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Second Best Environmental Policies under Uncertainty

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We thank S. Lahiri, A. Xepapadeas, E. Dioikitopoulos, S. Proost, Roseta Palma, the participants of the 16th annual EAERE conference, June 2008, and the seminar series of the Athens University of Economics and Business for their valuable suggestions and comments. Fabio Antoniou acknowledges funding by the Greek National Foundation of Scholarships (I.K.Y). The usual disclaimer applies.

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5 November 2009

Abstract

We construct a strategic trade model of an international duopoly, whereby production by exporting firms generates a local pollutant. Governments use environmental policies, i.e., an emissions standard or a tax, to control pollution and for rent shifting purposes. Contrary to their firm, however, governments are unable to perfectly foresee the actual level of demand, the cost of abatement and the damage caused from pollution. Under these modes of uncertainty we derive sufficient conditions under which the governments optimally choose an emissions tax over an emissions standard.

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1 Introduction

During the last three decades developed countries have recognized the need for regulating polluting agents, since they incur harmful and irreversible damage on human health and on the environment (see Stern, 2007). As a result national and international environmental agencies, such as EPA, founded in 1970, and EEA, founded in 1995, oversee and ensure the efficient and effective regulation of pollution.

In general, there are two ways to regulate industrial pollution: (a) through the use of quantity constraints, which translate into several forms of maximum emission standards or pollution permits; and (b) through emission taxes. A voluminous literature referred to as "strategic environmental policy literature" demonstrates how environmental policy instruments can be used as second best instruments for international trade purposes when traditional trade taxes, subsidies and quotas are prohibited or restricted due to international trade agreements. Specifically, in the context of international oligopolistic competition, among others, Conrad (1993), Barrett (1994), Kennedy (1994), Rauscher (1994), Ulph (1996a), Ulph and Valentini (2001) and Neary (2006) conclude that when firms compete in outputs governments, in an effort to enhance the international competitiveness of their exporting firms, have a unilateral incentive to pursue laxer environmental policy, i.e., use of lax emission standards or emission taxes.[1]

Another strand of the literature compares the welfare and pollution implications for open economies of the different environmental policy instruments, i.e., emissions standards vis-à-vis emissions taxes. For example, Ulph (1996b) in an imperfectly competitive trade model where two countries produce a single polluting commodity and firms are allowed to strategically invest in capital, demonstrates that, first, the use of emissions standards over taxes need not be a dominant strategy, and second the choice of the environmental policy instrument has an impact on producers' strategic (investment) behavior, output, pollution, and thus welfare.[2] Recently, Lahiri and Ono (2007) extend the above results by comparing the effects of an emissions tax and

[1]Empirical support concerning ecological dumping can be found in Fredriksson and Millimet (2002), Ederington and Minier (2003), Ederington et al. (2005) and Levinson and Taylor (2008).

[2]Ulph (1996b), assumes that governments select their policy instruments in a way satisfying international agreements. Hence, governments cannot select their policies strategically. An emissions tax (standard) leads to higher welfare over a standard (tax) if a country is a significant consumer (producer) of the polluting good. Moreover, emissions standards relative to taxes or to no environmental policy reduce a country's strategic incentive for overinvestment.

of a relative emissions standard on the levels of pollution and welfare. They conclude, among other things, that with a fixed number of firms a relative emissions standard is welfare-superior to an emissions equivalent emissions tax, while an emissions tax is emissions-superior to a welfare equivalent relative emissions standard. The authors, however, do not consider asymmetric cases where each country implements a different policy instrument, and thus do not obtain a full payoff matrix and do not attain Nash equilibria of the game. Yanase (2007) examines the welfare and pollution effects of emissions standards and taxes in a dynamic game model of international competition with many countries, cross-border pollution which accumulates over time, and governments which either all choose the same or different from each other policy instrument. He concludes that in a non-cooperative policy game, standards are favored over taxes since the latter entail larger strategic distortions, e.g., terms of trade, abatement costs and environmental damage effects, relative to emission taxes, thus resulting to higher pollution and lower welfare.

From the above reviewed literature it can be argued that, by and large, in the context of open economies and imperfect competition emissions standards relative to taxes lead to lower levels of pollution and higher welfare, since they leave firms with less flexibility, thus weakening the prisoner's dilemma amongst competing governments (countries).

A notable feature, among others, of the strategic environmental policy literature reviewed above is that of complete information for all agents, i.e., firms and governments. Here we develop a model of an international duopoly, where we assume that exporting firms are better informed than their respective national governments in regards to demand conditions, or cost of abatement or finally in terms of environmental damage caused by production of their polluting output. The modeling and methodology of the present paper synthesizes various analytical features of the above reviewed literature as well as features of the literature on strategic trade policy under imperfect competition. This synthesis, despite its practical and real world relevance has not been attempted to date. Specifically, we use a model of an international duopoly *a-la* Barrett (1994), while the invoked modes of uncertainty in demand, abatement cost and pollution damage functions follow along the lines of closed economy models of environmental policy, e.g., Weitzman (1974). The modes of strategic environmental policy we consider are equivalent to those of strategic trade policy with imperfectly competitive markets and uncertainty in the seminal paper by Cooper and Reizman (1989), henceforth C-R'89. In C-R'89, the sole source of uncertainty is the structure of demand, and governments choose strategically between trade quotas and trade subsidies in order to shift profits in favor of their exporting firms. Here, trade quotas and subsidies are replaced by emissions standards and emissions taxes, which we rank in terms of their expected welfare effects, when governments strategically choose these instruments in order not only to shift profits in favor of their exporting firms but also to regulate pollution.[3]

Our findings verify that in the context of imperfect competition and complete information emissions standards are welfare superior to emissions taxes. Furthermore, we argue that under certainty, using standards not only leads to welfare superior outcomes, but it also constitutes a dominant strategy for each regulator and thus a Nash equilibrium strategy for each government. Nonetheless, we also claim that uncertainty should play a key role in the decision of the optimal policy instrument. In particular we introduce uncertainty either in the demand intercept, or in the intercepts of the marginal abatement cost and marginal damage functions. Then we provide sufficient conditions under which it is optimal for the regulator to select an emissions tax to regulate pollution, in contrast to the aforementioned literature.

Our result is in line with several empirical studies. Few of them presented by Harrington et al. (2004), illustrate that different countries frequently face identical environmental problems through the use of different policy instruments. In particular, they provide twelve case studies on six environmental problems and they illustrate that the US and several EU countries apply different policy instruments in each case. As illustrated in Howe (1994), the United States has employed quantitative restrictions of emissions while EU countries preferred to control pollution through a tax. Additionally, many industries in Japan opposed the implementation of a carbon tax, yet there are increasing numbers of firms willing to conform with quantity constraints. This paper may help understand any possible preferences of standards over taxes and vice-versa.

2 The Model

We consider a model of a symmetric international duopoly, where each firm is located in a different country (home and foreign) and produces an identical and homogenous good consumed

[3] Nannerup (1998) introduced uncertainty about firms' costs in a strategic environmental policy model with a similar structure to ours. However, in contrast to our model, Nannerup allows the implementation of both standards and lump sum taxes, simultaneously, and thus the construction of a truth revealing contract is possible. Furthermore, Nannerup does not examine the choice of an optimal policy instrument which is the aim of this paper.

in a third country, e.g., rest of the world (ROW). Consumer preferences in ROW can be mapped into a quasi-linear utility function which yields an affine linear inverse demand, $p = B - x - X + \theta$, where B is the demand intercept, x and X are the output levels for the domestic and the foreign firm, respectively, and θ is a random variable reflecting positive or negative additive demand shocks. This random variable is assumed to follow a distribution with mean zero.[4]

Both firms have the same production technology, and for simplicity a unit of production generates a unit of a purely local pollutant (z). Further for simplicity we assume that an exogenous end-of-the-pipe abatement technology (a) exists for the firm and thus net pollution equals production minus abatement carried out by the firm,

$$z = x - a. \tag{1}$$

The abatement cost function is assumed to be convex of the form:

$$c_a = \frac{1}{2} g a^2 + au, \tag{2}$$

where g is a positive scalar, which determines the cost of pollution control and u is an error term following a distribution with zero mean. The introduction of the stochastic term u can be interpreted as a shock occurring in the abatement cost function, reflecting our assumption that governments, contrary to firms, are less informed about the exact position of c_a.[5] The profit function of the domestic firm depends on the policy instrument chosen by the government in order to regulate pollution and it is given by the following expression:

$$\pi = (B - x - X + \theta)x - cx - c_a - tz, \tag{3}$$

where c is the marginal cost of production (common for both firms) which exhibits constant

[4]Throughout the paper the foreign country's variables and functions are indicated with upper case letters. Due to assumed symmetry, the comparative statics analysis is carried out primarily in terms of home country variables. The variables of the foreign country are equivalently derived. Furthermore, the way uncertainty is introduced and all functions chosen throughout the paper are chosen such that the results obtained are comparable to the ones in the relevant literature. We assume that when θ takes negative values, interior solutions for our variables are still obtained. This could be described by a truncated normal distribution with zero mean.

[5]The form of the stochastic term (u) leads to parallel shifts of the marginal cost of the abatement function. For simplicity, we assume that the intercept of the marginal function equals to zero. This assumption appears to be innocuous since the implications remain unaffected if we assume an abatement cost function of the form $c_a = \frac{1}{2} g_1 a^2 + g_1 a + au + g_3$, where $g_i > 0$, $i = 1, 2, 3$.

returns to scale, and tz are the tax payments due to pollution when a tax is the policy instrument in use.[6] When the government implements an emissions standard, then $tz = 0$. The choice variables of the firms are output and the level of abatement.

Regulation of pollution by the governments takes place prior to production decisions. We examine two different ways of regulating pollution. First, we assume that governments can use an emissions standard, i.e., a quantity constraint setting the maximum allowed level of total emissions for the firms. Additional emissions must be abated by the firm. In this case the choice variable for the firm is the level of output. Production generated emissions must coincide with the standard (z) set by the government.[7] The alternative policy instrument available to the governments is a tax (t) for each unit of emissions. In this case, the choice variables for the firm are the level of output and pollution abatement. Governments in the two countries in both regimes choose the optimal level of regulation by maximizing social welfare given by:

$$w = \pi + tz - d, \tag{4}$$

where d stands for the damage caused from pollution and has the following form:

$$d = \frac{1}{2}kz^2 + z\xi, \tag{5}$$

where the coefficient k is positive and determines the injuriousness of the pollutant. Similarly to the abatement cost function, we assume that the damage function is stochastic and depends on a random variable, ξ, which also follows a distribution where its expected value equals zero.[8] Throughout the paper we assume that uncertainties in the demand, abatement cost and damage

[6]The results are not affected qualitatively if we allow for decreasing returns to scale. Note also that in order to calculate total marginal cost of production both in the cases of standards and taxes we need to take into account how changes in output affect the cost abatement and the tax expenditures respectively. Algebraically, total marginal cost of production in the case of taxes is $tmc_t = c + t$, while the corresponding one for the case of standards is $tmc_s = \begin{cases} c, & \text{for } x \leq z \\ c + g(x - z), & \text{for } x > z \end{cases}$.

[7]Note that standards and pollution permits are equivalent policy instruments only in the case where the latter are non-tradable. However, in our case tradable permits cannot be introduced since the pollutant is assumed to be local and thus there is no reason for the governments to accept licences of a firm located in a different country.

[8]It is more realistic to assume that ξ is unobservable by both the governments and the firms, as there is no reason to assume that the firms are better informed about the damages caused from pollution to the society. However, in order to have a unique informational structure in the model and remain consistent with the timing of revelation of the other modes of uncertainty we assume that, contrary to the governments, ξ is revealed to the firms. This does not affect the results, since uncertainty in the damage cost function appears to play no role in the decisions of the firms. ξ is also introduced in such a way that a shock results in a parallel shift of the marginal damage function.

functions are uncorrelated.

The time structure of the model follows that of C-R'89 and it is based on the assumption that governments in general are less informed about firms' demand and cost functions, than the firms are. Hence:

Stage 1 The governments choose the policy regime (standards or taxes).

Stage 2 The governments choose the actual policy levels (tax rate or emission standard) to maximize local welfare.

Stage 3 Uncertainty is revealed to the firms.

Stage 4 Firms compete in output to maximize profits.

3 Optimal Policy Instrument with Several Modes of Uncertainty

In order to determine which policy instrument is chosen we derive the Nash equilibrium of the game taking into account all the possible choices of both governments. In other words, we derive the full payoff matrix of expected welfare levels for every possible contingency, i.e., when the domestic and the foreign governments implement the same or different policy instruments.

3.1 Both Governments Implement Emission Standards

In order to derive the Bayes Nash equilibrium for this case we solve the problem backwards. Hence, our solution starts from the final stage of the game, where firms compete in outputs given that both governments choose emission standards to regulate pollution. Recall that, when standards are used as instruments, the only control variable left to firms is production, while abatement can only take the value that satisfies equation (1). Bearing this in mind, we maximize domestic profits with respect to output and obtain the reaction function of output,

$$\begin{aligned} \frac{d\pi}{dx} &= 0 \\ s.t.\ a &= x - z \\ &\iff x = \frac{B - c + \theta - u - X + gz}{2+g}, \end{aligned} \tag{6}$$

where $\frac{\partial x}{\partial X} = -\frac{1}{2+g} < 0$ is the slope of the domestic firm's reaction function. We observe from the reaction function given in (6) that output adjusts positively when a positive demand shock occurs, yet this adjustment is proportionally lower than the shock per se. Solving simultaneously the domestic and the respective foreign firms' reaction functions, we obtain equilibrium outputs as a function, among other things, of domestic and foreign emission standards:

$$x = \frac{(B - c + \theta - u)(1 + g) + g(2 + g)z - gZ}{(1 + g)(3 + g)}. \tag{7}$$

From equation (7) and the respective foreign equilibrium output we obtain that $\frac{dx}{dz} > 0$, $\frac{dX}{dZ} > 0$, $\frac{dx}{dZ} < 0$ and $\frac{dX}{dz} < 0$. The last two derivatives imply that when regulation abroad is relaxed, local output falls due to the negative slope of the reaction function (6). This derivative is the core of the so called "strategic environmental policy" literature, since it creates incentives for the governments to relax regulation in order to favor, i.e., shift profits, the exporting firms.

Since governments do not know the exact position of demand, abatement and damage functions, given equilibrium outputs in both countries, they select the optimal level of emission standards by maximizing expected welfare (i.e., $Ew = E\pi - Ed$):

$$\frac{dEw}{dz} = E\left\{ \underbrace{\frac{\partial \pi}{\partial x}\frac{\partial x}{\partial z}}_{\substack{\text{zero due to}\\ \text{F.O.C}}} + \underbrace{\frac{\partial \pi}{\partial z}}_{\substack{\text{direct}\\ \text{effect}\\ (+)}} + \underbrace{\frac{\partial \pi}{\partial X}\frac{\partial X}{\partial z}}_{\substack{\text{strategic}\\ \text{effect}\\ (+)}} - \underbrace{\frac{\partial d}{\partial z}}_{\substack{\text{regulation}\\ \text{benefit}\\ (+)}} \right\} = 0$$

$$\iff \quad z = \frac{g(2 + g)^2 \left[(B - c)(1 + g) - gZ\right]}{\zeta_1}, \tag{8}$$

where $\zeta_1 = g\left\{9 + 2g\left[8 + g(5 + g)\right]\right\} + (1+g)^2(3+g)^2k$. Equation (8) gives the reaction function of the domestic regulator. That is, $\frac{\partial z}{\partial Z} < 0$ implies that domestic and foreign emission standards are strategic substitutes (see Bulow et al., 1985). If the foreign regulator tightens its standard then the domestic laxes its own and the reverse. Strategic substitutability of standards follows when the standard is tighter in one country, thus, production in that country falls, which in turn increase the production of the rival firm through the output reaction function in (6). As a result, the firm in that country faces a higher marginal cost of abatement and the regulator a tighter strategic incentive which amplify the direct and strategic effects respectively, and in turn force the rival regulator to relax further the standard.

Solving simultaneously (7), the domestic government's reaction function (8) and the corresponding equations for the foreign firm and government we obtain the Bayes Nash equilibrium:

$$\left\{ \begin{array}{c} x^* = X^* = \frac{(B-c)(1+g)(3+g)(g+k)}{m} + \frac{\theta - u}{3+g} \\ z^* = Z^* = \frac{(B-c)g(2+g)^2}{m} \end{array} \right\}, \quad (9)$$

where $m = g[9+g(11+3g)]+(1+g)(3+g)^2k$. These are the equilibrium levels of outputs chosen by the firms and emission standards chosen by the governments. Abatement can be calculated through equation (1). Since the standard is set by the government it does not depend on θ and u, while output is volatile since demand and abatement are stochastic. However, equilibrium outputs increase (decrease) less in absolute terms when a positive shock occurs in the demand intercept (marginal cost of abatement), than the change per se and vice-versa. Moreover, the strategic effect is positive and creates an incentive to relax regulation (increase z) compared to the case where it is equal to zero, which describes the first best scenario where regulation is set such that marginal cost of abatement and marginal damage are equalized, i.e., $\frac{\partial \pi}{\partial z} = \frac{\partial d}{\partial z}$, and thus the externality is fully internalized. In order to determine the level of expected welfare in the case of standards we substitute equilibrium values given in (9) and the implied abatement level in (1), into (4). After taking expectations and some algebraic manipulation we get:[9]

$$Ew^*_{zZ} = \frac{(B-c)^2(g+k)(2+g)\zeta_1}{2m^2} + \underbrace{\frac{(2+g)}{2(3+g)^2}var(\theta)}_{CR \text{ benefit for standards}} + \underbrace{\frac{(2+g)}{2(3+g)^2}var(u)}_{\text{modified } CR \text{ benefit for standards}}, \quad (10)$$

where the subscripts denote that a standard is used in both countries, var(θ) is the mean-preserving spread distribution (variance) of the demand intercept and var(u) stands for the variance of marginal cost of abatement.

The second right hand side term of (10) indicates that expected welfare depends positively on var(θ), i.e., ex ante welfare increases with uncertainty. Two opposing effects determine this outcome. The positive effect is due to the convexity of the profit function in terms of the

[9] All the calculations in the paper are carried out using Mathematica 6.

demand intercept and it is similar to the ones introduced by C-R'89 and Creane and Miyagiwa's (2008) strategic trade models. Another interpretation of this result is that since firms are better informed about θ, expected profits, thus expected welfare depend positively on var(θ), as the damage from pollution is not affected by the demand variability because pollution is fixed at the selected level. The negative effect, absent from the strategic trade models, is attributed to the convexity of the abatement cost function, which implies that high $var(\theta)$ entails a negative impact on expected profits and thus welfare. Nonetheless, the positive effect is stronger than the negative one and thus the overall effect is positive. We denote the overall outcome as "CR" benefit due to the similarity with the one introduced in C-R'89 and, thus, expected welfare depends positively on $var(\theta)$ as illustrated in equation (10).

The third right hand side term of (10) may be interpreted similarly; The positive sign in front of var(u) reflects the fact that the firms are better informed than the governments. We denote this as "modified CR" benefit. This benefit stems from the form of the abatement cost function. Each firm, after observing the actual value of u, adapts abatement through output decisions creating a positive component in the expected welfare level. Again a negative effect appears with uncertainty attributed to lower expected revenues as var(u) magnifies. Since the positive effect outweighs the negative one, expected welfare depends positively on var(u).

3.2 Both Governments Implement Emission Taxes

We now assume that both governments impose taxes to control pollution. Now firms have two available control variables, output and the abatement level. Solving backwards we derive the first order conditions for the domestic firm:

$$\frac{d\pi}{dx} = 0 \iff x = \frac{B - c - t + \theta - X}{2}, \tag{11}$$

$$\frac{d\pi}{da} = 0 \iff ga + u = t \iff a = \frac{t-u}{g}. \tag{12}$$

The output reaction function of the domestic firm is given in equation (11). As in the case of standards, laxer environmental policy, i.e., lower tax, shifts the output reaction function outwards. This drives the firm to increase its output. Moreover, we observe that when taxes are used, the output reaction function becomes steeper than the corresponding one in the case of standards, and results to a more aggressive behavior in output rivalry. The profit maximizing condition with respect to abatement is given by equation (12) and states that the marginal cost of abatement equals the pollution tax. The equilibrium values of outputs as a function of taxes and the parameters of the model are obtained by solving the domestic and foreign firms' reaction functions simultaneously:

$$x = \frac{B - c + \theta - 2t + T}{3}. \tag{13}$$

From equation (13) and the respective foreign equilibrium output we obtain that $\frac{dx}{dt} < 0$, $\frac{dX}{dT} < 0$, $\frac{dx}{dT} > 0$ and $\frac{dX}{dt} > 0$. The strategic effect, similarly to the case of standards, is founded in the last two partial derivatives, which imply that when an emissions tax abroad is lowered, local output falls due to the negative slope of the reaction function (11).

Next we examine the domestic government's decision for the optimal tax. Governments maximize expected welfare with respect to the emissions tax. Thus, for home we have:

$$\begin{aligned} \frac{dEw}{dt} \quad &= \quad E\left\{\frac{\partial\pi}{\partial x}\frac{\partial x}{\partial t} + \frac{\partial\pi}{\partial a}\frac{\partial a}{\partial t} + \frac{\partial\pi}{\partial X}\frac{\partial X}{\partial t} + \frac{\partial\pi}{\partial t} + \frac{\partial(tz)}{\partial t} - \frac{\partial d}{\partial z}\frac{\partial z}{\partial t}\right\} = 0 \\ &\iff \quad t = \frac{g[3k + g(-1+2k)](B - c + T)}{\zeta_2}, \end{aligned} \tag{14}$$

where $\zeta_2 = g(9+4g) + (3+2g)^2 k$. Equation (14) gives the home government's reaction function in the case of emission taxes. If $3k + g(-1+2k) > 0$ taxes are strategic complements, which as we will see later, is a necessary condition for the existence of an interior solution in equilibrium, i.e., non-negativity of taxes. For example, when the domestic government lowers its tax, the domestic firm increases its output. This leads to lower foreign output through the reaction function and therefore the foreign tax is also reduced, implying the strategic complementarity of taxes. The main implication of strategic complementarity is that a potential rivalry in tax competition would cause a vicious cycle of relaxing taxes (i.e., a race to the bottom), which would inevitably harm both the environment and firms profits since firms produce too much output. On the other hand, if $3k + g(-1+2k) < 0$, taxes are strategic substitutes and results to a negative pollution tax (a pollution subsidy). This is infeasible as it implies a negative level of abatement (see equation (12)). For obvious reasons, this possibility is omitted from the rest of the analysis.

In order to obtain the equilibrium levels of outputs, taxes, and pollution in the two countries we solve simultaneously equations (1), (12), (13) and (14) and the corresponding equations for the foreign firm and government, to obtain:

$$\left\{ \begin{array}{c} x_t^* = X_T^* = \frac{(B-c)(3+2g)(g+k)}{n} + \frac{\theta}{3} \\ z_t^* = Z_T^* = \frac{2(B-c)g(2+g)}{n} + \frac{\theta}{3} + \frac{u}{g} \\ t^* = T^* = \frac{(B-c)g[3k+g(-1+2k)]}{n} \end{array} \right\}, \tag{15}$$

where $n = g(9 + 5g) + (3 + g)(3 + 2g)k$ and abatement in equilibrium is implied by (12), i.e., $a^* = \frac{t^* - u}{g}$. As already mentioned, $k > \frac{g}{3+2g}$ is a necessary and sufficient condition for the existence of an interior solution. Comparing the solutions (15) and (9) several inferences can be drawn that play a significant role in determining the expected national welfare levels. When emission taxes are implemented instead of standards, the greater slopes of output reaction functions and the strategic complementarity of taxes, lead to higher output and pollution in equilibrium.

Furthermore, in contrast to the case of emission standards, when taxes are implemented, pollution is stochastic as it depends on production and abatement, which are random due to involved demand and abatement cost uncertainty. This is so as, the total marginal cost of production runs steeper when a standard is used, in contrast to the case of a tax where the marginal cost is horizontal (see footnote 6). Hence, firms are more flexible in the case of taxes rather than in the case of standards. This is illustrated in Figure 1:

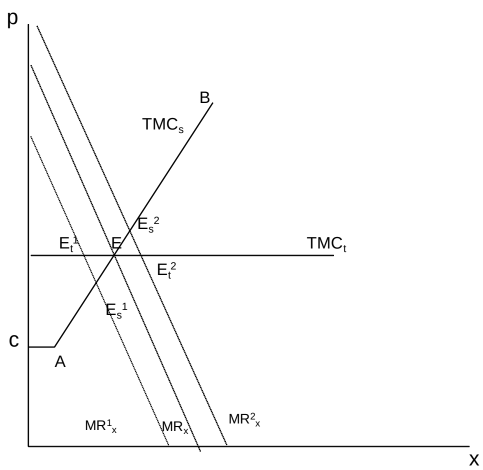

Figure 1

The total marginal cost of production when a tax is the policy instrument, is obtained through equation (3) and equals $c+t$, which is represented in Figure 1 by the horizontal line TMC_t. The total marginal cost of production when a pollution quota is the chosen policy instrument, is obtained again from (3) and is represented by the kinked line cAB. The kink at point A denotes that from this point onwards the standard becomes binding. We initially assume that the equilibrium is at point E, where the total marginal cost of output, when a standard or a tax is used, are equal and intersect the marginal revenue (MR_x). Two possible shocks are represented in the demand intercept (one negative and one positive, which shift marginal revenue from MR_x to MR_x^1 and MR_x^2, respectively) and four new equilibria are obtained (E_t^1 and E_t^2 for taxes, and E_s^1 and E_s^2 for standards). From this we observe that the equilibrium output becomes less responsive to demand variability when a standard is implemented rather than a pollution tax.

Substituting the new equilibrium levels from (15) and abatement obtained from (12) into (4) and taking expectations, we obtain the expected welfare for each country:

$$Ew_{tT}^{*} = \frac{(2+g)(g+k)(B-c)^2\zeta_2}{2n^2} + \underbrace{\frac{1}{9}var(\theta)}_{CR \text{ benefit for taxes}} + \underbrace{\frac{1}{2g}var(u)}_{\text{modified } CR \text{ benefit for taxes}}$$
$$-\frac{k}{18}var(\theta) - \frac{k}{2g^2}var(u) =$$
$$\frac{(2+g)(g+k)(B-c)^2\zeta_2}{2n^2} - \frac{(k-2)}{18}var(\theta) + \frac{(g-k)}{2g^2}var(u). \qquad (16)$$

In contrast to the case of standards, expected welfare is a negative function of var(θ) when $k > 2$. Nonetheless, if $k < 2$, expected welfare depends positively on the variance of the demand intercept. This reflects the fact that pollution is now stochastic as it is determined by the difference of production minus abatement carried out in equilibrium. Subsequently, the higher the variance of the demand function is, the more stochastic is pollution and has a negative effect on welfare. However, as in the previous case, expected profits depend positively on var(θ) due to the existence of the CR benefit. In particular, the CR benefit is magnified because firms have greater flexibility in output competition (see Figure 1) and abatement is deterministic which implies that abatement cost is constant. The overall effect of var(θ) on expected welfare is ambiguous. If the damage caused from the pollutant is severe enough ($k > 2$) then the negative effect implied by the variability in the damage function is greater than the CR benefit.

Expected welfare falls as uncertainty rises, while the opposite holds when the pollutant is less harmful.

A similar reasoning applies for the effect of uncertainty on marginal abatement cost over expected welfare. The presence of uncertainty implies higher expected welfare attributed to the modified CR benefit. Compared to the case of standards this benefit is now higher because firms have two choice variables. One is output and the other is abatement. Hence, the firms use their abatement decisions in order to conform with the actual level of abatement cost, while output decisions remain unaffected. This implies that the implementation of taxes creates only a positive effect in terms of expected profits. However, a negative effect on expected welfare also appears, since pollution is stochastic and thus damage from pollution is stochastic as well. Which of the two effects prevails, depends on the scalars g and k that determine the slopes of marginal cost of abatement and marginal damage, respectively. In particular, as it can be observed from equation (16) when $k > g$, i.e., the marginal damage is steeper than the marginal cost of abatement, the negative effect offsets the positive one, the expected welfare level depends negatively on $\text{var}(u)$, and vice-versa.

3.3 The Asymmetric Case

We turn now to the case where one government uses a standard and the rival imposes a tax. We only solve for the case where, in order to regulate pollution and shift rents towards the own exporting firm, the domestic government implements an emissions standard and the foreign uses an emissions tax. The reverse problem is equivalent since the model is symmetric.

The problem is again solved by backwards induction. At the final stage firms maximize profits. Because of the different choice of the policy instruments, the domestic firm maximizes profits with respect to output, while the foreign with respect to output and abatement. The reaction function of the output of the domestic firm is given by equation (6), while the first order conditions for the foreign firm are given by (11) and (12) respectively. Solving these simultaneously, we attain the equilibrium levels of outputs as a function of the domestic emissions standard and the foreign pollution tax:

$$x = \frac{B - c + \theta - 2u + 2gz + T}{3 + 2g} \text{ and } X = \frac{(B - c + \theta)(1 + g) - (2 + g)T - gz + u}{3 + 2g}. \quad (17)$$

From (17) we observe that when the domestic government relaxes its standard then domestic output rises, while the foreign one falls. The reverse holds when the foreign government reduces its own tax. Hence, even in the case that both governments select different policy instruments the incentive to relax environmental policy for rent shifting purposes is still present and only the magnitudes are affected.

In light of (17), and given the assumed uncertainties, both regulators select the optimal level of their policy instrument by maximizing expected welfare with respect to the corresponding instrument.[10] So, the domestic and foreign reaction functions are as follows:

$$z = \frac{(B - c + T)2g(2 + g)}{\zeta_2} \text{ and } T = \frac{g[-g + (1 + g)(3 + g)k][(B - c)(1 + g) - gz]}{\zeta_1}. \tag{18}$$

The domestic government's reaction function is positively sloped, since a decrease in the foreign tax lowers the domestic output. In turn, marginal cost of abatement and the strategic incentive are lowered and drive the regulator to tighten the standard. The foreign regulator's reaction function must be negatively sloped, since a decrease in the domestic standard increases foreign output which requires a higher tax.[11]

Solving equations (17) and (18) together with the corresponding ones of (1) and (12) for the foreign firm, we obtain the Bayes Nash equilibrium levels of outputs, the domestic and foreign pollution and the foreign tax:

$$\left\{ \begin{array}{c} x^*_{zT} = \frac{(B-c)(3+2g)(g+k)\zeta_3}{q} + \frac{\theta-2u}{3+2g} \\ X^*_{zT} = \frac{(B-c)(1+g)(g+k)(3+g)\zeta_4}{q} + \frac{(1+g)\theta+u}{3+2g} \\ z^*_{zT} = \frac{2(B-c)g(2+g)\zeta_3}{q} \\ Z^*_{zT} = \frac{(B-c)g(2+g)^2\zeta_4}{q} + \frac{(1+g)(g\theta+3u)}{g(3+2g)} \\ T^*_{zT} = \frac{(B-c)g[-g+(1+g)(3+g)k]\zeta_4}{q} \end{array} \right\}, \tag{19}$$

[10] We follow a process equivalent to (8) and (14) for the home and the foreign country respectively.

[11] Hence, the foreign tax and the domestic standard must be strategic substitutes (i.e. $-g+(1+g)(3+g)k > 0$), otherwise, as we will see right after, an interior solution for the foreign emission tax in equilibrium is not possible. It can be verified that the stability of the system is satisfied by the slopes of the reaction functions given in (18).

where

$$
\begin{aligned}
q &= g^2(3+2g)[9+2g(4+g)] + g\{54+g\{132+g[120+g(48+7g)]\}\}k \\
&\quad +(1+g)^2(3+g)^2(3+2g)k^2, \\
\zeta_3 &= g[3+g(g+3)] + (1+g)^2(3+g)k \text{ and } \zeta_4 = g(g+3)+(1+g)(3+2g)k.
\end{aligned}
$$

Following a similar reasoning to the one of the previous subsection we can understand why domestic output is less sensitive to unanticipated shifts in demand (see Figure 1). Using the equilibrium values given in (19) we are ready to calculate domestic and foreign expected welfare levels when the home country uses an emissions standard, while the foreign country uses an emissions tax:

$$
Ew^*_{zT} = EW^*_{tZ} = \frac{1}{2}(2+g)\left(\frac{(B-c)^2(g+k)\zeta_3^2\zeta_2}{q^2} + \frac{var(\theta)}{(3+2g)^2} + \frac{4var(u)}{(3+2g)^2}\right) \tag{20}
$$

$$
\text{and } EW^*_{zT} = Ew^*_{tZ} = \frac{1}{2}\left(\begin{array}{c} \frac{(B-c)^2(g+k)(2+g)\zeta_4^2\zeta_1}{q^2} - \frac{(1+g)^2(k-2)}{(3+2g)^2}var(\theta) \\ +\frac{\{g[9+2g(7+2g)]-9(1+g)^2k\}}{2g^2(3+2g)^2}var(u) \end{array}\right). \tag{21}
$$

From (21) we infer that in the country where a tax is levied to regulate pollution, its expected welfare, i.e., $EW^*_{zT} = Ew^*_{tZ}$, depends either positively or negatively on var(θ) and var(u). As in the previous section this depends on how injurious the pollutant is to the citizens of this country. In the country where an emissions standard is chosen, its expected welfare depends positively on var(θ) and var(u) because the CR benefit and the modified CR benefit are still present. This occurs regardless of the choice of the policy instrument in the rival country.

4 Form of Intervention

Having derived the expected welfare levels for all the possible policy combinations, we now turn to the Nash equilibrium choice of a country's policy instrument. In order to simplify the analysis and attribute exactly to each mode of uncertainty its effect on policy instrument choice we will separate the analysis in two subcases: a) Uncertainty in demand and b) uncertainty in abatement cost and damage functions.

4.1 Uncertainty in Demand

In this subcase we assume that the stochastic terms u and ξ are equal to zero which imply that $var(u) = var(\xi) = 0$. Before determing the Nash equilibria of the policy instrument choice game we provide the optimal response of the domestic regulator for each possible policy instrument chosen by the rival. Lemma 1 summarizes these results:[12]

Lemma 1*:*

a)When var(θ), var(u)$\rightarrow$ 0, i.e., near certainty, choosing an emissions standard dominates in terms of welfare the choice of an emissions tax, regardless of the other country's choice of policy instrument.

b) When var(θ) is sufficiently high and the rival country chooses an emissions standard, then choosing a tax is optimal iff $\frac{g}{(1+g)(3+g)} < k < \frac{g\{15+2g[12+g(6+g)]\}}{(1+g)^2(3+g)^2}$.

c) When var(θ) is sufficiently high and the rival country chooses an emissions tax, then choosing a tax is optimal iff $\frac{g}{(3+2g)} < k < \frac{g(15+8g)}{(3+2g)^2}$.

d) When var(θ) is sufficiently high and $\frac{g}{(3+2g)} < k < \frac{g(3+2g)}{(3+g)^2}$, then both countries choosing a tax welfare dominates to both choosing a standard.

Proof in Appendix■

Using Lemma 1, we define the Nash equilibrium both for the cases of certainty and uncertainty in the following proposition:

Proposition 1*:*

a) When var(θ), var(u)$\rightarrow$ 0, the Nash equilibrium suggests that both countries regulate pollution through emission standards.

b) When var(θ) is sufficiently high and $\frac{g}{(3+2g)} < k < \frac{g\{15+2g[12+g(6+g)]\}}{(1+g)^2(3+g)^2}$, then in the Nash equilibrium both countries choose an emissions tax as a policy instrument.

c) When var(θ) is sufficiently high and $\frac{g(15+8g)}{(3+2g)^2} > k > \frac{g\{15+2g[12+g(6+g)]\}}{(1+g)^2(3+g)^2}$, then we obtain two symmetric Nash equilibria in pure strategies where both countries select either a standard or a tax, and one in mixed strategies where each regulator selects a standard or a tax with positive probabilities.

[12]Because of the invoked symmetry in the model, the Nash equilibrium policy choices of the foreign given home's policy choices are identical to those in Lemma 1.

d) If $k > \frac{g(15+8g)}{(3+2g)^2}$, then both countries choose emission standards to deal with pollution problems regardless of var(θ). Finally, when $k \geq 2$, choosing standards is always an equilibrium strategy independently of the value of g.

Proof in Appendix■

The results in Lemma 1 and Proposition 1 can be interpreted as follows. First, as noted in the reviewed literature, e.g., Lahiri and Ono (2007), Ulph (1992, 1996b) and Yanase (2007), and as stated in parts (a) of Lemma 1 and Proposition 1, in the absence of uncertainty or when uncertainty converges to zero the Nash equilibrium choice of emissions standards over emission taxes by all rival countries leads to welfare superior outcomes. However, as stated in the remaining parts of the aforementioned lemma and proposition, at Nash equilibrium, this result may be reversed when uncertainty, here in terms of demand conditions, exists. In particular, when uncertainty is high and k is relatively low (lower than the critical values), then superior welfare outcomes emerge when both countries choose emission taxes to regulate pollution. The presence of demand uncertainty, given certain parameter values, it provides Nash equilibria in a choice game where governments not only may select different policy instruments, but also the use of emission taxes may be welfare superior to that of emission standards.

It can be shown that the derivatives of the critical values $\frac{g\{15+2g[12+g(6+g)]\}}{(1+g)^2(3+g)^2}$ and $\frac{g}{(3+2g)}$ (which imply the use of taxes in equilibrium) with respect to g are increasing. Moreover, the derivative of the first critical value is greater than that of the second, and it results to a greater range of values of k that can support the use of pollution taxes in equilibrium, as g increases. This is attributed to the fact that, for high values of g, when a standard is used as a policy instrument, output becomes less sensitive to any possible demand shocks, since the marginal cost of abatement and thus the marginal cost of production become steeper. As a result, the CR benefits, attributed to the firms and the high variability in demand, are now lower. This does not occur when a tax is chosen, as the marginal cost of production is independent of g. The CR benefits attributed to the firm due to the use of a tax, remain unchanged irrespective of the level of g. Moreover, the losses caused from the variability of pollution in the damage function are now lower, since a greater g implies a steeper marginal abatement cost and thus a lower variability in pollution. Putting these results together, intuitively we understand that taxes become more attractive as a policy instrument when g is higher. Unless, the injuriousness of the pollutant is extremely high (i.e., $k \geq 2$), emission taxes may emerge as an equilibrium strategy.

We now turn to the analysis of the mixed strategies in part (c) of Proposition 1. Could they be interpreted beyond the usual exercise of "flipping a coin over strategies"? One possible explanation is that a mixed strategy can be seen as a pure strategy in both instruments, that is, the regulator imposes both a standard and a tax. In line with this, the probability fraction might indicate the percentages of standards and taxes to be imposed, of the respective optimal levels of standards and taxes, when these instruments are imposed separately. However, this issue deserves a more detailed analysis which lies out of the scope of this paper.

The welfare implications of Proposition 1 are significant, since it notes cases where the exporting countries can be better off in terms of their expected welfare by choosing taxes over emission standards. Hence, a Pareto superior outcome can be achieved in terms of expected national welfare for the two exporting countries. Nonetheless, one might wonder what happens with expected welfare in ROW and more importantly what happens in expected global welfare, which is equal to the sum of the expected welfare values in each country. Concerning ROW's expected welfare it follows intuitively that taxes lead to a superior outcome since they imply greater production by the exporting firms and thus a lower price, increasing consumers' surplus. When uncertainty is very high, the implementation of taxes leads to higher expected welfare in every country and consequently to an increase of expected global welfare. If uncertainty is rather low and the two exporting countries select standards, then expected welfare is lower in ROW and therefore the effect on expected global welfare becomes ambiguous.[13]

In terms of pollution it can be shown that the common scenario suggests that emission standards lead to lower pollution in comparison to taxes, unless a significant negative shock affects the demand (see Appendix). However, this does not affect the third country's welfare since the pollutant is assumed to be local.

4.2 Uncertainty in the Cost of Abatement and Damage

We now consider the case of certainty in demand conditions, i.e., $\theta = 0$ which implies that $var(\theta) = 0$, while uncertainties in the cost of pollution abatement and damage caused from

[13] These results can be shown also algebraically. However, the value added is minimal as the implications follow directly from the analysis thus far. For an excellent survey see also Ulph (1997).

pollution are present, as introduced by the stochastic terms in equations (2) and (5). Moreover, recall that the stochastic terms (u) and (ξ) are assumed uncorrelated.

One implication that we discretely avoid to discuss during the solution procedure is that uncertainty about the damage function (var(ξ)) does not appear in the expected welfare levels; hence we do not expect that it will affect the selection of the policy instrument. This result is in line with Weitzman (1974), Fishelson (1976) and Adar and Griffin (1976). The explanation is that uncertainty in the damage function does not affect firms' decisions in the final stage of the game. However, as Stavins (1996) points out, this is true only in the case where the stochastic variables are uncorrelated.

The following lemma provides the optimal strategies for the determination of the new Nash equilibria in the policy instrument choice game:

Lemma 2*:*

a) When var(u) is sufficiently high and the rival country chooses a standard, choosing a tax is optimal $iff\ \frac{g}{(1+g)(3+g)} < k < \frac{g\{27+2g[27+g(16+3g)]\}}{3(1+g)^2(3+g)^2}$.

b) When var(u) is sufficiently high and the rival country chooses a tax, choosing a tax is optimal $iff\ \frac{g}{(3+2g)} < k < \frac{g(9+4g)}{(3+2g)^2}$.

c) When var(u) is sufficiently high, then both countries choosing standards, welfare dominates to choosing taxes $iff\ k > \frac{g(9+4g)}{(3+g)^2}$.

Proof in Appendix■

From Lemma 2 we can derive the following proposition:

Proposition 2*:*

a) When var(u) is sufficiently high and $\frac{g}{(3+2g)} < k < \frac{g(9+4g)}{(3+2g)^2}$*, then in the Nash equilibrium both countries choose emission taxes as a policy instrument.*

b) When var(u) is sufficiently high and $\frac{g(9+4g)}{(3+2g)^2} < k < \frac{g\{27+2g[27+g(16+3g)]\}}{3(1+g)^2(3+g)^2}$*, then we obtain two asymmetric Nash equilibria in pure strategies where one government selects a tax and the rival one chooses an emissions standard, and one in mixed strategies where each country selects a policy instrument assigning positive probabilities.*

c) If $k > \frac{g\{27+2g[27+g(16+3g)]\}}{3(1+g)^2(3+g)^2}$ *then both governments in equilibrium choose an emissions standard to deal with pollution problems regardless of var(u). Finally, when* $k \geq 2$ *, choosing standards is always an equilibrium strategy independently of the value of* g*.*

Proof in Appendix■

Proposition 2 establishes the necessary and sufficient conditions for taxes to constitute a Nash equilibrium strategy.[14] Similarly to the previous case, we observe that taxes constitute an equilibrium strategy only when the marginal damage cost coefficient is sufficiently low in absolute terms. However, a general policy rule can be proposed following the implications of Proposition 2: When the marginal damage is steeper than the marginal cost of abatement, i.e., $k > g$, then a standard yields a superior outcome in terms of expected welfare, compared to a tax. This appears because the critical value, $\frac{g\{27+2g[27+g(16+3g)]\}}{3(1+g)^2(3+g)^2}$, is lower than g. This result is similar to the one derived by Weitzman (1974) and other papers in the relevant literature, for the case of a regulator who is uncertain about the intercepts of abatement cost and damage functions.

Despite this, the reverse is not always true. When the marginal cost of abatement runs steeper than marginal damage, then several conditions must hold to favor a tax. As suggested by Proposition 2, k must lie below the critical value ($\frac{g(9+4g)}{(3+2g)^2}$) which is lower than g. This condition, renders taxes a superior policy instrument compared to a standard. Even in this scenario taxes do not always guarantee superior expected welfare outcomes as the outcome depends on the level of $\mathrm{var}(u)$. As suggested in part (c) of Proposition 2, when k takes values above a specific critical value ($\frac{g\{27+2g[27+g(16+3g)]\}}{3(1+g)^2(3+g)^2}$) then standards yield greater expected benefits compared to taxes, regardless of the level of $\mathrm{var}(u)$. Similarly to the case of demand uncertainty, when $k \geq 2$ a standard always leads to a superior outcome in terms of expected welfare.

As in the previous subsection, although the results seem rather cumbersome, the driving forces in the model are rather simple. Under uncertainty, when g is relatively high and k is relatively low, then a tax is superior in terms of welfare than a standard. In terms of Weitzman's modeling it can be said that this result holds and taxes might lead to higher expected welfare, yet only if uncertainty is sufficiently high. This is in line with the implications of Baldursson and von der Fehr (2004), although their results are based on the fact that the decisions of some agents are irreversible. In contrast to that, our bias towards taxes is attributed to the fact that the use of taxes postulates greater flexibility to the firms, in contrast to the use of standards. When k is relatively high, then the cost associated with the use of taxes rises because pollution

[14]Lemma 2 and Proposition 2 do not include the first part of the corresponding previous ones since the main result remains unaffected. When uncertainty is very low or close to zero, standards yield higher welfare regardless of the strategy of the rival.

volatility is very costly to the citizens. If g is low, modified CR benefits increase when both taxes and standards are implemented. Yet, even in such a scenario the implementation of taxes is very unlikely because in most of the cases k will be relatively higher.

Another important implication resulting from Proposition 2 is that uncertainty about the damage function does not affect the choice of the policy instrument. This occurs because the decisions of firms in final stage remain unaffected from any potential shocks in the damage function. It is important to note here that this result is sensitive to the assumption that uncertainties in the marginal cost of abatement and the marginal damage are uncorrelated. According to Stavins (1996) this does not hold when this assumption is retracted. Following Stavins' rationale we should expect that when uncertainties are positively correlated, the use of standards should become more likely. If uncertainties are negatively correlated then taxes should be more favorable.

To wrap up and provide comprehensive results from the analysis in this section we provide the following proposition:

Proposition 3*:*

When governments are uncertain about the intercepts of the marginal cost of abatement and damage functions, and uncertainties are uncorrelated then:

a) $k > g$ *is a sufficient condition such that a standard is superior to a tax,*

b) $k < g$ *is a necessary condition such that a tax is superior to a standard, and*

c) uncertainty in marginal damage does not affect the ranking of the policy instruments.

4.3 Simultaneous Uncertainty

Given the results above we may infer what happens in case that uncertainty is present in the demand, abatement and damage functions at the same time. In particular, when uncertainty is relatively low the use of emission standards by the two governments is optimal as the benefits attributed to the use of taxes are minimized. This is also the case when the parameter determining the damage from pollution, k, takes high values relative to the slope of marginal abatement cost. Variability in pollution leads to significant welfare losses making standards more favorable.

On the other hand we shall expect that governments select taxes when the slope of marginal abatement cost, g, becomes steeper since the firms gain an advantage compared to the case where standards are implemented. It should be clear that this is due to the fact that firms are less flexible. Yet, this positive effect is magnified and becomes a sufficient condition if and only if the stochastic terms are significantly large. The latter one is a core result of this paper, bringing into light the key role of the level of uncertainty. In terms of policy making this means that the regulator not only needs to compare the slopes or the elasticities of abatement cost and marginal damage functions respectively, yet must take also into account the current conditions in the economy. In uncertain times as nowadays, taxes may be implemented providing industries with a flexibility to adjust to any possible unexpected variations. In a different case standards offer a clear advantage. The fact that the economies are open strengthens the bias in favor of standards compared to the original case suggested by Weitzman and the relevant literature. Of course these results are not binding as in a real world setting things are much more complicated. It provides, however, with important implications for occasions where the governments use environmental policy instruments as "secondary" means to promote the exporting industries.

5 Concluding Remarks

The aim of this paper was to define the optimal choice of the environmental policy instrument in an international duopoly model, where governments use their policies not only to deal with pollution but to shift rents towards their own firms in an uncertain environment. The calculations needed in order to obtain the results are complex, but the obtained results are of general validity.

In particular, we illustrated that when the regulators have full information, then standards should be preferred to taxes in equilibrium in both countries. In other words, with no uncertainty standards constitute a Nash equilibrium strategy in the policy instrument choice game. This result is stronger than the result suggested by Lahiri and Ono (2007), Ulph (1996b) and Yanase (2007). However, in very uncertain environments taxes can break down the superiority of standards, when the slope of marginal damage is relatively low. This is true only when uncertainty is sufficiently high, which implies that the level of uncertainty matters.

Several concerns about the model may be expressed. For instance, the reader might wonder how our results are affected when we allow for transboundary pollution. Undoubtedly, climate change is a great challenge facing our economies today. As moderate estimates predict (Stern, 2007), if no immediate action takes place, future damages in GDP will range from $5\% - 20\%$ per year. Therefore, policy makers should design and implement CO_2 emissions regulation. In such a case our results are affected quantitatively but not qualitatively. Since foreign pollution is added to the local one, the damage caused from pollution to the society when one unit of pollution is emitted is now higher. This enforces the governments to tighten regulation regardless of the policy instrument used. In the sub-case where both governments implement a tax, the negative effect from the variability in pollution is now higher. This makes taxes less favorable for a greater range of values of k. So, taxes are less likely to be used when the pollutant is global.

Another objection to our model might be the absence of consumption of the exporting good in the two exporting countries, which might affect the derived welfare implications. Quirion (2004), Heuson (2008a, 2008b) and Hoel (1998) re-examine using closed economy models, Weitzman's question of "prices versus quantities" in second best environments. The authors claim that in such an environment taxes admit a greater advantage over standards. Hence, in our model we expect that the introduction of consumption in the two exporting countries, the imposition of a positive cost in public funds and the existence of unemployment will create an extra bias towards taxes.

Nonetheless, our proposals should be used with care in policy implementation as our model neglects the possibility of using other environmental policy instruments, such as mixed systems that could possibly lead to higher welfare levels. Moreover, our model does not take into account possible asymmetries between domestic and foreign functions, and only allows for risk neutral policy makers. These provide stimulus for future research.

Appendix

Proof of Lemma 1:

a) Define $\kappa_1 = 0.5g^3(B-c)^2(2+g)^2(g+k)^2\zeta_1$, $\kappa_2 = 0.5g^3(B-c)^2(2+g)^2(g+k)^2\zeta_2$ and $\kappa_3 = \{g^2(3+2g)[9+2g(4+g)]+g\{54+g\{132+g[120+g(48+7g)]\}\}k+(1+g)^2(3+g)^2(3+2g)k^2\}^2$.

If the foreign regulator chooses a standard we have:

$$\lim_{var(\theta),var(u)\to 0}(Ew^*_{zZ}-Ew^*_{tZ})=\frac{\kappa_1}{m^2}\frac{\begin{array}{c}g^2\{54+7g[12+g(6+g)]\}\\+g\{108+g\{264+g[238+g(95+14g)]\}\}k\\+2(1+g)^2(3+g)^2(3+2g)k^2\end{array}}{\kappa_3}>0. \quad (A1)$$

If the foreign regulator chooses a tax we have:

$$\lim_{var(\theta),var(u)\to 0}(Ew^*_{zT}-Ew^*_{tT})=\frac{\kappa_2}{n^2}\frac{\begin{array}{c}g^2\{54+g[84+g(46+9g)]\}\\+g(3+2g)\{36+g[64+g(38+7g)]\}k\\+2(1+g)^2(3+g)^2(3+2g)k^2\end{array}}{\kappa_3}>0. \quad (A2)$$

Using equations (A1) and (A2) we observe that when var(θ), var(u)$\to$ 0 standards are a dominant strategy Q.E.D.

b)It can be shown that:

$$Ew^*_{zZ}-Ew^*_{tZ}=\lim_{var(\theta),var(u)\to 0}(Ew^*_{zZ}-Ew^*_{tZ})+\frac{\begin{array}{c}-g\{15+2g[12+g(6+g)]\}\\+(1+g)^2(3+g)^2k\end{array}}{2(3+g)^2(3+2g)^2}var(\theta). \quad (A3)$$

For a tax to be preferred to a standard when the rival chooses a standard, $Ew^*_{zZ}-Ew^*_{tZ}<0$. If $k<\frac{g\{15+2g[12+g(6+g)]\}}{(1+g)^2(3+g)^2}$ and var(θ)$>-\frac{\lim_{var(\theta),var(u)\to 0}(Ew^*_{zZ}-Ew^*_{tZ})2(3+g)^2(3+2g)^2}{-g\{15+2g[12+g(6+g)]\}+(1+g)^2(3+g)^2k}$ then (A3) has a negative sign. Finally, we need to add the necessary condition for the existence of an interior solution which is $k>\frac{g}{(1+g)(3+g)}$ Q.E.D.

c) It can be shown that:

$$Ew^*_{zT}-Ew^*_{tT}=\lim_{var(\theta),var(u)\to 0}(Ew^*_{zT}-Ew^*_{tT})+\frac{-g(15+8g)+(3+2g)^2k}{18(3+2g)^2}var(\theta). \quad (A4)$$

For a tax to be preferred to a standard when the rival chooses a tax, the right hand side of (A4) should be negative. If $k<\frac{g(15+8g)}{(3+2g)^2}$ var(θ)$>-\frac{\lim_{var(\theta),var(u)\to 0}(Ew^*_{zT}-Ew^*_{tT})18(3+2g)^2}{-g(15+8g)+(3+2g)^2k}$ then (A4) has a negative sign. Finally, we need to add the necessary condition for the existence of an interior solution which is $k>\frac{g}{3+2g}$ Q.E.D.

d)It can be shown that:

$$Ew^*_{zZ} - Ew^*_{tT} = \lim_{var(\theta),var(u)\to 0}(Ew^*_{zZ} - Ew^*_{tT}) + \frac{-g(3+2g)+(3+g)^2k}{18(3+g)^2}var(\theta), \qquad \text{(A5)}$$

and $\lim_{var(\theta),var(u)\to 0}(Ew^*_{zZ} - Ew^*_{tT}) > 0$. For expected welfare when taxes are implemented (by both regulators), to be superior to the corresponding one when standards are used (by both governments), the right hand side of (A5) should be negative. If $k < \frac{g(3+2g)}{(3+g)^2}$ and var(θ)$>$ $-\frac{\lim_{var(\theta),var(u)\to 0}(Ew^*_{zZ}-Ew^*_{tT})18(3+2g)^2}{-g(3+2g)+(3+g)^2k}$ then (A5) has a negative sign. Additionally we need to insert the necessary condition for the existence of an interior solution which is $k > \frac{g}{3+2g}$ Q.E.D.

Proof of Proposition 1:

a) From part *a*) of Lemma 1 we get that when var(θ), var(u)$\to 0$ standards are a dominant strategy for both governments. Hence, when var(θ), var(u)$\to 0$ the unique Nash equilibrium is the one where both governments select standards Q.E.D.

b)If we compare the upper limits of the restrictions for k in b) and c) of Lemma 1 we obtain $\frac{g(15+8g)}{(3+2g)^2} - \frac{g\{15+2g[12+g(6+g)]\}}{(1+g)^2(3+g)^2} = \frac{g^2(2+g)[18+g(24+7g)]}{(1+g)^2(3+g)^2(3+2g)^2} > 0$. If we compare the lower limits of the restrictions for k in b) and c) of Lemma 1, we obtain $\frac{g}{(3+2g)} - \frac{g}{(1+g)(3+g)} = \frac{g^2(2+g)}{(1+g)(3+g)(3+2g)} > 0$. We further assume that the restrictions given for var(θ) satisfy both inequalities given in b) and c) of the previous lemma. Given b) and c) from Lemma 1, when $\frac{g}{(3+2g)} < k < \frac{g\{15+2g[12+g(6+g)]\}}{(1+g)^2(3+g)^2}$, choosing taxes for the domestic government will be a dominant strategy. Since the model is symmetric the same holds for the foreign regulator. This suffices for choosing emission taxes as policy instruments at the Nash equilibrium Q.E.D.

c) The equilibrium strategy for the domestic government is determined by the following: max$\{Ew^*_{zZ}, Ew^*_{tZ}\}$and max$\{Ew^*_{zT}, Ew^*_{tT}\}$. Given $\frac{g(15+8g)}{(3+2g)^2} > k > \frac{g\{15+2g[12+g(6+g)]\}}{(1+g)^2(3+g)^2}$, the results and the restrictions for var(θ) given in b) and c) of Lemma 1, we observe that when the foreign government selects a standard then it is optimal for the domestic government to pool to the same strategy (i.e., $Ew^*_{zZ} > Ew^*_{tZ}$). If the foreign regulator chooses a tax then the domestic government selects a tax as well (i.e., $Ew^*_{zT} < Ew^*_{tT}$). Hence, the equilibrium strategy of each regulator is conditional to the strategy of the rival. Given these we obtain two symmetric Nash equilibria in pure strategies where both governments select either standards or taxes. Since we have two symmetric equilibria in pure strategies it is directly implied that a Nash equilibrium in mixed strategies exists. In this equilibrium each government selects its policy instrument with a positive probability. This probability is derived as the weighted value of expected welfare when a standard is used, and equals the corresponding one when a tax is implemented. The weights are the probabilities assigned in the strategies of the rival regulator Q.E.D.

d) If $k > \frac{g(15+8g)}{(3+2g)^2}$, then using b) and c) from Lemma 1 we obtain that choosing standards is a dominant strategy and hence the unique Nash equilibrium involves both governments using standards, irrespective of var(θ).

If we differentiate the threshold level for k, $\frac{g(15+8g)}{(3+2g)^2}$, with respect to g we get $\frac{d\left(\frac{g(15+8g)}{(3+2g)^2}\right)}{dg} = \frac{9(5+2g)}{(3+2g)^3}$. This implies that the threshold level is continuously increasing in the level of g. If we take the limit of the threshold level as g tends to infinity we obtain $\lim_{g\to\infty} \frac{g(15+8g)}{(3+2g)^2} = 2$ Q.E.D.

Proof of Superiority of Standards in Terms of Pollution:

In order to provide a comparison of standards and taxes in terms of pollution we need to take the difference of pollution equilibrium levels when standards and taxes are used in both countries:

$$z^* - z_t^* = -\frac{(B-c)^2 g^2 (2+g)(3+g)(g+k)}{mn} - \frac{\theta}{3}. \tag{A6}$$

From (A6) we observe that pollution is greater in equilibrium when taxes are used instead of standards unless a significant negative shock occurs in demand Q.E.D.

Proof of Lemma 2:

a)It can be shown that:

$$Ew_{zZ}^* - Ew_{tZ}^* = \lim_{var(\theta),var(u)\to 0} (Ew_{zZ}^* - Ew_{tZ}^*) + \frac{\begin{matrix} 3\{-g\{27+2g[27+g(16+3g)]\} \\ +3(1+g)^2(3+g)^2 k\} \end{matrix}}{2g^2(3+g)^2(3+2g)^2} var(u). \tag{A7}$$

For a tax to be preferred to a standard when the rival chooses a standard $Ew_{zZ}^* - Ew_{tZ}^* < 0$. If $k < \frac{g\{27+2g[27+g(16+3g)]\}}{3(1+g)^2(3+g)^2}$ and var(u)$> -\frac{\lim_{var(\theta),var(u)\to 0}(Ew_{zZ}^* - Ew_{tZ}^*)2g^2(3+g)^2(3+2g)^2}{3\{-g\{27+2g[27+g(16+3g)]\}+3(1+g)^2(3+g)^2 k\}}$ this is true. Finally, we need to add the necessary condition for the existence of an interior solution which is $k > \frac{g}{(1+g)(3+g)}$ Q.E.D.

b) It can be shown that:

$$Ew_{zT}^* - Ew_{tT}^* = \lim_{var(\theta),var(u)\to 0} (Ew_{zT}^* - Ew_{tT}^*) + \frac{-g(9+4g)+(3+2g)^2 k}{2g^2(3+2g)^2} var(u). \tag{A8}$$

If $Ew^*_{zT} - Ew^*_{tT} < 0$ then a tax is preferred to a standard when the rival chooses a tax. In case that $k < \frac{g(9+4g)}{(3+2g)^2}$ and var(u)$> -\frac{\lim_{var(\theta),var(u)\to 0}(Ew^*_{zT}-Ew^*_{tT})2g^2(3+2g)^2}{-g(9+4g)+(3+2g)^2k}$ then (A8) has a negative sign. Finally, we need to add the necessary condition for the existence of an interior solution which is $k > \frac{g}{3+2g}$ Q.E.D.

c)It can be shown that:

$$Ew^*_{zZ} - Ew^*_{tT} = \lim_{var(\theta),var(u)\to 0}(Ew^*_{zZ} - Ew^*_{tT}) + \frac{-g(9+4g)+(3+g)^2k}{2g^2(3+g)^2}var(u). \tag{A9}$$

It can be shown that $\lim_{var(\theta),var(u)\to 0}(Ew^*_{zZ} - Ew^*_{tT}) > 0$. In case that $k < \frac{g(9+4g)}{(3+g)^2}$ and at the same time var(u)$> -\frac{\lim_{var(\theta),var(u)\to 0}(Ew^*_{zZ}-Ew^*_{tT})2g^2(3+g)^2}{-g(9+4g)+(3+g)^2k}$ then (A9) has a negative sign. Additionally we need to insert the necessary condition for the existence of an interior solution which is $k > \frac{g}{3+2g}$ Q.E.D.

Proof of Proposition 2:

a)If we compare the upper limits of the restrictions for k in *a*) and b) of Lemma 2 we obtain $\frac{g\{27+2g[27+g(16+3g)]\}}{3(1+g)^2(3+g)^2} - \frac{g(9+4g)}{(3+2g)^2} = \frac{g^2\{54+g\{162+g[174+g(77+12g)]\}\}}{3(1+g)^2(3+g)^2(3+2g)^2} > 0$. We further assume that the restrictions given about var(u) satisfy both inequalities given in *a*) and b) of the Lemma 2. Given these, when $\frac{g}{(3+2g)} < k < \frac{g(9+4g)}{(3+2g)^2}$, choosing taxes for the domestic government will be a dominant strategy. Since the model is symmetric the same holds for the foreign regulator as well. This is sufficient in order to achieve emission taxes as a Nash equilibrium Q.E.D.

b) The equilibrium strategy for the domestic government is obtained by: $\max\{Ew^*_{zZ}, Ew^*_{tZ}\}$ and $\max\{Ew^*_{zT}, Ew^*_{tT}\}$. Given $\frac{g\{27+2g[27+g(16+3g)]\}}{3(1+g)^2(3+g)^2} > k > \frac{g(9+4g)}{(3+2g)^2}$, the restrictions for var(u) and the results given in *a*) and b) of Lemma 2, we observe that when the foreign government selects a standard, then it is optimal for the domestic government to separate its own strategy (i.e., $Ew^*_{zZ} < Ew^*_{tZ}$). If the foreign regulator chooses a tax then the domestic government selects a standard (i.e., $Ew^*_{zT} > Ew^*_{tT}$). Hence, the equilibrium strategy of each regulator is conditional to the strategy of the rival. Given these, we obtain two asymmetric Nash equilibria in pure strategies. It follows directly that we attain a Nash equilibrium in mixed strategies where each government selects its policy instrument with a positive probability. This probability is derived as the weighted value of expected welfare, when a standard is used equals the corresponding one when a tax is implemented. The weights are the probabilities assigned in the strategies of the rival regulator Q.E.D.

c) If $k > \frac{g\{27+2g[27+g(16+3g)]\}}{3(1+g)^2(3+g)^2}$ then using a) and b) from Lemma 2 we obtain that choosing standards is a dominant strategy and hence the unique Nash equilibrium involves both governments using standards irrespective of var(u).

If we differentiate the threshold level of k, $\frac{g\{27+2g[27+g(16+3g)]\}}{3(1+g)^2(3+g)^2}$, with respect to g we get $\frac{d\left(\frac{g\{27+2g[27+g(16+3g)]\}}{3(1+g)^2(3+g)^2}\right)}{dg} = \frac{81+g\{216+g[207+4g(23+4g)]\}}{3(1+g)^3(3+g)^3}$. This implies that the threshold level is continuously increasing in the level of g. If we take the limit of the threshold level as g tends to infinity we obtain $\lim_{g\to\infty} \frac{g\{27+2g[27+g(16+3g)]\}}{3(1+g)^2(3+g)^2} = 2$ Q.E.D.

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