tax parameter necessary decreases with α and k, and increases with c and d. In addition, (A1) implies that the tax rates verify: $t_{DD} > t_{FD} = t_{DF} > t_{FF}$. We can check that abatement increases with v, whereas residual emissions, emission/output ratios and firms profits decrease with v.

Case FD with taxation

$$q_1^* = \frac{a-c}{3b'} = q_{DF}^t \;\; , \;\; q_2^* = \frac{vk^2(a-c)-b'd}{2bb'} + \frac{a-c}{3b'} = q_{FD}^t \;\; , \;\; Q^* = \frac{vk^2(a-c)-b'd}{2bb'} + \frac{2(a-c)}{3b'} = Q_{FD}^t$$

$$p^* = p(Q^*) = \frac{(2b+3vk^2)a+(4b+3vk^2)c+3b'd}{6b'} = p_{FD}^t$$

$$a_1^* = 0 = a_{DF}^t \quad , \quad a_2^* = \frac{vk^2(a-c)-b'd}{2bvk} = a_{FD}^t = A_{FD}^t$$

$$x_1^* = \frac{k(a-c)}{3b'} = x_{DF}^t \quad , \quad x_2^* = \frac{3b'd - vk^2(a-c)}{6b'vk} = x_{FD}^t \quad , \quad X^* = \frac{vk^2(a-c)+3b'd}{6b'vk} = X_{FD}^t$$

$$\Pi_1^* = \frac{(a-c)^2}{9b'} = f_{DF}^t \quad , \quad \Pi_2^* = \frac{\left[vk^2(a-c) - b'd\right]^2}{4bb'vk^2} + \frac{(a-c)^2}{9b'} = f_{FD}^t$$

$$\Phi_{FD}^t = f_{DF}^t + f_{FD}^t = \frac{\left[vk^2(a-c) - b'd\right]^2}{4bb'vk^2} + \frac{2(a-c)^2}{9b'}$$

The emission/output ratio of firm 1 is $(x/q)_{DF}^t = k$.

The emission/output ratio of firm 2 is $(x/q)_{FD}^t = \dfrac{b\left[3b'd - vk^2(a-c)\right]}{3v^2k^3(a-c) - 3b'dvk + 2bvk(a-c)} < k$.

$$x_{FD}^t \geq 0 \quad iff \quad 3b'd \geq vk^2(a-c) \quad i.e. \quad v \leq v_{A2} = \frac{3bd}{k^2(a-c-3d)} \tag{A2}$$

Therefore, the tax parameter must not exceed a certain value for the first innovator not to abate more than it pollutes.

By combining conditions (A1) and (A2), we get the set to which belongs the tax parameter :

$$v \in A(v) = \left]v_{A1}, v_{A2}\right] \tag{A3}$$

Appendix 2

In this appendix we give the proof of Theorem 1. Since expressions (9) and (10) are not differentiable in $t_1 = t_2 = t$, then, first, we derive the optimal adoption dates when $t_1 \neq t_2$ (diffusion). After that, using expression (11), we derive the optimal simultaneous adoption date. Finally, we compare the intertemporal payoffs of firms given by diffusion and simultaneous adoption.

• Assume that firms decide to innovate at different dates and that firm 1 is the first innovator (the situation where firm 2 is the first adopter is symmetric).

Firm 1 maximizes $V_1(t_1,t_2) = g_1^1(t_1,t_2)$, given by (9), with respect to t_1 :

$$\frac{\partial V_1(t_1^*,t_2^*)}{\partial t_1} = (f_{DD}^t - f_{FD}^t)e^{-rt_1^*} - r'(t_1^*) = 0 \tag{A4}$$

The resolution of (A4) and expressions (2) and (3) give :

$$t_1^* = \frac{\ln\left[(f_{FD}^t - f_{DD}^t)/bmr\right]}{(1-m)r} \geq 0 \tag{A5}$$

Using (A4) and the expression of ρ(t), second order condition becomes :

$$\frac{\partial^2 V_1(t_1^*,t_2^*)}{\partial t_1^2} = -r(f_{DD}^t - f_{FD}^t)e^{-rt_1^*} - r''(t_1^*) = (1-m)bmr^2e^{-mrt_1^*} < 0$$

Firm 2 maximizes $V_2(t_1,t_2) = g_2^2(t_1,t_2)$, given by (10) expressed for firm 2, with respect to t_2 :

$$\frac{\partial V_2(t_1^*,t_2^*)}{\partial t_2} = (f_{DF}^t - f_{FF}^t)e^{-rt_2^*} - r'(t_2^*) = 0 \tag{A6}$$

The resolution of (A6) gives :

$$t_2^* = \frac{\ln\left[(f_{FF}^t - f_{DF}^t)/bmr\right]}{(1-m)r} \tag{A7}$$

Using (A6) and the expression of ρ(t), second order condition becomes :

$$\frac{\partial^2 V_2(t_1^*,t_2^*)}{\partial t_2^2} = -r(f_{DF}^t - f_{FF}^t)e^{-rt_2^*} - r''(t_2^*) = (1-m)bmr^2 e^{-mrt_2^*} < 0$$

Using the expressions in Appendix 1 :

$$f_{FD}^t - f_{DD}^t = \frac{\left[vk^2(a-c) - b'd\right]^2}{4bb'vk^2} > 0 \text{ and } f_{FF}^t - f_{DF}^t = \frac{\left[vk^2(a-c) - b'd\right]^2}{9bb'vk^2} > 0 \tag{A8}$$

Consequently, $\frac{\partial t_1^*}{\partial v} < 0$, $\frac{\partial t_2^*}{\partial v} < 0$ and $0 \le t_1^* < t_2^* < +\infty$ as we have supposed.

• Assume that firms decide to innovate simultaneously, then, each firm i maximizes $V_i(t_1,t_2) = V_i(t) = g(t)$, given by (11), with respect to τ. We obtain[9] :

$$t^* = \frac{\ln\left[(f_{FF}^t - f_{DD}^t)/bmr\right]}{(1-m)r} > 0 \tag{A9}$$

• In the following we will show that the case in which firms innovate simultaneously is not a Nash equilibrium of the innovation game.

Let's remark that $t_2^* = t^*$ (because $f_{DD}^t = f_{DF}^t$) meaning that the second innovator (firm 2) adopts at the same date of the simultaneous adoption. From (10) and (11) expressed for firm 2, we have $V_2(t_1^*,t_2^*) = V_2(t^*)$. Therefore, each firm is indifferent between being the second innovator or innovating simultaneously. Concerning the first innovator (firm 1), we should compare $V_1(t_1^*,t^*)$ and $V_1(t^*)$. By using expressions (9) and (11), we have :

$$V_1(t_1^*,t^*) - V_1(t^*) = \left[\frac{1}{r}(f_{FD}^t - f_{DD}^t)e^{-rt_1^*} - be^{-mrt_1^*}\right] + \left[\frac{-1}{r}(f_{FD}^t - f_{DD}^t)e^{-rt^*} + be^{-mrt^*}\right]$$

Expressions in (A8) imply $f_{FD}^t - f_{DD}^t = \frac{9}{4}(f_{FF}^t - f_{DD}^t)$ and using (A5) and (A9) :

$$V_1(t_1^*,t^*) - V_1(t^*) = b\left(\frac{f_{FF}^t - f_{DD}^t}{bmr}\right)^{\frac{m}{m-1}}\left[(m-1)\left(\frac{9}{4}\right)^{\frac{m}{m-1}} - \frac{9}{4}m + 1\right]$$

This last difference is strictly positive iff f(m)>0, where function f is :

[9] Second order condition is satisfied by using the first order one.

$$f(x) = (x-1)e^{\frac{x}{x-1}\ln\frac{9}{4}} - \frac{9}{4}x + 1 \ , \quad \forall x > 1$$

We have $f'(x) = \left(1 - \frac{\ln(9/4)}{x-1}\right)e^{\frac{x}{x-1}\ln\frac{9}{4}} - \frac{9}{4}$ and $f''(x) = \frac{(\ln(9/4))^2}{(x-1)^3}e^{\frac{x}{x-1}\ln\frac{9}{4}} > 0$

Thus, f′ is strictly increasing with $\lim\limits_{1^+} f'(x) = -\infty$ and $\lim\limits_{+\infty} f'(x) = 0$. Hence, f′(x) < 0 i.e. f is strictly decreasing with $\lim\limits_{1^+} f(x) = +\infty$ and $\lim\limits_{+\infty} f(x) = \frac{9}{4}\left(\ln(9/4) - 1\right) + 1$ >0. Consequently, $f(x) > 0 \ , \ \forall x > 1$.

It's clear that each firm prefers to innovate first than innovating simultaneously. Thus, the situation in which the two firms adopt simultaneously is not a Nash equilibrium as one firm can deviate by innovating first. This innovation game is then characterized by two possible Nash equilibria in which one firm innovates before the other and gains more.

Appendix 3

To prove Theorem 2, first, we give a Lemma which shows that $\overline{v}_c = \frac{4}{3}l$ maximizes intertemporal total social welfare W^t when regulators set a tax. Second, we compare $W^t(\overline{v}_c)$ and W^0 (no environmental tax), to know if regulators should tax emissions. This comparison will show that $W^t(\overline{v}_c) > W^0$ when λ ∈ $\left]l_1^c \, , \, l_{A2}^c\right]$. Finally, we compare this last interval with A(v) (given by (A3)) expressed in λ to insure the feasibility of the solution.

Lemma 1. Assume (A1),(A2),v£2l and the discount rate is enough close to zero, then $\overline{v}_c = \frac{4}{3}l$ *maximizes the intertemporal total social welfare* W^t.

Proof : When conditions (A1),(A2) and v≤2λ are satisfied, Theorem 1 states that firms adopt the cleaner technology at finite but different dates. Assume further that the discount rate is enough close to zero. Since the time horizon is infinite, the maximization of W^t can be reduced to the maximization of W_{FF}^t because:

$$\lim_{r \to 0^+} \int_{t_2^*}^{+\infty} W_{FF}^t e^{-rt}\, dt = +\infty \quad \text{whereas} \quad \lim_{r \to 0^+} \left[\int_0^{t_1^*} W_{DD}^t e^{-rt}\, dt + \int_{t_1^*}^{t_2^*} W_{FD}^t e^{-rt}\, dt - r(t_1^*) - r(t_2^*) \right] < +\infty$$

From expression (14) and the results of cases DD and FF/t in Appendix 1, we have :

$$W_{DD} = \frac{4(a-c)^2(b - lk^2)}{9b^2} \quad \text{and} \quad W_{FF}^t = \frac{4(a-c-d)^2}{9b} + 2\left(\frac{d}{3vk}\right)^2 (3v - 2l) \qquad \text{(A10)}$$

The maximization of W_{FF}^t with respect to v gives $\overline{v}_c = \frac{4}{3}l$.

For the same previously cited reasons, to compare $W^t(\overline{v}_c)$ and W^0, we simply compare $W_{FF}^t(\overline{v}_c)$ and W_{DD}:

$$W_{FF}^t(\overline{v}_c) - W_{DD} = \frac{16k^4(a-c)^2 l^2 - 16bdk^2[2(a-c)-d]l + 9b^2d^2}{36b^2k^2 l}$$

So, $W_{FF}^t(\overline{v}_c) - W_{DD} > 0$ iff $l \in]0,\ l_0^c[\cup]l_1^c, +\infty[$ where :

$$l_0^c = \frac{bd\left[4(a-c) - 2d - \sqrt{[7(a-c)-2d](a-c-2d)}\right]}{4k^2(a-c)^2} > 0$$
$$l_1^c = \frac{bd\left[4(a-c) - 2d + \sqrt{[7(a-c)-2d](a-c-2d)}\right]}{4k^2(a-c)^2} > l_0^c$$

Moreover, the above condition on λ (or v) must be compatible with conditions (A1) and (A2).

When $v = \overline{v}_c$, conditions (A1) and (A2) become $l \in \left]l_{A1}^c,\ l_{A2}^c\right]$ with :

$$l_{A1}^c = \frac{3bd}{4k^2(a-c-d)} < l_{A2}^c = \frac{9bd}{4k^2(a-c-3d)}$$

We get the following classifying by using α - c > 3d :

$$0 < l_0^c < l_{A1}^c < l_1^c < l_{A2}^c$$

Therefore, $W^t(\overline{v}_c) > W^0$ iff $l \in \left]l_1^c, l_{A2}^c\right]$.

Appendix 4

Each firm i maximizes Π_i, given by expression (5), with respect to q_i and a_i. By solving the system of four equations and four unknown factors, we obtain[10]:

$$q_{FFi}^t = \frac{a-c-d}{3b} \quad , \quad a_{FFi}^t = \frac{k(a-c-d)}{3b} - \frac{d(2v_j - v_i)}{3kv_iv_j} \quad , \quad x_{FFi}^t = \frac{d(2v_j - v_i)}{3kv_iv_j}$$

$$f_{FFi}^t = \frac{(a-c-d)^2}{9b} + \frac{d^2(2v_j - v_i)^2}{9k^2v_iv_j^2} \quad , \quad CS_{FFi}^t = \frac{(a-c-d)^2}{9b} + \frac{d^2(v_i+v_j)\left[2v_i(2v_j - v_i) - l(v_i+v_j)\right]}{18k^2v_i^2v_j^2}$$

$$W_{FFi}^t = \frac{2(a-c-d)^2}{9b} + \frac{d^2\left[6v_iv_j(2v_j - v_i) - l(v_i+v_j)^2\right]}{18k^2v_i^2v_j^2}$$

To obtain non-negative values of emissions and abatement, we need, respectively :

$$v_i < 2v_j \text{ and } v_i > \frac{3bd}{k^2(a-c-d)} \quad , \forall\, i,j = 1,2 \qquad \text{(A11)}$$

[10] Second order conditions are satisfied.

All the other results of Proposition 1 are easily obtained by calculating partial derivatives and by using conditions (A11).

Appendix 5

This proof follows very closely that of Theorem 2.

Lemma 2. If regulators decide to tax emissions and the discount rate is sufficiently close to zero, then the taxation game between regulators has a dominant symmetric perfect Nash equilibrium $\overline{v}_{nc} = \frac{l}{3}$.

Proof : To know if firms will adopt the new technology F under the emission tax parameters v_i and v_j, we need to compare f^t_{FDi} to f^t_{DDi} and f^t_{FFi} to f^t_{DFi}, while supposing the discount rate enough close to zero. To avoid difficult computations, we can choose between two solutions. The first is to look for the symmetric non-cooperative equilibria $v_i = v_j = v$. In such a case, Theorem 1 states that firms will adopt the cleaner technology at different dates (if (A1), (A2) and $v \leq 2\lambda$ are verified). The second is to assume that firms, under the emission tax parameters v_i and v_j, will adopt the new technology. We choose this last solution (and prove the first) as we think that firms will adopt the friendly technology because the present value cost of adopting it at date t is a finite value (majored by $\rho(0)$), and that firms would take advantage from the tax environmental policy since they behave for an infinite horizon with a discount rate sufficiently close to zero (i.e. they give relatively great importance to their future payoffs). As for regulators, they want to induce firms to adopt the cleaner technology in order to produce more with less pollution. We think that a free-riding behavior of regulators does not affect the adoption of the new technology but affects the adoption dates which will be delayed.

If the discount rate is enough near zero, we can reduce the maximization of the intertemporal social welfare of regulator i to the maximization of W^t_{FFi}. Thus, regulator i maximizes W^t_{FFi}, given in Appendix 4, with respect to v_i taking as given v_j.

We get the following reaction functions[11]: $v_i = h(v_j) = \frac{l v_j}{6 v_j - l}$.

So, all (v_i, v_j) verifying (A11), $v_i = h(v_j)$ and $6v_i - l > 0$, i, j=1, 2, are potential equilibria. But which of them are really fulfillable ?

[11] Second order conditions are verified iff $6v_j - l > 0$, j =1, 2.

Since $W^t_{FF}(v_i, h(v_i)) = W^t_{FFi}(v_i, h(v_i)) + W^t_{FFj}(v_i, h(v_i)) = \dfrac{4(a-c-d)^2}{9b} - \dfrac{2d^2}{lk^2}$, total social welfare in the FF/t technological configuration is independent of v_i and v_j when $v_j = h(v_i)$.

On the other hand, we have $W^t_{FFi}(v_i, v_j) - W^t_{FFj}(v_i, v_j) = \dfrac{d^2(v_j - v_i)}{k^2 v_i v_j} = \begin{cases} 0 & \textit{iff} \;\; v_i = v_j \\ > 0 & \textit{iff} \;\; v_i < v_j \end{cases}$

Therefore, each regulator is tempted to set a domestic tax parameter lower than that of the other in order to get a higher share of the constant total social welfare (FF/t case). It appears that the taxation game between regulators has a dominant symmetric perfect Nash equilibrium: $v_i = v_j = \overline{v}_{nc} = \dfrac{l}{3}$. Let's recall that Theorem 1 concerns the symmetric tax parameters. So, when $v_i \neq v_j$, it is not sure that firms will adopt the cleaner technology and, in this respect, are not surely Nash equilibria.

Lemma 2 shows that $\overline{v}_{nc} = \dfrac{l}{3}$ is a dominant perfect Nash equilibrium for the environmental taxation game between regulators when they tax pollution. In the following, we will show that there exists a non-empty interval in λ for which taxation is preferred i.e. $W^t_i(\overline{v}_{nc}) > W^0_i$.

Because of symmetry, $W^t_{FFi}(\overline{v}_{nc}) = 1/2 W^t_{FF}(\overline{v}_{nc})$ and $W_{DDi} = 1/2 W_{DD}$ can be obtained from (A10).

Once again, we simply evaluate :

$$W^t_{FFi}(\overline{v}_{nc}) - W_{DDi} = \frac{2k^4(a-c)^2 l^2 - 2bk^2 d\left[2(a-c)-d\right]l - 9b^2d^2}{9k^2b^2l}$$

The numerator of the above fraction has two roots in λ:

$$l^{nc}_0 = \frac{bd\left[2(a-c) - d - \sqrt{\left[2(a-c)-d\right]^2 + 18(a-c)^2}\right]}{2k^2(a-c)^2} < 0$$

$$l^{nc}_1 = \frac{bd\left[2(a-c) - d + \sqrt{\left[2(a-c)-d\right]^2 + 18(a-c)^2}\right]}{2k^2(a-c)^2} > 0$$

Hence, $W^t_{FFi}(\overline{v}_{nc}) - W_{DDi} > 0$ iff $l > l^{nc}_1$.

If $v = \overline{v}_{nc} = \lambda/3$, conditions (A1) and (A2) become respectively :

$$l > l^{nc}_{A1} = \frac{3bd}{k^2(a-c-d)} \quad \text{and} \quad l \leq l^{nc}_{A2} = \frac{9bd}{k^2(a-c-3d)}$$

Therefore, a positive tax parameter is beneficial iff $l \in \left]l^{nc}_1, +\infty\right[\cap \left]l^{nc}_{A1}, l^{nc}_{A2}\right]$.

By calculating the difference $l^{nc}_{A2} - l^{nc}_1$, we can show that $l^{nc}_1 < l^{nc}_{A2}$.

We can also prove that $l^{nc}_{A1} < l^{nc}_1$ iff $a - c > (6 + \sqrt{31})d$.

Thus, the non-empty interval in λ for which $W^t_i(\overline{v}_{nc}) > W^0_i$ is :

$\left]l_{A1}^{nc}, l_{A2}^{nc}\right]$ if $3d < a - c \le (6+\sqrt{31})d$ and $\left]l_1^{nc}, l_{A2}^{nc}\right]$ if $a - c > (6+\sqrt{31})d$

Appendix 6

We can sum up the results of Appendix 3 and 5 as follows :

• In the cooperative regime: if $l \in \left]l_1^c, l_{A2}^c\right]$, then $\bar{v}_c = 4l/3$.

• In the non-cooperative regime: $\begin{cases} if \quad a-c > (6+\sqrt{31})d \quad and \quad l \in \left]l_1^{nc}, l_{A2}^{nc}\right], \quad then \quad \bar{v}_{nc} = l/3 \\ if \quad 3d < a-c \le (6+\sqrt{31})d \quad and \quad l \in \left]l_{A1}^{nc}, l_{A2}^{nc}\right], \quad then \quad \bar{v}_{nc} = l/3 \end{cases}$

Suppose 3d<α-c<9d, then we have the following ranking :

$$0 < l_1^c < l_1^{nc} < l_{A1}^{nc} < l_{A2}^c < l_{A2}^{nc}$$

Thus, if $l \in \left]l_{A1}^{nc}, l_{A2}^c\right]$ and 3d<α-c<9d, we have $\bar{v}_c = 4l/3$ and $\bar{v}_{nc} = l/3$.

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