Endogenous Timing in Strategic Environmental Policymaking

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6 March 2011

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Version: March 6, 2011

Abstract

In this paper, we endogenize the timing of policymaking in a simple two-country model of strategic environmental policy. We consider a timing game in which two policymakers non-cooperatively decide their preferred sequence of moves before setting emission tax rates. We show that whether the policymakers implement emission tax policies simultaneously or sequentially crucially depends on the magnitude of environmental damages: When the damages are insignificant, the tax rates are strategic substitutes and the simultaneous-move policymaking emerges in equilibrium. In contrast, when the damages are significant, the tax rates are strategic complements and the sequential-move policymaking emerges. In addition, we extend the model by allowing for differences in the vulnerability to environmental damages between countries. When the differences are large, the unique equilibrium of the game is the situation where the less vulnerable country acts as a leader. In the case where multiple equilibrium emerges, the risk dominant equilibrium is also that the less vulnerable country leads.

Keywords: Strategic environmental policy, Endogenous timing, Environmental tax, Duopoly.

JEL classification: Q56, Q28, L13, C72.

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*This work was supported by KAKENHI (22730210) of JSPS, Japan.

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1 Introduction

The literature on strategic environmental policy has shown that governments may distort their environmental policies due to strategic reasons. In some cases, governments may implement too lax environmental policies for the purpose of shifting profits from foreign to domestic firms (known as ecological dumping) or for the purpose of bolstering other countries' efforts to reduce transboundary pollutions (known as free-riding). In other cases, governments may implement too stringent policies for the purpose of shifting pollution to foreign countries (known as Not In My Backyard: NIMBY). These different possibilities imply that policymakers should take into account the strategic interdependencies carefully when deciding on the stringency of domestic environmental regulations.

However, the challenge for policymakers is not only to determine the desirable *level* of regulation but also to determine the desirable *timing of moves* in their policymaking. It is important for policymakers to consider whether they should set their preferred level of environmental regulation *before* or *after* policymakers in other countries do. This is because alternate order of moves in policymaking often gives rise to significantly different results.[1] Nevertheless, almost all the literature on strategic environmental policy has not considered the importance of the timing issues. In particular, previous studies generally assume exogenously given simultaneous-move policymaking (Conrad 1993; Barrett 1994; Kennedy 1994; Simpson and Bradford 1996; Greaker 2003; Roelfsema 2007).

In this paper, we extend the standard model of strategic environmental policy by endogenizing the timing of decisions made by policymakers. We analyze the following positive and normative questions. First, we address the normative question of whether policymakers should act as a leader or a follower in their policymaking. Second, adopting the endogenous timing game proposed by Hamilton and Slutsky (1990), we determine the endogenous order of moves in policymaking in a Subgame Perfect Equilibrium (SPE). This endogenous timing of environmental policymaking enables us to answer the positive question of which is the most appropriate timing of moves, either simultaneous or sequential policymaking. Third, we address the normative question of whether their timing of policymaking should be coordinated or not. Finally, since the endogenous timing game may have multiple SPEs, we solve the coordination issue that appears as equilibrium selection problem by resorting the concepts of risk-dominance offered by Harsanyi and Selten (1988).[2] Applying this concept, we answer the positive question of what type of country eventually acts as a leader regarding environmental policymaking.

To address the issues, we consider a three-stage game involving two countries (policymakers) making decision on emission taxes and two polluting firms producing a homogenous product and selling them in a world market. In the first stage of the game, the policymakers simultaneously and non-cooperatively state which role (leading or following) regarding subsequent policymaking it prefers. In the second stage, policymakers non-cooperatively determine their

[1] Since the seminal studies by Gal-Or (1985) and Dowrick (1986), the industrial organization literature has pointed out the importance of the timing of moves (whether there is a first- or second-mover advantage) in many types of games.

[2] The same procedure for equilibrium selection in the endogenous timing literature is used in the context of price leadership in Bertrand competition (van Damme and Hurkens 2004; Amir and Stepanova 2006), in the context of capital tax competition (Kempf and Rota-Graziosi 2010a), and in private provision of public goods (Kempf and Rota-Graziosi 2010b).

emission tax rates. Whether the timing of moves in the second stage is simultaneously or sequentially is determined according to the solution of the first stage. In the third stage, firms simultaneously choose a quantity to produce, and the production process causes transboundary pollution.

We show that the slope of marginal environmental damage curve (hereafter we call it as *the damage parameter* or *the vulnerability to environmental damages*) is crucial for determining the endogenous timing of moves in environmental policymaking. When the damage parameters in both countries are smaller than a certain level, policymakers' choices about tax rates are strategic substitutes. In this case, both policymakers can enjoy a first-mover advantage and the simultaneous policymaking (Nash policymaking game) is the SPE of the timing game. In contrast, when the damage parameters are larger, tax rates are strategic complements. In this case, both policymakers can enjoy a second-mover advantage and the two sequential policymaking situations (Stackelberg policymaking games) are the SPEs of the timing game. The result contributes to the literature on strategic environmental policy by demonstrating the importance of considering the sequential-move policymaking. In addition, we show that in the strategic complements case, both countries are better off (i.e., attain Pareto-improvement) by coordinating their timing decisions in a way that their policies are set sequentially instead of simultaneously.

We then extend the model by allowing for differences in vulnerability to environmental damages (or equivalently differences in the damage parameter) between countries. The extension enables us to predict which country will act as a leader (i.e., the endogenous order of moves). We show that under certain condition, the unique SPE of the timing game is the Stackelberg policymaking where the less vulnerable country acts as a leader. However, the reverse, a situation where the more vulnerable country acts as a leader, is never a SPE. Furthermore, in the case where there exists multiple SPEs of the timing game that correspond to the two Stackelberg situations, we apply the concept of risk-dominance as defined by Harsnyi and Selten (1988) to select among SPEs. We show that the equilibrium in which the policymaker in the less vulnerable country acts as a leader will be the risk-dominant equilibrium.

Our study closely relates to Bàcena-Ruiz (2006), which investigates endogenous timing in policymaking using a strategic environmental policy model. He finds that whether governments set environmental taxes sequentially or simultaneously crucially depends on the degree of pollution spillovers.[3] The differences between our study and Bàcena-Ruiz (2006) is as follows. First, our study shows that the results of endogenous timing depend not only on the degree of pollution spillovers but also on the magnitude of environmental damages.[4] Second, our study allows for the difference in the vulnerability to environmental damages between countries so that we can identify which country is likely to be a leader whereas Bàcena-Ruiz (2006) considers only symmetric equilibria for identical countries. Finally, our study address the coordination issue on the timing decisions of policymakers (i.e., the equilibrium selection problem).[5]

[3] In particular, Bàcena-Ruiz (2006) shows that taxes are strategic complements and both the leader and the follower obtain greater welfare than under a simultaneous tax setting if the pollution spillovers are low enough. Thus, in this case, governments set taxes sequentially. On the other hand, if the pollution spillovers are high enough, taxes are strategic substitutes and governments set taxes simultaneously.

[4] Bàrcena-Ruiz (2006) fixes the slope of marginal environmental damage curve at unity.

[5] Fujiwara (2009) also investigate the endogenous timing in a two-country oligopolistic model with transboundary pollution. He shows that the equilibrium timing is crucially affected by the degree of transboundary pollution and marginal environmental damages. Our study differs from Fujiwara (2009) in some important as-

This paper is organized as follows. Section 2 presents the basic structure of the model. Section 3 derives the equilibria of simultaneous and sequential policymaking games and compares them. Stage 4 determines the SPEs of the timing game. In section 5, we extend the model by incorporating heterogeneity in damage parameters between countries and determine the SPEs. In addition, we solve the coordination issue regarding multiple SPEs by using the concept of risk-dominance. Section 6 concludes the paper.

2 The Basic Model

Consider two countries labeled by i ($i = 1, 2$). In each country, there is one representative firm. Emitting transboundary pollution, each firm i ($i = 1, 2$) produces homogenous products (q_i) and sells them in a world market à la Cournot. We assume that one unit of output generates one unit of emission. Then, the profit function of firm i is given by:

$$\pi_i = p(Q)q_i - t_i q_i, \tag{1}$$

where $p(Q)$ is the inverse demand of the world market, $Q = q_1 + q_2$ is the total output produced by the two firms, t_i is the rate of emission tax or subsidy in country i.[6] The inverse demand is assumed to be linear as $p(Q) = 1 - q_1 - q_2$. The social welfare function of country i is defined as:

$$W_i = \pi_i + t_i q_i - \big[D(q_i) + \beta D(q_j)\big], \tag{2}$$

where $D(\cdot)$ is the environmental damage function and the parameter $\beta \in [0, 1]$ represents the degree of transboundary pollution.[7] The environmental damage is assumed to be quadratic as $D(q_i) = \frac{d}{2}\big(q_i\big)^2$, where the parameter d, which we call it as the *damage parameter* or the *vulnerability to environmental damages*, represents the slope of the marginal environmental damage curve and is assumed to be the same between two countries. The assumption will be relaxed in section 6.

The model has three stages. In the first stage, the policymaker of each country non-cooperatively chooses its preferred order of moves (either leads or follows). Once the order of moves has been defined, policymakers act accordingly in the second stage. That is, policymakers non-cooperatively set their emission tax (or subsidy) rates according to the order of moves selected in the first stage. In the third stage, each firm decides its output simultaneously.[8]

pects: (1) Furjiwara (20090 assumes environmental damages to be linear whereas we assume them to be convex (which is the standard assumption in environmental regulation literature). (2) Fujiwara (2009)'s model specification produces only the strategic substitutability of environmental tax rates. Thus, the possibility of multiple sequential-move equilibria is provided just by the difference in the shape of iso-welfare curves between countries. (3) Fujiwara (2009) does not consider the question of which country chooses to be a leader (or follower).

[6] For simplicity, we assume that marginal production costs equal zero.

[7] This type of transboundary pollution is employed by Roelfsema (2007) and Hattori (2010). The parameter $\beta \in [0, 1]$ can be considered as altruistic preference of policymakers for environmental damages that happen in other countries. In addition, following some earlier studies on strategic environmental policy (e.g., Conrad 1993; Barrett 1994; Greaker 2003; Roelfsema 2007), we excludes consumers' surplus from the definition of social welfare. This assumption can be justified if countries are small so that the domestic consumption is sufficiently small when compared to world consumption.

[8] We do not consider the endogenous timing of two firms' moves because it is obvious in our setting. In a simple Cournot model with homogeneous products and homogenous production costs, the firms' outputs are known to be strategic substitutes. Therefore, the simultaneous timing can be supported as an equilibrium by applying the timing game of Hamilton and Slutsky (1990).

3 Simultaneous and Sequential Policymakings

The model is solved backwards. In the third stage, each firm simultaneously chooses its output, taking as given both the rival firm's output and the emission tax rates set by governments. From the first-order conditions of profit maximization, we have $q_i(t_i, t_j) = (1 - 2t_i + t_j)/2$ for $i = 1, 2$ and $i \neq j$, which indicate $\partial q_i/\partial t_i < 0$ and $\partial q_i/\partial t_j > 0$.

In the second stage, policymakers decide on emission tax rates simultaneously or sequentially. We refer the simultaneous-move and the sequential-move situations as *Nash policymaking game* and *Stackelberg policymaking game*, respectively.

3.1 Nash policymaking game in the second stage

We then derive the second-stage equilibrium in a case where emission tax rates are chosen simultaneously by two governments. From the first-order condition of the welfare maximization problem of policymaker i, we have the following reaction function of policymaker i:

$$t_i = R_i(t_j) = \frac{d(2-\beta)-1}{d(4+\beta)+4} + \left[\frac{2d(1+\beta)-1}{d(4+\beta)+4}\right] t_j. \tag{3}$$

Lemma 1 *Tax rates are strategic substitutes (complements) when* $d < (>)\ \frac{1}{2(1+\beta)}$.

The reaction function of policymaker i is downward (upward) sloping $R_i' < 0$ ($R_i' > 0$) when the slope of the marginal environmental damage curve is flat (steep).[9] The intuition is as follows. On the one hand, an increase in t_j shifts production and emission from country j to country i by increasing q_i and decreasing q_j. Thus, policymaker i has an incentive to increase its tax rates to refrain firm i's emission. On the other hand, because $-\partial^2(p(Q)q_i)/\partial t_i \partial t_j = 1/9 > 0$, an increase in t_j also increases firm i's marginal revenue from reducing t_i. Thus, policymaker i has an incentive to lower its tax rates to boost firm i's profits. When d is large (small) enough, the former (latter) incentive dominate the latter (former), and thus the tax rates are strategic complements (substitutes).

The equilibrium tax rates are obtained by solving (3) for i and j:

$$t^N = \frac{d(2-\beta)-1}{d(2-\beta)+5}, \tag{4}$$

where the superscript N represents the equilibrium values in Nash policymaking game.[10] Differentiating t^N in d and β yields:

$$\frac{\partial t^N}{\partial d} = \frac{6(2-\beta)}{\big[5+d(2-\beta)\big]^2} > 0, \quad \frac{\partial t^N}{\partial \beta} = -\frac{6d}{\big[5+d(2-\beta)\big]^2} < 0.$$

Thus, the equilibrium tax rates in Nash policymaking game are increasing function of d and is decreasing function of β. Using the equilibrium tax (4), the equilibrium output and welfare as:

$$q^N = \frac{2}{5+d(2-\beta)}, \quad W^N = \frac{2\big[d(1-2\beta)+1\big]}{\big[d(2-\beta)+5\big]^2}, \tag{5}$$

and the equilibrium profits are $\pi^N = (q_N)^2$.

[9] It is clear that when $d = 1/[2(1+\beta)]$, the tax choices of both policymakers are independent of each other.

[10] Since we consider a symmetric solution here, we omit subscript i.

3.2 Stackelberg policymaking game in the second stage

We then derive the second-stage equilibrium in a case where one of the two policymakers (referred as policymaker L) is the first player to set its emission tax rates and then the other policymaker (referred as policymaker F) chooses its own tax rates.

The reaction function of policymaker F is given by (3) (replacing i by F and j by$L$) because the welfare maximization of policymaker F is the same as in Nash policymaking game. In contrast, the welfare maximization of policymaker L, the leader, is given by $\max_{t^L} W^L(t^L, R_F(t^L))$. After some mathematical manipulations, we obtain the equilibrium tax rates:

$$t^L = \frac{d\big[2d(4+\beta) + d^2(4+\beta^3) - 3\beta - 1\big] - 2}{\Delta}, \tag{6}$$

$$t^F = \frac{d\big[2d(4-\beta^2) + d^2(4+\beta^3) - 4\beta - 3\big] - 1}{\Delta}, \tag{7}$$

where $\Delta \equiv 6 + 5d(5+2\beta) + 4d^2(5+\beta-\beta^2) + d^3(4+\beta^3) > 0$.

Using (6) and (7), the equilibrium output and welfare of countries L and F are derived as:

$$q^L = \frac{3 + 4d(2+\beta) + 2d^2(2-\beta^2)}{\Delta}, \quad q^F = \frac{2 + 5d(2+\beta) + 2d^2(2+\beta)}{\Delta}, \tag{8}$$

$$W^L = \frac{1 + 4d + 4d^2(1-\beta-\beta^2)}{2\Delta^2}, \qquad W^F = \frac{\Sigma}{2\Delta^2}, \tag{9}$$

where

$$\begin{aligned}\Sigma \equiv\ & 4 + d(44+5\beta) + d^2(156 + 34\beta - 22\beta^2) + d^3(196 - 105\beta^2 - 20\beta^3) \\ & + 2d^4\big[(2+\beta)(24 - 22\beta - 4\beta^2 + 13\beta^3)\big] + 4d^5(4 - 4\beta - \beta^2 + 6\beta^3 + \beta^4 + \beta^5).\end{aligned}$$

The equilibrium profits are $\pi_L = (q_L)^2$ and $\pi_F = (q_F)^2$, respectively.

Lemma 2 *The equilibrium values of Stackelberg policymaking game must satisfy:*

(a) If $d < \frac{1}{2(1+\beta)}$*, then* $t^L < t^F$, $q^F < q^L$*, and* $W^F < W^L$.

(b) If $d > \frac{1}{2(1+\beta)}$*, then* $t^F < t^L$, $q^L < q^F$*, and* $W^L < W^F$.

Proof. See Appendix. □

This lemma implies that if the tax rates in the second stage are strategic substitutes (complements), then each country has a *first-mover advantage* (*second-mover advantage*), which is commonly known in the industrial organization literature (Gal-Or 1985; Dowrick 1986).[11] In the case of strategic substitutes, a leader chooses lower tax rates than a follower. This is because the leader knows that if he lowers its taxes, the follower will raise its taxes. Thus, the leader is better off than the follower by enjoying the higher industrial profits and the free-riding benefits of environmental regulations. On the other hand, in the case of strategic complements, a leader sets a higher tax than a follower because the leader fears that setting lower tax will induce the follower to lower its tax. Thus, the follower is better off than the leader.

[11] In our study, the definitions of the first- and second-mover advantages are following Amir and Stepanova (2006).

3.3 Comparison of two policymaking games

We then compare the equilibrium values in Nash policymaking game with those in Stackelberg policymaking game. From equations (4) to (9), we obtain the following lemma:

Lemma 3 *The equilibrium values of Nash and Stackelberg policymaking games must satisfy:*

(a) If $d < \frac{1}{2(1+\beta)}$*, then* $t^L < t^N < t^F$*,* $q^F < q^N < q^L$*, and* $W^F < W^N < W^L$*.*

(b) If $\frac{1}{2(1+\beta)} < d < \frac{2}{\beta}$*, then* $t^N < t^F < t^L$*,* $q^L < q^N < q^F$*, and* $W^N < W^L < W^F$*.*

(c) If $d > \frac{2}{\beta}$*, then* $t^N < t^F < t^L$*,* $q^L < q^F < q^N$*, and* $W^N < W^L < W^F$*.*

Proof. See Appendix. □

When the tax rates are strategic complements ($d > 1/[2(1+\beta)]$), the both leader's and follower's tax rates are higher than the tax rates in Nash policymaking game ($t^N < t^F < t^L$). Therefore, both the leading and following countries are better off than in the case where they act simultaneously ($W^N < W^L$ and $W^N < W^F$). This is because the simultaneous policy-setting case is a prisoners' dilemma situation in which both policymakers will be better off if they can agree to set higher tax rates. On the other hand, when the tax rates are strategic substitutes ($d > 1/[2(1+\beta)]$), the leader enjoys first-mover advantages implementing lower tax rates ($t^F < t^N$), which forces the follower to set higher tax rates ($t^N < t^F$). Therefore, leading country is better off and following country is worse off than in the case where they act simultaneously ($W^N < W^L$ and $W^N > W^F$).[12]

Furthermore, from the comparison of the outputs under different equilibria, we find the preference relations of a policymaker and a firm on the timing of environmental policymaking. When $d < 1/[2(1+\beta)]$, both the firm and the policymaker in the same country have the same preference order over the timing of policymaking. However, when $d > 1/[2(1+\beta)]$, their preferences conflict with each other. Particularly when $d > 2/\beta$, the policymakers prefer acting as a leader or a follower rather than act simultaneously whereas the firms prefer the policymakers to act simultaneously rather than act sequentially.

4 Timing game in the first stage

We then investigate the endogenous timing of moves by applying the observable delay game of Hamilton and Slutsky (1990). In the first stage, policymakers non-cooperatively choose whether they prefer to move early or late in the second stage. Following Hamilton and Slutsky (1990), we assume that if both policymakers choose to move early (strategy *Leads*) or to move late (strategy *Follows*), Nash policymaking game will be enforced in the second stage. If one policymaker chooses *Leads* and the other chooses *Follows*, Stackelberg policymaking game will be enforced in the second stage.

Table 4 shows the normal form representation of the first-stage game. Now we obtain the following propositions:

[12] Note also that when $d = 1/[2(1+\beta)]$, there are no strategic interdependencies between policymakers and thereby $t^L = t^F = t^N$, $q^L = q^F = q^N$, and $W^L = W^F = W^N$.

	Policymaker 2	
	Leads	*Follows*
Policymaker 1		
Leads	$W_1^N,\ W_2^N$	$W_1^L,\ W_2^F$
Follows	$W_1^F,\ W_2^L$	$W_1^N,\ W_2^N$

Table 1: Payoff matrix of endogenous timing in the first stage

Proposition 1

(a) *If* $d < \frac{1}{2(1+\beta)}$*, then the Subgame Perfect Equilibrium (SPE) of the timing game is the Nash policymaking equilibrium.*

(b) *If* $d > \frac{1}{2(1+\beta)}$*, then the Subgame Perfect Equilibria (SPEs) of the timing game are the two Stackelberg policymaking equilibria. In this case, moving sequentially instead of simultaneously is Pareto-improving for both countries.*

Proof. Immediately from Table 4 and Lemma 3. □

When the damage parameter is small, strategy *Leads* becomes a dominant strategy for both policymakers and there is unique SPE that corresponds to Nash policymaking games. This is because both policymakers want to exploit a first-mover advantage and the second-mover's welfare are smaller than that under Nash policymaking equilibrium. In contrast, when the damage parameter is large (equivalently, tax rates are strategic complements), there are two possible SPEs of the timing game that correspond to the two Stackelberg situations. This is because, in any case, both the first- and second-mover's welfare are larger than that under Nash policymaking game ($W^L > W^N$ and $W^F > W^N$). In addition, the two Stackelberg policymaking equilibria are Pareto-superior to the Nash policymaking equilibrium: both policymakers have a common interest in avoiding the Nash policymaking game, and they can do so by accepting that one of them leads environmental policymaking.[13]

Our results are closely related to the study by Bárcena-Ruiz (2006), which examines endogenous timing in policymaking in a model of strategic environmental policy. In his study, the damage parameter d is assumed to be fixed ($d = 1$) and thereby the results of endogenous timing in policymaking are characterized only by the degree of transboundary pollution. He shows that when the transboundary spillovers are low (high) enough, in equilibrium of the timing game, policymakers set taxes sequentially (simultaneously). These results hold in our model as well: when β is small (large), the tax rates are likely to be strategic complements (substitutes), and thereby policymakers are more likely to move sequentially (simultaneously). Not only that, our study shows that the magnitude of the damage parameter affects the strategic relationship between policymakers and thereby the outcome of endogenous timing of moves.

[13] When $d = 1/[2(1+\beta)]$, then any possible order of moves are SPEs of the timing game because there are no strategic interdependencies between players. In this case, the policymakers do not care whether they act as a leader or a follower.

5 Heterogenous Environmental Damages

In this section, we extend the basic model by incorporating heterogeneity in damage parameters (or vulnerability to environmental damages) between countries. This extension enables us to examine the endogenous order of moves, i.e., which countries, either less or more vulnerable country, chooses to move first.

The welfare in country i is now defined as

$$\widehat{W}_i = \pi_i + t_i q_i - \big[D_i(q_i) + \beta D_j(q_j)\big], \tag{10}$$

where

$$D_i(q_i) = \frac{d_i}{2}(q_i)^2$$

Here, the damage parameter d_i is not necessarily the same between the countries (i.e., we allow for $d_i \neq d_j$). Obviously, the case of $d_1 = d_2$ is equivalent to the symmetric case analyzed in the previous sections. To have a meaningful analysis, we exclude the possibility that there are extremely large differences between d_i and d_j.[14]

In this section, we particularly focus on the endogenous order of moves in policymaking. Therefore, we do not exhibit and compare the equilibrium tax rates, outputs, and profits but only the welfare. In addition, because the derivation is similar to that engaged by the previous sections, we omit the detailed derivations here.

The reaction functions in Nash policymaking game is given by:

$$t_i = \frac{2d_i - \beta d_j - 2}{4d_i + \beta d_j + 4} + \left[\frac{2(d_i + \beta d_j) - 1}{4d_i + \beta d_j + 4}\right] t_j, \tag{11}$$

which indicates that the tax rates are strategic substitutes (complements) when $d_i < (>)\ \frac{1-2\beta d_j}{2}$.

After some tedious mathematical derivations, we obtain the equilibrium welfare of country i in Nash policymaking game and that of leading and following countries in Stackelberg policymaking game as $\widehat{W}_i^N$, $\widehat{W}_i^L$, and $\widehat{W}_i^F$, respectively (these values are shown in Appendix). Then, we have the following comparison results.

Lemma 4 *The equilibrium welfare of Nash and Stackelberg policymaking games must satisfy:*

(a) $\widehat{W}_i^F \gtreqless \widehat{W}_i^N$ *if* $d_i \gtreqless \frac{1-2\beta d_j}{2}$.

(b) $\widehat{W}_i^L = \widehat{W}_i^N$ *if* $d_i = \frac{1-2\beta d_j}{2}$, *and* $\widehat{W}_i^L > \widehat{W}_i^N$ *if otherwise.*

Proof. See Appendix. □

Notice that we do not compare $\widehat{W}_i^L$ with $\widehat{W}_i^F$ because the comparison is fairly complex and it does not affect the results of endogenous order of moves in the first stage. We now state the following proposition:

[14] The differences in d_i can be interpreted as differences in the level of technology for emission abatement or pollution adaptation between countries: if a country has the superior (inferior) technology, then one unit of emission imposes lesser (greater) environmental costs on society. Therefore, $d_i < d_j$ describes the situation where country i has a relatively superior emission abatement or adaptation technology than country j.

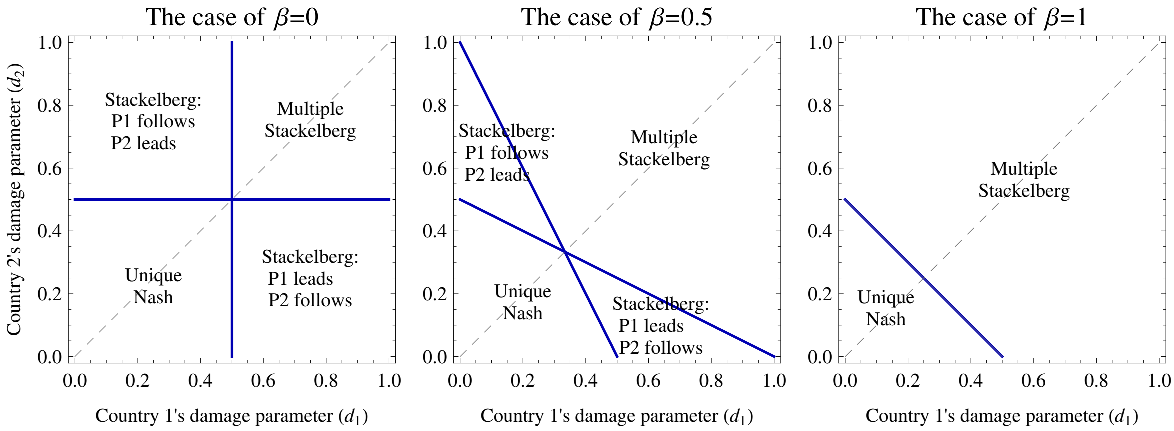

Figure 1: SPEs of the timing game: the case of heterogenous environmental damages.

Proposition 2

(a) If $d_i < \frac{1-2\beta d_j}{2}$ holds for $i = 1, 2$, then SPE of the timing game is the simultaneous (Nash) moves situation.

(b) If $d_i < \frac{1-2\beta d_j}{2}$ and $d_j > \frac{1-2\beta d_i}{2}$ hold, then SPE of the timing game is the sequential (Stackelberg) moves situation in which policymaker i leads and policymaker j follows.

(c) If $d_i > \frac{1-2\beta d_j}{2}$ holds for $i = 1, 2$, then SPEs of the timing game is the sequential (Stackelberg) moves situation. That is, (Leads, Follows) and (Follows, Leads) are both SPEs of the timing game.

Proof. Immediately from Lemma 4. □

There is a unique SPE of the timing game that corresponds to Nash policymaking game in the second stage when the environmental damages are insignificant in both countries(assertion (a)) while there are two possible SPEs that correspond to two Stackelberg policymaking games when they are significant (assertion (c)). The novel finding is that there is a unique SPE where Stackelberg policymaking emerges when there are relatively large differences in the damage parameter. Proposition 2-(b) implies that a policymaker in a country with relatively small (large) damage parameter is more likely to become a leader (follower), but the converse does not hold. In other words, ceteris paribus, a policymaker in the less vulnerable country will become a leader in policymaking. Figure 1 illustrates the SPEs of the timing game in three cases: $\beta = 0$, $\beta = 0.5$, and $\beta = 1$. In the figure, $d_1 = (1 - 2\beta d_2)/2$ and $d_2 = (1 - 2\beta d_1)/2$ lines are depicted in (d_1, d_2) plane. The $d_1 = d_2$ (45-degree) line is shown as dashed one. $P1$ ($P2$) indicates the policymaker 1 (2), respectively. The region labeled by "Multiple Stackelberg" represents the region where there are two SPEs that correspond to two Stackelberg policymaking situations but the exact order of moves are undetermined. It shows that the smaller β, the larger the region in which the order of moves is unambiguously determined.

We then move onto the issue of coordination, that is, the issue of how to select one of the two possible SPEs. In order to solve the issue, we employ the concept of risk-dominance criterion

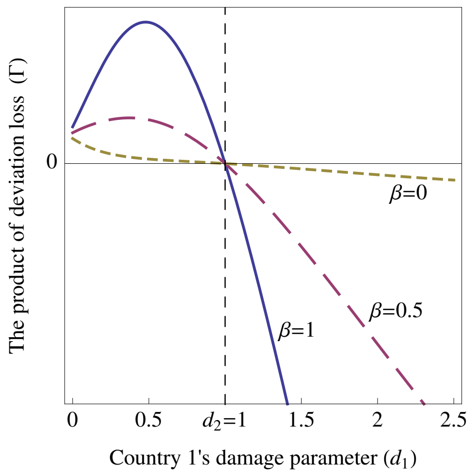

Figure 2: Risk dominance: the value of the product of deviation losses ($d_1 = 1$)

defined by Harsanyi and Selten (1988).[15] In our framework with heterogenous damage parameter (or heterogenous vulnerability to environmental damages), equilibrium $(Leads, Follows)$ (policymaker 1 leads and policymaker 2 follows) risk-dominates equilibrium $(Follows, Leads)$ if the former is associated with the larger product of deviation losses Γ. Specifically, the condition is:

$$\Gamma \equiv \left(\widehat{W}_1^L - \widehat{W}_1^N\right)\left(\widehat{W}_2^F - \widehat{W}_2^N\right) - \left(\widehat{W}_1^F - \widehat{W}_1^N\right)\left(\widehat{W}_2^L - \widehat{W}_2^N\right) > 0.$$

However, the conditions for the above inequality to hold are analytically very difficult to derive. Therefore, we engage numerical analysis carried out by a computer program[16] and derive the conditions summarized by the following proposition.

Proposition 3 *If $d_1 < d_2$, then $\Gamma > 0$. Thus, the equilibrium in which a policymaker in a country with relatively smaller (larger) damage parameter acts as a leader (follower) risk-dominates the equilibrium in which a policymaker in a country with relatively smaller (larger) d_i acts as a follower (leader).*

This proposition reinforces the result in Proposition 2: a policymaker in the less (more) vulnerable country tends to become a leader (follower). Figure 2 confirms the results, offering some illustrations of Γ in the case of $d_2 = 1$. In the figure, all curves cross the horizontal axis at the same point ($d_1 = d_2$), and the value of Γ must be positive when $d_1 < d_2$. We find that the larger the value of β, the greater the deviation losses, and thereby the more likely that the situation where less vulnerable country leads is a safer equilibrium.

[15]The definition of the risk-dominance is that an equilibrium risk-dominates another equilibrium when the former is less risky than the latter, that is, the risk-dominant equilibrium is the one for which the product of the deviation losses is the largest.

[16]The numerical analyses are performed in Mathematica 7.0. The code is available upon request.

6 Concluding Remarks

Policymakers need to consider not only how but also when to implement policies in any kind of policymaking. In this paper, we extend the standard model of strategic environmental policy by endogenizing the timing of decisions made by policymakers. Three main results are obtained: (1) Whether the policymakers implement emission tax policies simultaneously or sequentially crucially depends on the magnitude of environmental damages: When the damages are insignificant, the tax rates are strategic substitutes. In this case, the simultaneous policymaking is the unique SPE of the timing game. When the damages are significant, the tax rates are strategic complements, and the sequential policymaking situations are the two SPEs of the timing game. (2) When the differences in the magnitude of environmental damages between countries are large, the unique SPE is that the less (more) vulnerable country leads (follows). (3) A risk dominance criterion selects the equilibrium where the less (more) vulnerable country leads (follows). Because a conventional approach in the strategic environmental policy model is to consider a simultaneous-move policymaking, these results contribute to the literature by demonstrating the importance of considering the sequential-move policymaking.

We have used the simplest possible model that can identify the endogenous timing in environmental policymaking. However, our main results are likely to be robust to different policy instruments and to different competition mode (Bertrand). Hattori (2010) derives policymaker's strategic relationships in their policymaking for different policy instruments and for different competition mode in a similar model to ours. In particular, emission taxes are necessarily strategic complements in Bertrand competition case whereas emission caps (standards) are necessarily strategic substitutes in both Cournot and Bertrand cases. From these strategic relationships indicated by Hattori (2010), we can expect the results of endogenous timing for each case: The strategic substitutability (complementarity) case will lead to the simultaneous-(sequential-)move policymaking.[17]

In this paper, we assume that domestic consumption is sufficiently small compared to world consumption and thereby do not include any consumer surplus into policymakers' objective. One interesting extension of our model is to consider what happens when either one or both countries have a large domestic market. In this case, a policymaker in a country with large market will care for the domestic consumer surplus when setting domestic environmental policies. This extension will enable us to examine which country (either large or small) acts as a leader regarding environmental policymaking. This awaits future research.

Appendix

Proof for Lemmas 2 and 3

Comparing (6) with (7), we have

$$t^L - t^F = \frac{(1+\beta d)\left[2d(1+\beta)-1\right]}{\Delta} \gtreqless 0 \;\Leftrightarrow\; d \gtreqless \frac{1}{2(1+\beta)}.$$

[17]However, the result in the issue of coordination in the case of multiple SPEs may differ from ours, but this is left for future research.

In addition, from (8) and (9), we have

$$q^L - q^F = \frac{(1+\beta d)\big[1-2d(1+\beta)\big]}{\Delta} \gtreqless 0 \;\Leftrightarrow\; d \lesseqgtr \frac{1}{2(1+\beta)},$$
$$W^L - W^F = \frac{(1+\beta d)^2\big[2+d(9+5\beta+6d+24\beta d)\big]}{2\Delta^2}\big[1-2d(1+\beta)\big] \gtreqless 0 \;\Leftrightarrow\; d \lesseqgtr \frac{1}{2(1+\beta)},$$

which proves Lemma 2.

Next, comparing (4) with (6) and (7), we have

$$t^L - t^N = \frac{(1+\beta d)\big[4+d(4+\beta)\big]}{\big[5+d(2+\beta)\big]\,\Delta}\big[2d(1+\beta)-1\big] \gtreqless 0 \;\Leftrightarrow\; d \gtreqless \frac{1}{2(1+\beta)},$$
$$t^F - t^N = -\frac{(1+\beta d)\big[2d(1+\beta)-1\big]^2}{\big[5+d(2+\beta)\big]\,\Delta} \leq 0,$$

which proves that $t^L < t^N < t^F$ holds for $d < 1/[2(1+\beta)]$ and $t^N < t^F < t^L$ holds for $d > 1/[2(1+\beta)]$. In addition, from (5), (8), and (9), we have

$$q^L - q^N = \frac{(3+2d)(1+\beta d)\big[1-2d(1+\beta)\big]}{\big[5+d(2+\beta)\big]\,\Delta} \gtreqless 0 \;\Leftrightarrow\; d \lesseqgtr \frac{1}{2(1+\beta)},$$
$$q^F - q^N = \frac{(1+\beta d)(2-\beta d)\big[2d(1+\beta)-1\big]}{\big[5+d(2+\beta)\big]\,\Delta} > (<)\ 0 \quad \text{if} \quad \frac{1}{2(1+\beta)} < d < \frac{2}{\beta} \text{ (if otherwise)},$$
$$W^L - W^N = \frac{(1+\beta d)^2\big[2d(1+\beta)-1\big]^2}{2\big[5+d(2+\beta)\big]^2\,\Delta^2} \geq 0,$$
$$W^F - W^N = \frac{(1+\beta d)^2[4+d(4+\beta)]\,\Omega}{2\big[5+d(2+\beta)\big]^2\Delta^2}\big[2d(1+\beta)-1\big] \gtreqless 0 \;\Leftrightarrow\; d \gtreqless \frac{1}{2(1+\beta)},$$

where

$$\Omega \equiv 11+4d(13+6\beta)+d^2(40+5\beta-12\beta^2)+2d^3(4-\beta-\beta^2+\beta^3) > 0.$$

This completes the proof of Lemma 3. □

Proof for Lemma 4

Using (11), after solving for the various stages, we obtain the following equilibrium welfare of country i ($i = 1, 2,\ i \neq j$):

$$\widehat{W}_i^N = \frac{\begin{pmatrix} 2+8d_j+4d_j^2(2+\beta)+2d_i\big[1+d_j^2(1-\beta)(2+\beta)^2 \\ +d_j(4-4\beta-3\beta^2)\big]-2\beta d_i^2 d_j(2+\beta)^2 \end{pmatrix}}{\big[5+2d_j(3+\beta)+d_i(6+4d_j+2\beta-\beta^2 d_j)\big]^2} \tag{A1}$$

$$\widehat{W}_i^L = \frac{1+4d_j\big[1+d_j-\beta d_i(1+\beta)\big]}{2\beta^3 d_i^2 d_j+4\big[3+2d_j(4+2d_j+\beta)\big]+2d_i\big[9+6\beta+4d_j(3+d_j+\beta-\beta^2)\big]} \tag{A2}$$

$$\widehat{W}_i^F = \frac{\Omega}{2\beta^3 d_i^2 d_j+4\big[3+2d_j(4+2d_i+\beta)\big]+2d_i\big[9+6\beta+4d_j(3+d_j+\beta-\beta^2)\big]}, \tag{A3}$$

where

$$\begin{aligned}
\Omega \;\equiv\;& 4+d_j\Big[24+\beta(5-16d_i^4)+2d_j(3+\beta)(6+5\beta)\Big]\\
&+d_i\Big[20+2\beta^3d_j^3(6+5\beta)+8d_j(11-\beta-4\beta^2)+d_j^2(84+64\beta-25\beta^2-4\beta^3)\Big]\\
&+4d_i^3\Big[4-8d_j(-1+2\beta+\beta^2)+d_j^2(4-\beta^2+4\beta^3)\Big]\\
&+4d_i^2\Big[8+d_j^3\beta^3(2+\beta-\beta^2)+4d_j(6-4\beta-5\beta^2-\beta^3)\\
&\quad+d_j^2(16+6\beta-7\beta^2+8\beta^3+4\beta^4)\Big].
\end{aligned}$$

Comparing $\widehat{W}_i^F$ with $\widehat{W}_i^N$, we have

$$\widehat{W}_i^F-\widehat{W}_i^N=\frac{\Psi}{2\,\Theta\Lambda}\Big(2d_i+2\beta d_j-1\Big)\gtreqless 0 \;\Leftrightarrow\; d_i\gtreqless\frac{1-2\beta d_j}{2},$$

where

$$\begin{aligned}
\Theta \;\equiv\;& \Big[5+2d_j(3+\beta)+d_i\Big(2(3+\beta)+d_j(4-\beta^2)\Big)\Big]^2>0\\
\Lambda \;\equiv\;& \Big[6+4d_i^2(2+d_j)+d_j(9+6\beta)+d_i\Big(\beta^3d_j^2+4(4+\beta)+4d_j(3+\beta-\beta^2)\Big)\Big]^2>0\\
\Psi \;\equiv\;& (4+4d_i+\beta d_j)\Big[1+2d_i(1+\beta)+\beta d_id_j(2+\beta)\Big]\times\\
&\Big[11+d_j(42+40\beta)+4{d_j}^2(9+15\beta+5\beta^2)+2\beta{d_i}^3d_j\Big(14+6\beta+d_j(8+2\beta-\beta^2)\Big)\\
&+d_i\Big(32+6\beta\underbrace{-4\beta^3{d_j}^3}_{\dagger1}+d_j(88+115\beta+27\beta^2)+{d_j}^2(48+100\beta+40\beta^2-6\beta^3)\Big)\\
&+{d_i}^2\Big(4(5+\beta)\underbrace{-2\beta^3{d_j}^3(2-\beta-\beta^2)}_{\dagger2}+d_j(40+92\beta+44\beta^2+8\beta^3)\\
&+{d_j}^2(16+64\beta+30\beta^2-15\beta^3-8\beta^4)\Big)\Big].
\end{aligned}$$

The sign of Ψ is generally positive except for the case where d_j is extremely greater than d_i. Actually, in the above equation of Ψ, only the two terms indicated by †1 and †2 are negative and are both multiplied by $\beta^3d_j^3$. For example, if $d_i=1$ and $\beta=1$, then $d_j\leq 102$ is sufficient for $\Psi>0$. If $d_i=1$ and $\beta=0.5$, then $d_j\leq 296$ is sufficient for $\Psi>0$. It proves assertion (a).

Comparing $\widehat{W}_i^L$ with $\widehat{W}_i^N$, we have

$$\widehat{W}_i^L-\widehat{W}_i^N=\frac{(2d_j+2d_i\beta-1)^2\big[1+2d_j(1+\beta)+\beta d_id_j(2+\beta)\big]^2}{6+\beta^3d_i^2d_j+4d_j(4+2d_j+\beta)+d_i\big[9+6\beta+4d_j(3+d_j+\beta-\beta^2)\big]}\geq 0,$$

which proves assertion (b). □

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