Tax differentials and environmental R&D strategic alliances *

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Abstract

1 Introduction

Government regulations provide powerfull incentives for firms to invest in environmental research and development. While a significant part of environmental innovations are autonomous, most of them can be appropriately described as induced[1]. It is well-known that firms have little incentives to invest in environmental R&D in the absence of environmental regulations. However, environmental policy interventions (e.g., effluent charges) render emissions more expensive and changes in relative prices incite firms to reduce emission intensity by substituting non-polluting inputs for polluting inputs and clean production processes for dirtier

****Premilinary version**

[1] Recent empirical evidences tend to support the view that environmental policy instruments induce innovation. The reader is referred to Landjouw and Mody (1996), Jaffe and Palmer (1997) and Brunnermeier and Cohen (2003). See also the excellent survey by Jaffe, Newell and Stravins (2002).

processes. Since innovation affects directly substitution possibilities, firms tend to respond to stricter environmental policies by an increase in R&D investments.

However, even if it acts as a spur to innovation[2], environmental policy alone will usually fail to direct enough resources to environmental R&D. The reason is twofold. First, firms may respond to government regulations by a reduction in output (and not an increase in R&D efforts). Second, economic incentives stemming from environmental policies may not prove sufficient to fill the gap between perceived private and social returns to R&D – a potential source of market failure on the innovation market.

In order to encourage innovation, governments have several policy pathways at their disposal. A first avenue is to reduce the cost of undertaking environmental innovation. For example, the government may grant R&D subsidies to the firms. A second avenue is to ensure that the innovator will be fully rewarded for her R&D efforts. This can be achieved through a strengthening of patent laws that garantees to the innovator monopoly righs on her innovation. The last avenue is to relax antitrust policies in order to allow firms to engage in collaborative R&D and benefit from the internalisation of knowledge spillovers, economies of scope and economies of scale. In actual practive, governments tend to use these policies in combination.

In recent years, the relaxation of antitrust policies in the US, Japan and Europe has had a dramatic impact upon the innovation market. This policy has resulted in a major increase in the number of strategic research partnerships through which firms undertake R&D. Empirical works (e.g., Hagedoorn (1996) et Hagedoorn et al. (2000)) have highlighted that this development has been accompanied by a significant change in the nature of partnerships. While traditionally innovation has been pursued through equity-based research joint ventures, now most of partnerships take the form of non-equity based joint R&D and technology sharing agreements.

The starting point of this paper is the recognition that little is known about the impact of environmental regulations on the structure of environmental R&D collaboration networks. To the best of our knowledge, it is the first attempt to

[2]That expression is borrowed from Hicks (1932) who pioneered the view that changes in relative factor prices provide firms with incentives to innovate.

characterize how environmental regulations affect firms' incentives to sign bilateral environmental R&D agreements. In the last two decades, new approaches have been developed to analyse the endogeneous formation and stability of partnerships networks[3]. These approaches differ with respect to their assumptions, research questions and methodologies. A first body of litterature studies the formation of *multilateral* agreements through *non-cooperative games of link formation*. Qin (1996), Dutta *et al.* (1998) and Bala and Goyal (2000) analyse stable multilateral agreements as the outcome of a non-cooperative games of link formation in which all players announce simultaneously the set of links they want to form. A more recent strand of litterature studies the formation of *bilateral* agreements. Goyal and Joshi (2003) study the formation of bilateral cost-reducing alliances under price and quantity competition. They identify stable network structures using the concept of Pairwise Stability, initially introduced by Jackson and Wolinsky (1996). Their analysis shows that the structure of stable networks depends on the nature of the market competition. Under *moderate* competition (e.g., Cournot or differentiated product markets), a firm always has an incentive to form a bilateral alliance. As a result, the unique stable network is the complete graph. By contrast, under *agressive* competition (Bertrand oligopoly) the unique stable network is the empty network.

Our paper is closely related to that second strand of litterature. A first difference with respect to Goyal and Joshi (2003) concerns the kind of R&D activities we consider. They study bilateral agreements through which two firms simultaneously reduce their marginal production cost whereas we assume that firms form bilateral environmental R&D agreements to reduce their emissions and, thereby, their *effectiv*e marginal cost. A second difference is that we consider an industry located in two different economic regions that impose different tax rates on polluting emissions. Therefore, firms belonging to different juridictions differ in their *effective* marginal production cost. By contrast, Goyal and Joshi (2003) consider *ex-ante* identical firms.

We show that when firms compete a la Cournot and the tax differential is small enough the unique stable network structure is the complete graph. This result is

[3] See Bloch (2002) for a selective survey of the litterature on coalition and network formation in industrial organization.

consistent with Goyal and Joshi (2003). However, when the tax differential is large enough the only stable graph is a segmentation of the graph in two disjoint parts. Inside a given region, all pair of firms sign bilateral R&D agreements whereas pairs of firms located in different regions do not form collaboration links. In other words, a large tax differential prohibits the formation of interregional R&D agreements.

The rest of the paper is organized as follows. Section 1 describes the model while sections 2 and 3, analyse environmental R&D networks in which firms sign bilateral agreements to reduce their rate of emission by unit of output. In Section 2, we suppose that the rate of emission is linearly decreasing in the number of links formed by each firm. In Section 3, we relax the linearity assumption and allow for a quadratic reduction in the rate of emission. The last section contains concluding comments.

2 The Model

Consider a two-region (A and B) economy with each region administered by a different government. These regions export a polluting homogeneous good q on a world market. It is assumed that regions A and B are the sole suppliers for this good and the oligopolistic industry produces only for export. The industry comprises n identical firms, of which n_A are located in region A and n_B in region B. We denote by N_A (N_B) the set of firms that are based in zone A (B) and by $N = N_A + N_B$ the whole industry. Entry on the market is assumed to be effectively blocked. Let q_i denotes firm i's output and $Q = \sum_{i=1}^{n} q_i$ the aggregate industry-output. Assumming transportation costs negligible, the inverse demand function is

$$P(Q) = \alpha - \beta Q. \tag{1}$$

All firms have constant marginal production costs c and face a pollution tax $\tau_i \geq 0$ on every unit of pollution they emit.

Production generates polluting emissions which we assume to be proportional to output. In both regions, the initial rate of emissions by unit of output is assumed to be equal to s_0. It is assumed that individual producers have no technology available for abating pollution. However, firms can make a more effective use of their technology and reduce their emissions through collaborative R&D and information exchange. We assume that each pair of firms $(i, j) \in N$ can form a bilateral collaboration link in order to reduce its ratio of emissions per unit of output. The structure of collaborations between firms is represented by a non-directed graph g. Formally, g is thus a pair (N, L) where N is the set of firms and L is the set of linked pairs in N. We denote by G the set of all non-directed graphs defined on N. Also, let us denote by $\eta_i(g)$ the number of links that firm i has formed in some graph g. Firm i's unitary rate of emission is assumed to be decreasing in $\eta_i(g)$. Therefore, firm i's rate of emissions per unity of output is given by $\varepsilon_i(g) = \varepsilon_i(\eta_i(g))$ and satisfies

$$\varepsilon_i(0) = s_0 \text{ and } \varepsilon_i(\eta_i(g)) > \varepsilon_i(\eta_i(g)+1) \geq 0, \quad \forall i \in N, \forall g \in G. \tag{2}$$

We assume that governments in both regions levy differentiated emission taxes τ_i $(i \in \{A, B\})$ in order to mitigate polluting emissions. The discrepancy between τ_A and τ_B may result from different environmental awareness or possibly strategic distortions. In presence of taxation, firm i's profit level is given by

$$\pi_i(q_i, q_{-i}) = (\alpha - \beta Q)\, q_i - c_i^e(g) q_i \tag{3}$$

where $c_i^e(g) = (c + \tau_i \varepsilon_i(g))$ is the *effective* marginal cost of firm i. Therefore, any network g defines a cost configuration $\{c_i^e(g)\}_{i \in N}$. Finally, we assume that firms have complete information about market structure and competitors' technology. They face no capacity constraints and have already incurred some sunk cost that prevents entry of new firms.

Let us introduce additional notations. We shall write $g_{i,j} = 1$ if some pair $(i, j) \in N$ is linked in g and $g_{i,j} = 0$ if it is not linked in g. The graph $g + g_{ij}$ (respectively, $g - g_{ij}$) is the graph g augmented by (respectively, less) the link between $(i,\ j)$. Therefore, the graphs $g^A = \{g_{i,j} = 1, \forall i, j \in N_A$ and $g_{i,j} = 0$, otherwise$\}$, $g^B = \{g_{i,j} = 1, \forall i, j \in N_B$ and $g_{i,j} = 0$, otherwise$\}$ and $g^c = \{g_{i,j} = 1, \forall i, j \in N_B$ and $g_{i,j} = 0$, otherwise$\}$ are respectively the complete graph defined on N_A, N_B and N. Finally, we denote by "/" the operation of set substraction. For example, $N/\{i\} = \{1, 2, ..., i-1, i+1, ..., n\}$.

In the following analysis a network will be said to be stable if it satisfies Pairwise-Stability as defined by Goyal and Joshi (2003).

Definition 1 (Pairwise Stability) *A network g is stable if the following conditions are satisfied:*

1. *For $g_{i,j} = 1$, $\pi_i(g) > \pi_i(g - g_{i,j})$ and $\pi_j(g) > \pi_j(g - g_{i,j})$;*

2. *For $g_{i,j} = 0$, if $\pi_i(g + g_{i,j}) > \pi_i(g)$, then $\pi_j(g + g_{i,j}) \leq \pi_j(g)$.*

In other words, a network structure g is said to be stable if any pair of linked firms (i, j) has an incentive to maintain its link and any pair of unliked firms (i, j) has no stict incentive to severe a collaboration link.

3 Linear-Homogeneous Product Oligopoly

In this section, we study networks of collaboration in the context of a market with homogeneous products and quantity competition. We start by assuming that firm i's emission rate in network g satisfies

$$\varepsilon_i(\eta_i(g^e)) = s_0, \quad \varepsilon_i(g) = \varepsilon_i(\eta_i(g)) = s_0 - s\eta_i(g), \tag{4}$$

and thus is a linearly decreasing function of the number of collaboration links.

3.1 Cournot Competition

Given a network g, firms choose quantities to maximize their oligopoly profits. Standard derivations show that equilibrium quantities are equal to

$$q_i^N(g) = \frac{1}{(n+1)}\left[(\alpha - c) + n\overline{T}(g) - (n+1)\tau_i\varepsilon_i(g)\right], \quad \forall i \in N, \tag{5}$$

where $\overline{T}(g) = \sum_{i=1}^{n} \tau_i\varepsilon_i(g)$ is the average tax bill and equilibrium profits are given by

$$\pi_i\left(q_i^N, g\right) = \left[q_i^N(g)\right]^2. \tag{6}$$

We note that equilibrium profits of firm i are an increasing and convex function of its equilibrium quantities. Furthermore, the distribution of equilibrium profits is governed by the deviation of individual marginal emission costs from the industry average, $(n\overline{T}(g)-(n+1)\tau_i\varepsilon_i(g))$. Plugging (4) in equilibrium output levels (5) yields:

$$q_i^N(g)=\tfrac{1}{(n+1)}\left[(\alpha-c)+s_0\left(T-(n+1)\tau_i\right)+ns\left(\tau_i\eta_i(g)-\overline{T}(g/\{i\})\right)\right], \tag{7}$$

where $T=\sum_{i=1}^{n}\tau_i$ and $\overline{T}(g/\{i\})=\frac{1}{n}\sum_{j\neq i}\tau_j\eta_j(g)$.

These derivations allow us to state the following two lemmas.

Lemma 2 (Negative externality) *Suppose that both governments tax polluting emissions* $(\tau_A>0,\ \tau_B>0)$ *then for all* $i,j,k\in N$ *and any network* $g\in G$*, we have* $\Delta\pi_i^N\left(g_{j,k},g\right)<0$ *and* $\Delta\pi_i^N\left(g,g_{j,k}\right)<0$.

Proof. Consider a network g. This network defines a configuration of effective marginal costs $\{c_i(g)\}_{i\in N}$ which in turn leads to equilibrium profit levels $\left\{q_i^N(g)\right\}_{i\in N}$. Consider some firm i and any pair of firms $(j,k)\in N/\{i\}$ such that $g_{j,k}=0$. Suppose that (j,k) decides to form a collaboration link. As a result, firm i's equilibrium output level will increase by a quantity

$$\Delta q_i^N\left(g_{j,k},g\right)=q_i^N(g+g_{j,k})-q_i^N(g), \tag{8}$$

$$=-\tfrac{s}{(n+1)}\left(\tau_j+\tau_k\right)\leq 0. \tag{9}$$

Since firm i's equilibrium profit $\pi_i^N(q_i^N(g))$ is monotonically increasing in $q_i^N(g)$ and $q_i^N(g+g_{j,k})<q_i^N(g)$, firm i's equilibrium profit is reduced as a result of the new link. Furthermore, note that $\left(\eta_j(g)-\eta_j(g+g_{j,k})\right)=-\left(\eta_j(g)-\eta_j(g-g_{j,k})\right)=-1$. Therefore, we have $\Delta q_i^N\left(g,g_{j,k}\right)\geq 0$ and $\Delta\pi_i^N\left(g,g_{j,k}\right)\geq 0$. In other words, when a pair of firms $(j,k)\in N/\{i\}$ broke its collaboration link firm i's profit increase. ■

Lemma 3 (Interregional links) *Suppose that region A imposes a higher tax on polluting emissions than region B; that is* $\tau_A>\tau_B>0$*. Then for all pair* (i,j) *such that* $i\in N_A$ *and* $j\in N_B$ *and any graph* $g\in G$ *we have* $\Delta\pi_i^N\left(g_{i,j},g\right)\gtreqless 0$ *if* $n\gtreqless(\tau_B/\tau_A)$ *and* $\Delta\pi_i^N\left(g,g_{i,j}\right)\lesseqgtr 0$ *if* $n\lesseqgtr(\tau_B/\tau_A)$.

Proof. Consider a graph g an some pair $(i,j)\in N$ such that and $g_{i,j}=0$. Suppose that (i,j) forms a collaboration link. As a result, firm i's equilibrium output level will increase by a quantity

$$\Delta q_i \left(g_{i,j}, g\right) = q_i^N \left(g + g_{i,j}\right) - q_i^N \left(g\right) \tag{10}$$

$$= \tfrac{s}{(n+1)} \left(n\tau_i - \tau_j\right). \tag{11}$$

That quantity is positive, negative or zero depending on whether $(n\tau_i - \tau_j)$ is positive, negative or zero. Assume that $i \in N_A$ and $j \in N_B$. Then, firm i's profit will be increased, decreased or unaltered depending on whether $n \gtreqless (\tau_B/\tau_A)$. By symmetry, $\Delta q_i \left(g, g_{i,j}\right) = -\Delta q_i \left(g_{i,j}, g\right)$ and thus firm i's profit will be increased, decreased or unaltered depending on whether $n \lesseqgtr (\tau_B/\tau_A)$. ■

Lemma 4 (Intraregional links) *Consider some pair of firms (i, j) located in the same juridiction and any graph $g \in G$, we have $\Delta\pi_i^N \left(g_{i,j}, g\right) > 0$ and $\Delta\pi_i^N \left(g, g_{i,j}\right) <$ 0.*

Proof. Let us assume that $\tau_i = \tau_j = \tau$. Then, equation (11) becomes

$$\Delta q_i \left(g_{i,j}, g\right) = \tfrac{s}{(n+1)} \left(n-1\right) \tau > 0. \tag{12}$$

Therefore, we have $\Delta\pi_i^N \left(g_{i,j}, g\right) > 0$ and, by symmetry, $\Delta\pi_i^N \left(g, g_{i,j}\right) < 0$. ■

These lemmas provide key insights into the strategic features of the link formation game. Consider that some firm j forms a bilateral link with some other firm k. Lemma 1 states that such a link affects negatively any other firm i in the industry. Indeed, when firms agree to form a collaboration link, they reduce their effective marginal costs, and are thus more competitive reducing the profit of their rivals. It is important to note that this conclusion holds regardless of whether we consider intraregional or interregional links.

Lemma 2 shows that firms' willingness to form *interregional* collaboration links depends on the magnitude of the tax differential. Let us assume that $\tau_A > \tau_B > 0$. Consider any graph $g \in G$ and any pair of firms (i, j) such that $i \in N_A$, $j \in N_B$ and $g_{i,j} = 0$. If $n > (\tau_B/\tau_A)$, then firm i has an incentive to form a link with firm j. Conversely, firm j will accept to form a link with i if $n > (\tau_A/\tau_B)$. Since $(\tau_A/\tau_B) > (\tau_B/\tau_A)$, the pair (i, j) will form a link if and only if $n > (\tau_A/\tau_B)$.

By contrast, Lemma 3 shows that firms' incentives to form *intraregional* collaboration links is not affected by the magnitude of the tax differential.

3.1.1 Stable networks

We study how differentials in tax rates across regions impact upon environmental R&D strategic alliances. Our analysis proceeds by succesive examination of relevant magnitudes of the tax differential. Let us start with a situation in which both regions impose equal effluent charges. The following proposition holds:

Proposition 5 *Suppose there is quantity competition among the firms and firms are taxed the same in both regions* $(\tau_A = \tau_B)$*. If emission rates satisfy (2) and demand satisfies (1) then the complete network,* g^c*, is the unique stable network.*

Proof. This result is a direct corollary of Theorem 3.1 in Goyal and Joshi (2003). ■

In other words, when emissions are taxed the same in the two regions, the only stable collaboration structure is such that every pair of firms undertakes joint environmental R&D.

Now, suppose that governments subject their firms to different tax rates. More precisely, let us assume that $\tau_A > \tau_B > 0$. The next proposition establishes that a relatively small tax differential does not affect the structure of stable collaboration networks.

Proposition 6 *Suppose there is quantity competition among the firms and firms belonging to different juridictions face different tax rates with* $n < \tau_A/\tau_B$*. The network* g^c *is the unique stable network.*

Proof. See Appendix. ■

As long as the tax differential remains relatively small, the complete network remains the unique stable collaboration network. Furthermore, it provides each and every firm with the ability to exploit all (intraregional and interregional) opportunities for emissions abatement. The intuition for this result is provided by Lemma 2 which shows that small tax differentials does not alter firms' incentives to form interregional R&D collaboration links. Therefore, let us consider large tax differentials. The next proposition shows that a large difference in tax rates $(n < \tau_A/\tau_B)$, disrupts the complete graph g^c.

Proposition 7 *Suppose there is quantity competition among the firms and firms belonging to different juridictions face different tax rates with $n > \tau_A/\tau_B$. The network g^{A+B} is the unique stable network.*

Proof. See Appendix. ■

Thus, when the tax differential is relatively large, the unique stable network is such that: i) all pairs of firms located in the same region have a collaboration link and ii) no pair of firms located in different juridictions is linked. In other words, a large difference in tax rates among two economics regions acts as a disincentive to interregional environmental R&D. The intuition for this result is provided by lemmas 2 and 3. Lemma 2 shows that a large tax differential incite firms to broke their interregional links while Lemma 3 indicates that differences in taxation do not alter firms' incentives to maintain or form intraregional links.

Finally, suppose that one region implements an environmental policy while the other does not tax polluting emissions.

Proposition 8 *Suppose there is quantity competition among the firms and firms based in region A (respectively, B) are not subjected to taxation. If emission rates satisfy (2) and demand satisfies (1) then the complete network, g^B (respectively, g^A), is the unique stable network.*

This result flows immediately from the previous proposition because firms have no incentive to invest in innovation in the absence of taxation.

4 Quadratic cost reduction

In this section, we relax the assumption of linear emission reduction in the number of collaboration links by allowing for a quadratic reduction in the rate of emission per unit of output. Formally, we assume that the emission rate is given by $\varepsilon_i(g) = \varepsilon_i(\eta_i(g))$ and satisfies

$$\varepsilon_i(\eta_i(g^e)) = \varepsilon_i(0) = s_0 \text{ and } \varepsilon_i(\eta_i(g)) = s_0 - \frac{s_1}{2}\eta_i(g)^2, \forall g \neq g^e, \tag{13}$$

where $s_0 > 0$ and $s_1 > 0$. Plugging (13) in (5) gives

$$q_i^N(g) = \frac{1}{(n+1)}\left[(\alpha - c) + s_0(T - n\tau_i) + \frac{ns_1}{2}\left(\tau_i\eta_i(g)^2 - \overline{T}(g/\{i\})\right)\right], \quad (14)$$

where $T = \sum_{j\neq i}\tau_i$ and $\overline{T}(g/\{i\}) = \frac{1}{n}\sum_{j\neq i}\tau_i\eta_i(g)^2$. Again, equilibrium profits are given by $\pi_i\left(q_i^N, g\right) = \left[q_i^N(g)\right]^2$.

Lemma 9 (Negative externality) *Suppose that both governments tax polluting emissions $(\tau_A, \tau_B > 0)$ then for any network $g \in G$ and for all $i, j, k \in N$, we have $\Delta\pi_i^N(g_{j,k}, g) < 0$ and $\Delta\pi_i^N(g, g_{j,k}) > 0$.*

Proof. It suffices to note that

$$\Delta q_i^N(g_{j,k}, g) = -\tfrac{s_1}{2(n+1)}\left[\tau_j\left(2\eta_j(g)+1\right) + \tau_k\left(2\eta_k(g)+1\right)\right] < 0, \quad (15)$$

for all $i, j, k \in N$. ■

As in the linear case, the formation of bilateral links induces negative externalities on other firms in the industry. The following two lemmas indicate how our assumption regarding emissions reduction affect firms' incentives to form interregional and intraregional bilateral links.

Lemma 10 (Interregional links) *Suppose that region A imposes a higher tax on emissions than region B; that is $\tau_A > \tau_B > 0$. Then for any graph $g \in G$ and any pair $(i, j) \in N$ such that $i \in N_A$, $j \in N_B$ and $g_{i,j} = 0$, we have $\Delta\pi_i^N(g_{i,j}, g) \gtreqless 0$ if $n \gtreqless \frac{\tau_B(1+2\eta_j)}{\tau_A(1+2\eta_i)}$ and $\Delta\pi_i^N(g, g_{i,j}) \lesseqgtr 0$ if $n \lesseqgtr \frac{\tau_B(1+2\eta_j)}{\tau_A(1+2\eta_i)}$.*

Proof. Notice that

$$\Delta q_i^N(g_{i,j}, g) = \tfrac{s_1}{2(n+1)}\left[n\tau_i\left(1+2\eta_i(g)\right) - \tau_j\left(1+2\eta_j(g)\right)\right] \quad (16)$$

is of the same sign as $\left(n\tau_i\left(1+2\eta_i(g)\right) - \tau_j\left(1+2\eta_j(g)\right)\right)$. Assume that $i \in N_A$, $j \in N_B$ so that $\tau_i = \tau_A$ and $\tau_j = \tau_B$. Since equilibrium profits are increasing in output, we have

$$\Delta q_i^N(g_{i,j}, g) > 0 \text{ and } \Delta\pi_i^N(g_{i,j}, g) > 0 \text{ if } n > \tfrac{\tau_B(1+2\eta_j)}{\tau_A(1+2\eta_i)}, \quad (17)$$

$$\Delta q_i^N(g_{i,j}, g) \leq 0 \text{ and } \Delta\pi_i^N(g_{i,j}, g) \leq 0 \text{ if } n \leq \tfrac{\tau_B(1+2\eta_j)}{\tau_A(1+2\eta_i)}. \quad (18)$$

Furthermore, observe that $\Delta q_i^N(g, g_{i,j}) = -\Delta q_i^N(g_{i,j}, g)$. Thus, $\Delta\pi_i^N(g_{i,j}, g) \lesseqgtr 0$ if $n \gtreqless \frac{\tau_B(1+2\eta_j)}{\tau_A(1+2\eta_i)}$. ■

Lemma 11 (Intraregional links) *Consider any graph $g \in G$ and some pair of firms (i, j) located in the same region such that $g_{i,j} = 0$, we have $\Delta\pi_i^N(g_{i,j}, g) \gtreqless 0$ if $n \gtreqless \frac{(1+2\eta_j)}{(1+2\eta_i)}$ and $\Delta\pi_i^N(g, g_{i,j}) \lesseqgtr 0$ if $n \lesseqgtr \frac{(1+2\eta_j)}{(1+2\eta_i)}$.*

Proof. Simply by replacing $\tau_i = \tau_j$ in the proof of Lemma 11. ■

Lemmas 10 and 11 show that the non-linear relation between the emission rate and the number of collaboration links formed alter significantially the strategic features of the model of bilateral environmental R&D collaboration. By contrast with the linear case, when emissions decrease quadratically with the number of links formed, firm i's willingness to form a bilateral collaboration link with any firm j depends on the number of bilateral agreements i and j have already signed.

4.1 Stable graph structures

Now, let us turn to the characterization of stable graph structures. As before, we proceed by succesive examination of relevant magnitudes of the tax differential. In the absence of tax differentiation, we have the following result:

Proposition 12 *Suppose there is quantity competition among the firms and firms are taxed the same in both regions ($\tau_A = \tau_B$). If emission rates satisfy (13) and demand satisfies (1) then the complete network g^c is* a *stable network.*

Proof. *See Appendix.* ■

Again, the complete network g^c is pairwise stable. However, notice that g^c is no longer the unique stable network. Consider the following example. Let us assume that $N = \{1, 2, 3, 4\}$. Consider the complete graph defined on N. From proposition (10) we know that g^c is pairwise stable. Now, consider the graph $g_{-1} = \{g_{ij} = 1, \forall(i, j) \in N/\{1\}$ and $g_{i1} = 0, \forall i \in N/\{1\}\}$. Let us show that this is a stable network. Notice that in the absence of tax differentiation, Lemma 11 applies. By definition, we have $\eta_1(g_{-1}) = 0$ and $\eta_2(g_{-1}) = \eta_3(g_{-1}) = \eta_4(g_{-1}) = 2$. First, we prove that g_{-1} satisfies condition 2. Consider the pair $(1, 2) \in N$. Notice that $(1+2\eta_1)/(1+2\eta_2) = 1/5 < n$ and thus $\Delta\pi_2^N(g_{1,2}, g) > 0$. In other words, firm 2 has an incentive to form a collaboration link with firm 1. However, note that $(1+2\eta_2)/(1+2\eta_1) = 5 > n$ and thus $\Delta\pi_1^N(g_{1,2}, g) < 0$. That is, firm 1 will refuse to form a link with firm 2. Finally, note that firm 1 is in a symmetric position with respect to all its competitors. Therefore, it has no incentive to form collaboration links with its competitors. Therefore, g^{-1} satisfies condition 2.

Now, we turn to condition 1. Let us consider some pair of firms $(i, j) \in N/\{1\}$. Observe that $(1+2\eta_j)/(1+2\eta_i) = 1/5 < n, \forall(i, j) \in N$. From Lemma 11 it comes that $\Delta q_i^N(g, g_{i,j}) < 0$ and $\Delta\pi_i^N(g, g_{i,j}) < 0, \forall(i, j) \in N/\{1\}$. For no firm has an incentive to broke its collaboration link, condition 1 is verified. Finally, since g^{-1} satisfies conditions 1 and 2, it is pairwise stable.

Finally, note that the same result holds for every conceivable graph $g_{-k} = \{g_{ij} = 1, \forall(i, j) \in N/\{1\}$ and $g_{ik} = 0, \forall i \in N/\{1\}\}$.

Therefore, our relaxation of the linearity assumption increases the number of stable network structures. However, as the following proposition shows, it does not affect the stability properties of the complete network g^c uncovered in the linear case.

Proposition 13 *Suppose there is quantity competition among the firms and the tax differential is relatively small ($n > \frac{\tau_A}{\tau_B}$). If emission rates satisfy (13) and demand satisfies (1) then the complete network g^c is a stable network.*

Proof. See Appendix. ■

The intuition for this result is as follows. Under the network structure g^c all firms in the industry have the same number of collaboration links. Therefore, the condition $n > \frac{\tau_B(1+2\eta_j)}{\tau_A(1+2\eta_i)}$ reduces to $n > \frac{\tau_B}{\tau_A}$ so that firms' incentives to form collaboration links depends exclusively on the magnitude of the tax differential as in the linear case. Since the complete graph is symmetric, it is pairwise stable as long as $n > \frac{\tau_B}{\tau_A}$.

Now, let us consider a relatively large tax differential. The following proposition shows that a large tax differential disrupts the complete graph g^c.

Proposition 14 *Suppose there is quantity competition among the firms and the tax differential is relatively large ($n < \frac{\tau_A}{\tau_B}$). If emission rates satisfy (13) and demand* *satisfies (1) then the complete network g^c is not a stable network.*

Proof. See Appendix. ■

Furthermore, the structure of stable R&D networks depends on the relative economic size of the two regions as indicated by the following two propositions.

Proposition 15 *Suppose there is quantity competition among the firms, the tax differential is relatively large ($n < \frac{\tau_A}{\tau_B}$) and the economic size of the "green" region is at least equal to that of the "dirty" region ($n_A \geq n_B$). If emission rates satisfy (13) and demand satisfies (1) then the network g^{A+B} is a stable network.*

Proof. See Appendix. ■

It is important to note here that firms located in the "green" region cannot have a lower effective marginal cost than firms located in the "dirty" region.

Proposition 16 *Suppose there is quantity competition among the firms, the tax differential is relatively large ($n < \frac{\tau_A}{\tau_B}$) and most of the industry is located in the "dirty" region ($n_B > n_A$). Assume that emission rates satisfy (13) and demand satisfies (1) then the network g^{A+B} is not pairwise stable if $\frac{\tau_i(2n_A-1)-n\tau_j}{2n\tau_j} < n_B < \frac{n\tau_i(2n_A-1)-\tau_j}{2\tau_j}$. Otherwise, it is pairwise stable.*

Proof. See Appendix. ■

As a matter of fact, the cost advantage of firms located in the "dirty" region is even stronger when they represent most of the industry. Consider a situation where g^{A+B} is not pairwise stable. As they represent the major part of the industry and only intraregional links will form, firms based in the "dirty" region benefit not only from a lower tax rate on emissions per unit of output but also from a higher reduction in their effective marginal cost. Now, let us consider a situation where g^{A+B} is not pairwise stable. It is easy to see that any stable R&D network g' will be such that $g'_{i,j} = 1, \forall (i,j) \in N_A$ or N_B and

$$\frac{\tau_i\left(1+2\eta_i(g')\right)-n\tau_j}{2n\tau_j} < \eta_j(g') < \frac{n\tau_i\left(1+2\eta_i(g')\right)-\tau_j}{2\tau_j}. \tag{19}$$

The last condition implies that in every stable network structure, firms located in the "dirty" region will form more collaboration links and therefore will be more innovative than firms located in the "green" region.

5 Conclusion

The view that the impact on technological change must be a criterion for the evaluation of different policy instruments is widespreads in environmental economics[4]. In an early contribution, Orr (1976) has argued that emission taxes are superior to known alternative economic instruments because of their effect on innovation. One of his main argument is that

> "the possibility that regional differences in charges will seriously affect the competitive position of plants within an industry at different locations is likely to make substantial differentials politically unacceptable (Orr, p. 446)."

Our analysis reveals that the consequences of tax differentials on the competitiveness of firms is not as straightforward as Orr (1976) seems to suggest. Indeed, the relationship between emission taxes and firms innovative capacity is mediated by interfirms collaborative R&D agreements. In order to determine whether or not environmental tax differential are politically inacceptable it is necessary to understand their consequences on firms' incentives to sign bilateral R&D agreements. As a first step in that direction, this paper shows that firms located in a low-tax region can be more innovative than firms located in a high-tax region provided that the number of firms located in the first region is greater the number of firms located in the second region and the difference in emission taxation is large.

6 Appendix

Proofs. Proofs of propositions 5,6,7,8,9 and 10 follow.

Proof of proposition 6. *Stability*: Notice that stability condition (2) is satisfied because all firms are connected in g^c by definition. Thus, we only need to check whether condition (1) is satisfied. Assume that some pair of firms (i, j) brokes its collaboration link. The resulting network is $g^c - g_{i,j}$. Notice that $\Delta q_j^N (g^c, g_{i,j}) < 0$ and $\Delta \pi_j^N (g^c, g_{i,j}) < 0, \forall (i, j) \in N$. Thus, no pair of firms has an incentive to broke its collaboration link. For the network structure g^c satisfies stability conditions (1) and (2), it is a paiwise stable network. *Unicity*: Consider

[4] Recent contributions include Cadot and Sinclair-Desgagné (1996), Chiou and Hu (2001) and Katsoulacos and Xepapadeas (1996b).

some stable network $g' \neq g^c$. Such a network is necessarily incomplete and contains at least one unlinked pair (i,j). Assume that some previously unlinked pair of firms (i,j) forms a collaboration link. The resulting network is $g^c + g_{i,j}$. Notice that $\Delta q_i^N(g_{i,j}, g') > 0$, $\Delta\pi_i^N\left(g_{i,j}, g^{'}\right) > 0$ and by symmetry $\Delta q_j^N(g_{i,j}, g') > 0$, $\Delta\pi_j^N(g_{i,j}, g') > 0$. Therefore, there is no stable graph $g' \neq g^c$ and g^c is the unique stable graph. ■

Proof of proposition 7. *Stability*: Consider the first stability condition. The network structure g^{A+B} satisfies stability condition (1) if this condition is verified by each of its connected components (g^A, g^B). Because intra-regional tax rates are equal and strictly positive, proposition (4) applies and stable regionals networks are complete. Let us turn to stability condition (2). Assume that $\tau_i \geq \tau_j, \forall i \in N_A, j \in N_B$. We prove that no pair of firms (i,j) such that $i \in N_A$ and $j \in N_B$ has an incentive to form a collaboration link. Notice that $\Delta q_i\left(g_{i,j}, g^{A+B}\right) > 0$. Since firm i's equilibrium profit is increasing in its own production it is profitable for firm i to form a collaboration link with firm j. However, $\Delta q_j\left(g_{i,j}, g^{A+B}\right) < 0$ and $\Delta\pi_j\left(g_{i,j}, g^{A+B}\right) < 0$. In other words, it is detrimental for firm j to accept such a link. Thus, no interregional link will form. For the network structure g^{A+B} satisfies stability conditions (1) and (2), it is a paiwise stable network. *Unicity*: Consider a stable network $g' \neq g^{A+B}$. By definition, g' satisfies either i) $\left[\exists(i,j) \in N_A | g'_{i,j} = 0\right]$ or ii) $\left[(\exists(i,j), i \in N_A, j \in N_B) \vee (\exists(i,j), i \in N_B, j \in N_A) | g'_{i,j} = 1\right]$. To begin with, consider proposition i). It states that some pair of firms $(i,j) \in N_A$ is not lined under g'. However, we can check that $\Delta q_i^N\left(g'_{i,j}, g'\right) > 0$, $\Delta\pi_i^N\left(g'_{i,j}, g'\right) > 0$ and $\Delta q_j^N\left(g'_{i,j}, g'\right) > 0$, $\Delta\pi_j^N\left(g'_{i,j}, g'\right) > 0$. In other words, both firms have an incentive to form a collaboration link. Thus, there is no stable graph g' satisfying proposition (i) . Now, we turn to proposition (ii). It states that some firm $i \in N_A$ has formed a link with a firm $j \in N_B$. We prove that such an interregional link is unstable. Notice that we have $\Delta q_j^N\left(g', g'_{i,j}\right) > 0$ and $\Delta\pi_j^N\left(g', g'_{i,j}\right) > 0$. That is, firm j has an incentive to destroy its link with i. Thus, there is no stable graph g' satisfying proposition (ii). In conclusion, g^{A+B} is the unique stable graph. ■

Proof of proposition 8. $\times$Assume that $\tau_i = 0, \forall i \in N_A$ and $\tau_j = \tau_k > 0, \forall j,k \in N_B$. First, since firms have no incentive to form collaboration links in the absence of taxation, it must be the case that $\eta_i(g') = 0, \forall i \in N_A$ in any stable network g'. Second, note that firms based in juridiction A are taxed the same. Therefore, by proposition (4), the unique stable network is g^A. ■

Proof of proposition 9. *Condition 2.* All firms are connected in g^c. By definition, the external stability condition (2) is satisfied. *Condition 1.* Observe that under the complete graph structure g^c we have $\eta_i(g^c) = \eta_j(g^c) = n-1$ for every pair $(i,j) \in N$. Furthermore, $\frac{1+2\eta_j}{1+2\eta_i} = 1 < n, \forall (i,j) \in N$. From (**??**), it comes that $\Delta q_i^N(g, g_{i,j}) < 0$ and $\Delta\pi_i^N(g, g_{i,j}) < 0$ for all pair $(i,j) \in N$. In other words, no pair of firms has an incentive to broke its collaboration link. Since, the graph structure g^c satisfies the internal stability condition (1). Since the complete graph g^c satisfies internal stability and external stability, it is a pairwise stable graph. ■

Proof of proposition 12. *Condition 2*. All firms are connected in g^c and thus condition (2) is automatically satisfied. *Condition 1*. We have to prove that no connected pair in g^c has an incentive to broke its collaboration link. By definition of g^c, we have $g^c_{i,j} = 1, \forall (i,j) \in N$. Let us consider a given pair $(i,j) \in N$. Firm i (respectively, j) has no incentive to broke its collaboration link with firm j (respectively, i) if and only if $\Delta\pi_i^N(g, g_{i,j}) < 0$ ($\Delta\pi_j^N(g, g_{i,j}) < 0$); i.e., $\Delta q_i^N(g, g_{i,j}) < 0$ ($\Delta q_j^N(g, g_{i,j}) < 0$). Note that $\eta_i(g^c) = \eta_j(g^c) = n-1$ for every firm $i \in N$. Furthermore, under the assumption $\tau_i > \tau_j \geq 0$, we have $\Delta q_i^N(g^c, g_{i,j}) < 0$ and $\Delta q_j^N(g^c, g_{i,j}) < 0$ if $n > (\tau_i/\tau_j)$. Therefore, no pair of firms has an incentive to broke its collaboration link. Since, the graph structure g^c satisfies internal and external stability conditions, it is a pairwise stable graph. ■

Proof of proposition 13. The proof is straightforward. Consider a pair (i,j) such that $i \in N_A$ and $j \in N_B$. By definition of the complete network g^c, we have $g_{ij} = 1$. Under the assumption $\tau_i > \tau_j \geq 0$, $n < (\tau_i/\tau_j)$ implies $\Delta q_i^N(g^c, g_{i,j}) > 0$ and $\Delta q_j^N(g^c, g_{i,j}) > 0$. In other words, when the tax differential is relatively large, firms belonging to different juridictions have an incentive to broke their collaboration links. Therefore, the graph structure g^c violates the condition of internal stability. ■

Proof of proposition 15. *Condition 2*. Every pair of firms $(i,j) \in N_A$ and $(i,j) \in N_B$ is connected in g^{A+B}. In order to prove that the graph g^{A+B} is internally stable it is sufficient to show that no firm $j \in N_B$ will accept to form a collaboration link with a firm $i \in N_A$ if $\tau_i > \tau_j \geq 0$. Assume that the tax differential is relatively large, $n < \frac{\tau_i}{\tau_j}$. *First*, let us assume that $n_A = n_B$. Then, $\eta_i(g^{A+B}) = \eta_j(g^{A+B})$, $\forall (i,j) \in g^{A+B}$. Recall that firm j has an incentive to form a link with firm i if $\Delta\pi_j(g_{i,j}, g) > 0$. Note that $\Delta\pi_j(g_{i,j}, g) > 0$ if $\Delta q_j(g_{i,j}, g) > 0$ or $n > (\tau_i(1+2\eta_i)) / (\tau_j(1+2\eta_j))$. Plugging $\eta_i(g^{A+B}) = \eta_j(g^{A+B})$ in the last condition gives $\Delta q_j(g_{i,j}, g) > 0$ if $n > (\tau_i/\tau_j)$ which contradicts our assumption $n < (\tau_i/\tau_j)$. Therefore, if the tax differential is relatively large and economic regions are of equal size, no firm $j \in N_B$ will accept to form a collaboration link with a firm $i \in N_A$. *Second*, let us assume that $n_A > n_B$. Now, we have $\eta_i(g^{A+B}) > \eta_j(g^{A+B})$, $\forall i \in N_A$ and $\forall j \in N_B$. Note that $\Delta\pi_i(g_{i,j}, g) > 0$ if $\Delta q_i(g_{i,j}, g) > 0$ or $n > (\tau_j(1+2\eta_j)) / (\tau_i(1+2\eta_i))$ and $\Delta\pi_j(g_{i,j}, g) > 0$ if $\Delta q_j(g_{i,j}, g) > 0$ or $n > (\tau_i(1+2\eta_i)) / (\tau_j(1+2\eta_j))$. However, for $\eta_i(g^{A+B}) > \eta_j(g^{A+B})$ and $\tau_i > \tau_j > 0$, it is straightforward to see that these conditions cannot be satisfied simultaneously. Therefore, if the tax differential is relatively large and if the green region is the largest, no firm $j \in N_B$ will accept to form a collaboration link with a firm $i \in N_A$. *Condition 1*. Remark that $\tau_i = \tau_j$, $\forall (i,j) \in N_A$ and $\forall (i,j) \in N_B$. Furthermore, recall that $\eta_i(g^{A+B}) = \eta_j(g^{A+B}), \forall(i,j) \in N_A$ and $\forall(i,j) \in N_B$. Under these conditions, from (**??**) it comes that $\Delta q_i(g, g_{i,j}) < 0$ and $\Delta q_j(g, g_{i,j}) < 0, \forall(i,j) \in N_A, \forall(i,j) \in N_B$ and $\Delta\pi_i(g, g_{i,j}) < 0$ and $\Delta\pi_j(g, g_{i,j}) < 0, \forall(i,j) \in N_A, \forall(i,j) \in N_B$. Therefore, no pair of firms linked in the network g^{A+B} has an incentive to broke its collaboration link. Since, the graph structure g^c satisfies internal and external stability conditions, it is a pairwise stable graph. ■

Proof of proposition 16. In order to prove that the graph g^{A+B} is not Pairwise Stable it is sufficient to show that firms are willing to form interregional links. Consider the network g^{A+B}. Notice that $\eta_i(g^{A+B}) = n_A - 1 < \eta_j(g^{A+B}) = n_B - 1$, $\forall i \in N_A$ and $\forall j \in N_B$. Now, consider a pair of firms (i,j) such that $i \in N_A$ and $j \in N_B$. This pair of firm is willing to form a collaboration link if $\Delta\pi_i(g_{i,j}, g) > 0$ and $\Delta\pi_j(g_{i,j}, g) > 0$; that is, if $n > (\tau_j (1 + 2(n_B - 1))) / (\tau_i (1 + 2(n_A - 1)))$ and $n > (\tau_i (1 + 2(n_A - 1))) / (\tau_j (1 + 2(n_B - 1)))$. Note that these two conditions are satisfied if $\frac{\tau_i(2n_A-1)-n\tau_j}{2n\tau_j} < n_B < \frac{n\tau_i(2n_A-1)-\tau_j}{2\tau_j}$ when $\tau_A > \tau_B \geq 0$ and $n < \frac{\tau_A}{\tau_B}$. The remaining of the proof is left to the reader. ■ ■

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