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under International Carbon Leakage

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Abstract

This paper studies environmental management policy when two fossil-fuel-consuming countries non-cooperatively regulate greenhouse-gas emissions through emission taxes or quotas. The presence of carbon leakage caused by fuel-price changes affects the tax-quota equivalence. We explore each country's incentive to choose an environment regulation instrument within a framework of a two-stage policy choice game and find subgame-perfect Nash equilibria. This sheds a new light on the question of why adopted policy instruments could be different among countries. We also analyze the welfare effect of creating an international market for emission permits. International trade in emission permits may not benefit the fuel-consuming countries.

1 Introduction

Governments around the world are gradually adopting measures to tackle the issue of global warming. A major element of these measures in many countries is the introduction of emission taxes and quotas (including the creation of markets to trade emission permits). Previous studies on environmental regulation suggest that, within a closed economy, emission taxes and quotas are essentially equivalent instruments. In an open-economy framework, however, this is usually not the case.[1] In particular, carbon leakage across countries could arise and affect the equivalence.

There are three main channels through which international carbon leakage can arise. The first channel is changes in a country's industrial structure as discussed in Copeland and Taylor (2005) and Ishikawa et al. (2011). When a country adopts emission regulations, the comparative advantage of the emission-intensive industry could shift abroad. The second channel is the relocation of plants in response to emission regulations, particularly in emission-intensive industries (see Markusen et al., 1993; Markusen et al., 1995; Ulph and Valentini, 2001; and Ishikawa and Okubo, 2008, for example). The third channel, finally, is changes in the price of fossil fuels, as shown in Ishikawa and Kiyono (2000). A decrease in fossil fuel demand caused by emission regulations in one country lowers the global price of fossil fuels, boosting fossil fuel demand and hence greenhouse-gas (GHG) emissions in other countries.

An important point is that the emission regulations adopted by one country do not affect GHG emissions of other countries if these countries employ emission quotas which are binding. That is, carbon leakage does not occur once other countries directly control their GHG emissions. Thus, the toughness of each country's anti-global warming policies is affected by the policy choices of other countries, in turn affecting global environmental quality. In other words, emission taxes and quotas are unilaterally equivalent for each country given the policy decisions of other countries (unilateral equivalence). However, they are not unilaterally equivalent once each country understands

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[1] In this study, the term "tax-quota equivalence" is understood to mean that subject to the objective of national welfare maximization, the government can achieve the same resource allocation through either an emission tax or an emission quota. However, the term has several different meanings in the previous literature. For example, when the replacement of an emission tax with a quota that is set to equal emission levels under the tax-ridden equilibrium gives rise to the same resource allocation across the economy. Within a partial equilibrium framework in the absence of uncertainty and incomplete information, such equivalence holds in a perfectly competitive market (see Xepapadeas, 1997) as well as in an imperfectly competitive market without strategic abatement investment by firms before the government policy decision (see Ulph, 1996). However, the equivalence breaks down in a general equilibrium model, as shown in Ishikawa and Kiyono (2006) and Ishikawa and Okubo (2008). This is mainly because an emission quota puts a cap on a country's total greenhouse gas emissions whereas the emissions are endogenously determined under emission tax policy.

that the policy instrument choices of other countries may be affected by its own choice under strategic interdependence among countries subject to the carbon-leakage effect (strategic non-equivalence).[2] [3]

In this paper, we first demonstrate unilateral equivalence and strategic non-equivalence more rigorously. When the equivalence does not hold, an interesting research question is why some countries adopt emission taxes while some others adopt emission quotas.[4] We then address this question. We specifically consider Nash equilibrium when countries non-cooperatively choose their own policy instrument. Our analysis is also instructive to examine the welfare effects when creating an international market to trade emission permits. Therefore, we explore the conditions under which the creation of international markets to trade emission permits makes all the participants better off.

When constructing our theoretical model, we incorporate a few specific features, which are not satisfactorily taken into account in the existing theoretical literature. First, we focus on international carbon leakage caused by changes in the fuel price. To our knowledge, there is no theoretical work (except for another paper of ours, Kiyono and Ishikawa, 2003) that explicitly deals with international carbon leakage through fuel price changes.[5] Another specific feature is that power generation and heat supply is the major source of GHG emissions. According to the International Energy Agency (IEA), the shares of world CO_2 emissions from fuel combustion for electricity and heat, transport, and industry are, respectively, 41%, 23%, and 20% in 2007.[6] In particular, 26% of world total CO_2 emissions is generated by thermal power generation using coal. Since energy such as electricity is not traded much, the GHG-emission share of the non-tradable is fairly high. Thus, we introduce the non-tradable sector as the source of GHG emissions into our theoretical model.

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[2]The issue of unilateral equivalence and strategic non-equivalence has been discussed rigorously in Kiyono (1985).

[3]Even in the absence of carbon leakage, the tax-quota equivalence may break down in a general equilibrium framework when pollution intensities differ across industries. See Ishikawa and Kiyono (2000,2006).

[4]Emission trading is implemented by EU and New Zealand. Australia and Canada are going to introduce emission trading. Finland was the first country to introduce emission taxes in 1990. Now a number of European countries employ emission taxes. South Africa introduced a carbon tax in 2010. Countries such as China are planning to adopt emission taxes.

[5]CGE analyses such as Felder and Rutherford (1993), Burniaux and Martins (2000), and Böringer et al. (2010) identify international carbon leakage through fuel price changes. Felder and Rutherford (1993) and Böringer et al. (2010) argue that the changes in fuel price dominate in the source of international carbon leakage.

[6]Similarly, according to the Department of Energy and Climate Change in the UK, 39% of CO_2 were from the energy supply sector, 24% from road transport, 16% from business and 16% from residential fossil fuel use in 2009. CO_2 accounted for about 84% of the UK's man-made GHG emissions in 2009.

We build a model with one fuel-producing (or fuel-exporting) country and two fuel-consuming (or fuel-importing) countries. In the fuel-consuming countries, the non-tradable sector emits GHG and causes global warming. We consider a two-stage policy game in which both fuel-consuming countries independently choose their emission regulation instrument, either emission taxes or emission quotas, and then, in the second stage, after observing which emission regulation instrument the other country has chosen, determine the specific level of the policy instrument chosen in the first stage.

Depending on the instrument choices, different policy game equilibria emerge. When both countries choose emission taxes (emission quotas), the second-stage subgame is the tax-tax policy game (the quota-quota policy game). When one country chooses emission taxes and the other emission quotas, the resulting second-stage game is the tax-quota policy game. We examine which combination of instruments emerges as a subgame perfect Nash equilibrium for our full game. This analysis sheds a new light on the question of why adopted policy instruments could be different among countries.

In Kiyono and Ishikawa (2003), we discussed the issue of unilateral equivalence and strategic non-equivalence with carbon leakage through fuel price changes. However, the analysis there was conducted in a much simpler framework using partial equilibrium analysis. In addition to providing a general equilibrium analysis, the present study analyzes the game of choice of policy instrument. It is also shown that the creation of an international market for the trade in emission permits may not benefit fuel-consuming countries.

There are many papers that compare various environmental policies including emission taxes and quotas.[7] Some of them argue what policy instruments should be used. To our knowledge, however, no study has examined the endogenous environmental-policy choices as a result of a policy game between countries. We explore the subgame perfect equilibrium when the countries commit to either taxes or quotas before determining specific instrument levels.

Copeland and Taylor (2005) develop a general equilibrium model of international trade and examine the welfare effects of emission trading. They consider a Heckscher-Ohlin model with three countries (i.e., two North countries: West and East, and South) and assume that West and East are constrained by the emission treaty, but South is not. It is shown that emission trading between West and East may make them worse off and may not cause carbon leakage in South although South is free from emission control.[8]

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[7]See Ulph (1996), Ishikawa and Kiyono (2006), Lahiri and Ono (2007), and Ishikawa and Okubo (2008), among others.

[8]As is well known, in the Heckscher-Ohlin model, the factor prices are equalized in free trade equilibrium when countries are incompletely specialized. This property holds in Copeland and Taylor (2005) so that the prices of emission permits are equalized in free

Our analysis differs from theirs not only in the structure of the model employed but also in that they explore the welfare effect led by a marginal involvement in permit trade (i.e. a limited, small volume of permit trade), whereas we discuss the total gains and losses from the country's full involvement in permit trade. In Copeland and Taylor (2005), the change in the terms of trade (TOT) for commodities plays an important role in governing the welfare effects. In our analysis, however, when the carbon-leakage effect is strong enough, the direction of the change in the TOT for fuel, which is our counterpart to their TOT for commodities, may not predict whether a country gains or loses by engaging in permit trade.

Another study that discusses the welfare effects of international trade in emission permits on each country is that by Ishikawa et al. (2011). They use a two-country (North-South) model having both the Heckscher-Ohlin and Ricardian features. Asymmetric technologies result in a difference in the permit prices between North and South under free trade equilibrium. It is shown that carbon leakage may arise and that emission trading may not benefit both countries. Although the results are somewhat similar to ours, their deriving force is different from ours because trade in fossil fuel is not considered. Moreover, in their model, carbon leakage is caused when only one country introduces an emission quota, but in our model, in contrast, even if both countries employ environmental measures, carbon leakage could arise between them. This is because one or both countries may implement emission taxes.

The rest of the paper is organized as follows. In Section 2, we construct a model of two fuel-consuming countries emitting GHG and one fuel-producing country, and show that the relative difference in the emission coefficient, that is the GHG emission per unit of fossil fuel, between the fuel-consuming countries determines the size of the carbon-leakage effect. In Section 3, we discuss the properties of the equilibria when the two fuel-consuming countries choose emission taxes. We also discuss the unilateral equivalence between emission taxes and quotas, while in Section 4, we show the strategic non-equivalence between emission taxes and quotas. In Section 5, we explore each country's incentive to choose an environment regulation instrument within a framework of a two-stage policy choice game and find subgame-perfect Nash equilibria. The results and tools for the analysis in Section 5 are further applied in Section 6 to consider the welfare effects of creating an international market for the trade in emission permits. Section 7 concludes.

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trade equilibrium with incomplete specialization. Obviously, in such an equilibrium, there is no incentive for trade in emission permits. To consider permit trade between countries, they assume that West is completely specialized in the clean good, while East produces both clean and dirty goods. As a result, permits are exported from East to West.

2 Model

Consider a world consisting of three countries, with countries 1 and 2 both consuming the fossil fuel supplied by the third country, s. The economy of each country is characterized by perfect competition. Each of the fuel-consuming countries produces two goods: a homogeneous tradable commodity (other than the fossil fuel) produced only by labor, and a non-tradable (say, electricity) produced by labor, fossil fuel, and environment resources. Production of each good is subject to constant returns to scale, and the non-tradable sector requires the use of a certain combination of fossil fuel and the environment. The use of fossil fuel results in GHG emissions, which degrade global environmental quality.

In this paper, the volume of the GHG emissions is represented by the environment as an input factor. Thus, the tradable good is what we may call a "clean" good and the non-tradable good a "dirty" one. We refer to either of the fuel-consuming countries by superscripts $i, j, k \in \{1, 2\}$ where i and $j(\neq i)$ represent the different countries and k represents either one. The third country, s, a single country supplying the fossil fuel, produces the fossil fuel and the homogeneous tradable commodity.[9]

Thus, each of the fuel-consuming countries produces and exports the tradable commodity to the fuel-supplying country and imports fossil fuel to produce the non-tradable good. The government of neither of the three countries directly intervenes in the trade in the commodity or the fossil fuel. Hereafter, we use the non-fuel tradable good as the numeraire. The constant-returns-to-scale production technology used to produce it means that we can choose the units of output and input so that one unit of the tradable needs one unit of labor. This means that the wage rate should be equal to unity across the world.

As our benchmark, we construct a model in which both fuel-consuming countries regulate their GHG emissions by means of emission taxes.

2.1 Fuel-Consuming Country

Supply-side   We start with the supply side. In a fossil-fuel-consuming country, production of the dirty non-tradable good emits GHG and worsens the quality of the global environment hurting the welfare of households across the world. According to Meade (1952), the emitted GHG is an "unpaid factor of production", pricing of which is made by the government in the country having the dirty industry. The specific emission tax rate on GHG serves as the factor price of the environmental resource for firms in

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[9]We assume for simplicity that country s's output of the non-tradable good is tiny relative to that of countries 1 and 2 and hence the demand for fossil fuel and GHG emissions in country s can be ignored.

the dirty non-tradable sector.[10]

Next, let r denote the world price of the fossil fuel, t_i, the emission tax rate set by the government in fuel-consuming country $i \in \{1, 2\}$, and $c^i(r, t_i)$ the unit cost function for the dirty non-tradable sector in country $i \in \{1, 2\}$.[11] The assumption of perfect competition subject to constant returns to scale means that the equilibrium holds only when the price of the non-tradable denoted by p_i is equal to the unit cost, i.e.,

$$p_i = c^i(r, t_i)$$

Hereafter, we assume that the unit cost function $c^i(r, t_i)$ satisfies all the standard assumptions except perfect compelentarity between the fuel and the GHG emissions in the sense that there exists a certain value $e_i(> 0)$ such that

$$c_t^i(r, t_i) = e_i c_r^i(r, t_i) \tag{1}$$

for $\forall(r, t_i)$, where $c_t^i(r, t_i) \overset{\text{def}}{=} \partial c^i(r, t_i)/\partial t_i$ and $c_r^i(r, t_i) \overset{\text{def}}{=} \partial c^i(r, t_i)/\partial r$. We call this e_i the <u>emission coefficient</u> of country $i \in \{1, 2\}$.

One should also note that, by virtue of Shephard's lemma, $c_r^i(r, t_i)$ gives the input of fossil fuel required per unit of the non-tradable good and $c_t^i(r, r_i)$ is the counterpart for the GHG emissions in the dirty non-tradable sector. Note that this assumption of complementarity (1) leads to

$$c_{tt}^i = e_i c_{rt}^i < 0,$$

where use was made of the strict concavity of the unit cost function with respect to the fuel price.

Next, let x_i represent the output of the non-tradable. Then, we may express the fossil fuel demand denoted by f_i and the GHG emissions denoted by z_i as follows:

$$
\begin{aligned}
f_i &= c_r^i(r, t_i)x_i, \\
z_i &= c_t^i(r, t_i)x_i = e_i f_i.
\end{aligned}
$$

Demand-side   Let us now consider the demand side. The utility of a representative consumer is given by

$$u^i(x_i^c) + y_i^c - \theta_i D(z_W),$$

where x_i^c denotes the consumption of the non-tradable, y_i^c the consumption of the tradable, $z_W \overset{\text{def}}{=} \sum_k z_k$ world total GHG emissions, $D(z_W)$ the world damage from global warming in terms of the numeraire good, and $\theta_i(> 0)$

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[10] See also Copeland and Taylor (1994).

[11] The wage rage, being always unity, is suppressed in the unit cost function.

what extent country i perceives this damage to be a damage to its own environment. We assume $D'(z_W) > 0$ and $D''(z_W) > 0$.

The consumer maximizes the above utility given world total GHG emissions subject to the budget constraint

$$m_i = p_i x_i^c + y_i^c,$$

where m_i denotes the national income and p_i the domestic price of the non-tradable good in country $i \in \{1, 2\}$. Since there arise no excess profits in either sector, the national income is the sum of labor income and emission tax revenue, i.e.,

$$m_i = L_i + t_i z_i,$$

where L_i denotes the labor endowment of country i and use was made of the wage rate being equal to unity.

Further, assume that the utility function $u^i(x_i^c)$ satisfies all the standard assumptions as well as

$$\lim_{x \downarrow 0} u_x^i(x) = +\infty, \text{ and } \lim_{x \uparrow +\infty} u_x^i(x) = 0,$$

which assures production of the non-tradable good to be always strictly positive in each country.

Then, one may define the indirect utility function as follows:

$$v^i(p_i) + L_i + t_i z_i - \theta_i D \left(\sum_k z_k \right),$$

where $v^i(p_i) \stackrel{\text{def}}{=} \max_x \left\{ u^i(x) - p_i x_i \right\}$. In the analysis that follows, we also make use of the relation $x^i(p_i) \stackrel{\text{def}}{=} \arg_x \left\{ u^i(x) - p_i x_i \right\}$. Finally, it should be noted that $v^{i\prime}(p_i) = -x^i(p_i)$ holds by Shephard's lemma.

National welfare   To sum up, suppressing the labor endowment term in the above equation, we employ the following expression for the welfare of country i.

$$\tilde{w}^i(r, t_i) \stackrel{\text{def}}{=} v^i(p_i) + t_i z_i - \theta_i D \left(\sum_k z_k \right) \tag{2}$$

subject to

$$v^{i\prime}(p_i) = -x^i(p_i), \tag{3}$$

$$p_i = c^i(r, t_i), \tag{4}$$

$$f_i = f^i(r, t_i) \stackrel{\text{def}}{=} c_r^i(r, t_i) x^i \left(c^i(r, t_i) \right), \tag{5}$$

$$z_i = z^i(r, t_i) \stackrel{\text{def}}{=} c_t^i(r, t_i) x^i \left(c^i(r, t_i) \right) = e_i f^i(r, t_i). \tag{6}$$

Differentiation of (2) yields:

$$
\begin{aligned}
\partial \tilde{w}^i / \partial t_i &= (t_i - \theta_i D') z_t^i, \\
\partial \tilde{w}^i / \partial r &= (t_i - \theta_i D') z_r^i - (f_i + \theta_i D' z_r^j), \\
\partial \tilde{w}^i / \partial t_j &= -\theta_i D' z_t^j.
\end{aligned}
\tag{7}
$$

One should also note the following relations for the succeeding discussion:

$$
\begin{aligned}
f_r^i &\overset{\text{def}}{=} \partial f^i / \partial r = c_{rr}^i x_i + (c_r^i)^2 x_p^i < 0, \quad & f_t^i &\overset{\text{def}}{=} \partial f^i / \partial t_i = e_i f_r^i, \\
z_r^i &\overset{\text{def}}{=} \partial z^i / \partial r = e_i f_r^i < 0, \quad & z_t^i &\overset{\text{def}}{=} \partial z^i / \partial t_i = e_i f_t^i = e_i z_r^i < 0,
\end{aligned}
\tag{8}
$$

by virtue of the technological complementarity between fossil fuel and GHG. As the third and fourth equations of (8) show, each country's GHG emissions decrease as the fuel price or the emission tax rate increases, which is the source of carbon leakage considered in our analysis.

2.2 Fuel-Supplying Country

As in the fuel-consuming countries, the wage rate in the fuel-supplying country is equal to unity. For the purpose of focusing on the effects of fossil fuel trade and carbon leakage, we assume that production of fossil fuel is subject to decreasing returns to scale though the other commodities are subject to constant returns to scale. By letting $\Phi(r)$ represent the maximum profit function of the fossil-fuel sector, Hotelling's lemma implies that $\Phi'(r)$ gives the supply function of the fossil fuel, which we represent by $s(r)$.

2.3 World Trade Equilibrium

To express the equilibrium, it suffices to write down the world fossil-fuel market clearing condition, i.e.,

$$
s(r) - \sum_j f^j(r, t_i) = 0.
\tag{9}
$$

Given the emission tax policies of the fuel-consuming countries $\boldsymbol{t} \overset{\text{def}}{=} (t_1, t_2)$, the world fuel price is determined via (9), the relation of which we express by $\hat{r}(\boldsymbol{t})$. When either fuel-consuming country raises the emission tax rate, this dampens its fuel demand, thus leading to a decline in the equilibrium fuel price. To show this effect on the price, we define the following:

$$
\Delta_r \overset{\text{def}}{=} s'(r) - \sum_k f_r^k (> 0),
\tag{10}
$$

$$
\zeta_\ell \overset{\text{def}}{=}
\begin{cases}
-f_r^i / \Delta_r & \text{for } \ell \in \{1, 2\} \\
s'(r) / \Delta_r & \text{for } \ell = s
\end{cases}.
\tag{11}
$$

8

Here, ζ_i represent the <u>relative price sensitivity of fuel-demand</u> by country $i \in \{1, 2\}$ and ζ_s the <u>relative price sensitivity of fuel-supply</u> by the fuel-supplying country. By definition, the following holds:

$$\zeta_\ell \in (0, 1), \quad \sum_\ell \zeta_\ell = 1.$$

In terms of these relative price sensitivities, one can express the effect of an increase in fuel-country i's emission tax rate on the fuel price as follows:

$$\hat{r}_i(\boldsymbol{t}) \stackrel{\text{def}}{=} \partial \hat{r}/\partial t_i = -e_i \zeta_i < 0, \qquad (12)$$

where use was made of (8). The following lemma is straightforward from (12).

Lemma 1 *(i) The world fuel price always declines as one of the fuel-consuming countries raises its emission tax rate. (ii) The decrease in the world fuel price caused by an increase in a fuel-consuming country's emission tax rate becomes greater as its emission coefficient and relative price sensitivity of fuel demand increase.*

Note that, with fuel-consuming countries facing an upward-sloping fuel-supply function $s'(r) > 0$, the above lemma critically depends on the market power of each fuel-consuming country. If country i is small with no market power in the world fuel market, then it cannot affect the world fuel price.

2.4   Emission Taxes and GHG Emissions

Before investigating each country's strategic incentive for environment regulation, let us look into the effects of emission tax increases on GHG emissions.

For this purpose, we first redefine the demand for fuel and GHG emissions as a function of the emission tax rates of the two countries, i.e., the emission-tax profile $\boldsymbol{t} = (t_1, t_2)$.

$$\hat{f}^i(\boldsymbol{t}) \stackrel{\text{def}}{=} f^i(\hat{r}(\boldsymbol{t}), t_i), \, \hat{z}^i(\boldsymbol{t}) \stackrel{\text{def}}{=} z^i(\hat{r}(\boldsymbol{t}), t_i). \qquad (13)$$

These input demand functions satisfy

$$\begin{aligned}
\hat{f}^i_i &= f^i_t + f^i_r \hat{r}_i = -\Delta_r e_i (1 - \zeta_i)\zeta_i < 0 \\
\hat{f}^i_j &= f^i_r \hat{r}_j = \Delta_r e_j \zeta_i \zeta_j > 0 \\
\hat{z}^i_i &= e_i \hat{f}^i_i = -\Delta_r e_i^2 \zeta_i (1 - \zeta_i) < 0 \\
\hat{z}^i_j &= e_i \hat{f}^i_j = \Delta_r e_i e_j \zeta_j \zeta_i = \hat{z}^j_i > 0
\end{aligned} \qquad (14)$$

where $\hat{f}^i_k \stackrel{\text{def}}{=} \partial \hat{f}^i(\boldsymbol{t})/\partial t_k$ and $\hat{z}^i_k \stackrel{\text{def}}{=} \partial \hat{z}^i(\boldsymbol{t})/\partial t_k$ for $i, k = 1, 2$ and use was made of (8). The above equations show that an increase in the emission tax rate by a fuel-consuming country decreases its own fuel demand as well as

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its own GHG emissions, while it increases those of the other fuel-consuming country (only when there is a decrease in the world fuel price).

An increase in the emission-tax by one country lowers the fuel price, leading to an increase in the fuel-demand of the other country and hence an increase in its GHG emissions. This is the basic mechanism of carbon leakage via trade in fuel considered in this study. This carbon-leakage effect involves the possibility of an increase in world total GHG emissions even with an increase in the emission tax rate of one of the countries.

To show this possibility of an increase in world total GHG emissions, let

$$\hat{z}^W(\boldsymbol{t}) \stackrel{\text{def}}{=} \sum_k \hat{z}^k(\boldsymbol{t}), \hat{f}^W(\boldsymbol{t}) \stackrel{\text{def}}{=} \sum_k \hat{f}^k(\boldsymbol{t}),$$

respectively represent world total GHG emissions and fuel demand as a function of the tax profile. Using (12) and (14), the effect of an increase in $t_i(i = 1, 2)$ on world total GHG emissions and fuel demand can be represented as:

$$
\begin{aligned}
\hat{f}_i^W &\stackrel{\text{def}}{=} \partial \hat{f}^W(\boldsymbol{t})/\partial t_i &=& \; s'(r)\hat{r}_i = -s'(r)e_i\zeta_i < 0, \\
\hat{z}_i^W &\stackrel{\text{def}}{=} \partial \hat{z}^W(\boldsymbol{t})/\partial t_i &=& \; \Delta_r e_i \zeta_i \{ e_j \zeta_j - e_i(1 - \zeta_i) \},
\end{aligned}
$$

the latter of which can also be rewritten as:

$$\hat{z}_i^W = \Delta_r e_i e_j (1 - \zeta_i)\zeta_i \left\{ \frac{\zeta_j}{1 - \zeta_i} - \frac{e_i}{e_j} \right\}. \tag{15}$$

Thus, an increase in the emission tax by either of the two countries unambiguously reduces the world fuel-demand, but, as (15) shows, it may increase world total GHG emissions.

Lemma 2 *Suppose that country $i \in \{1, 2\}$ raises its emission tax rate. Then, world total GHG emissions decrease if and only if $e_i/e_j > \zeta_j/(1 - \zeta_i)$.*

Hereafter, without loss of generality, we assume that the emission coefficient is not larger in country 1 than in country 2, i.e., $e_1 \leq e_2$.[12] Then, there are two possible cases when discussing the change in world total GHG emissions through an increase in either country's emission tax rate. They are illustrated in Figure 1.

When the relative emission coefficient e_1/e_2 is in *Region N*, an increase in either country's emission tax rate decreases world total GHG emissions. If it is in *Region A*, however, then an increase in the emission tax rate by country 1, provided its emission coefficient is sufficiently smaller than that of country 2, increases world total GHG emissions. This is because such a tax

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[12] $e_1 < e_2$ could stem from differences in artificial and/or natural carbon sinks.

increase lowers the fuel demand and thus GHG emission by country 1 with the smaller emission coefficient but the resulting decrease in the fuel price boosts the fuel demand by country 2 with the larger emission coefficient, leading to a large increase in GHG emissions.

As already mentioned, the possibility of an increase in world GHG emissions as a result of an increase in the emission tax in a country depends on the country's market power in the world fuel market. In fact, when the fuel price is constant, the increase in a country's emission tax rate only affects its own GHG emissions, so that in this case world total GHG emissions always decrease.

The above analysis establishes the following proposition.

Proposition 1 *1. When $\zeta_2/\left(1-\zeta_1\right) < e_1/e_2$ holds and hence the emission coefficients of the two fuel-consuming countries do not differ to a great extent, an increase in the emission tax rate by either country decreases world total GHG emissions.*

2. When $e_1/e_1 < \zeta_2/\left(1-\zeta_1\right)$ holds and hence the emission coefficient differ a lot, an increase in the emission tax rate by country 1 with the smaller emission coefficient increases, rather than decreases, world total GHG emissions.

Moreover, the following results hold when both fuel-consuming country simultaneously raise their emission tax rates.[13]

Lemma 3 *There always holds $\hat{z}_1^W + \hat{z}_2^W < 0$.*

Therefore, even when an increase in the emission tax by country 1 with the smaller emission coefficient increases world total GHG emissions, there must be a decrease in world total GHG emissions if both countries jointly raise their emission tax rates by the same infinitesimal amount.

Finally, let us consider the welfare implications. To do so,

3   The Individually Optimal Emission Tax

Next, we discuss the properties of the equilibria when the two fuel-consuming countries non-cooperatively choose optimal emission taxes and/or quotas. We begin by looking at the case in which each fuel-consuming country sets its emission tax rate knowing the tax rate set by the other country, which we call the tax-tax policy equilibrium. Since the optimal tax rate should maximize each country's national welfare given the other's tax rate, we refer to it as the individually optimal emission tax rate in the following discussion.

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[13]The proof is provided in Appendix A.

3.1 Determinants of the Optimal Emission Tax

In this subsection, we point out that there are three determinants of the individually optimal emission tax rate. For this, we obtain the individually optimal emission tax rate. Inserting the equilibrium fuel-price function into (2), we can express each country's welfare as the following function of the tax profile:

$$\hat{w}^{iT}(\boldsymbol{t}) \overset{\text{def}}{=} \tilde{w}^i(t_i, \hat{r}(\boldsymbol{t})). \tag{16}$$

We assume that the above welfare function is strictly concave in the country's own emission tax rate.

Since the optimal tax rate is chosen non-cooperatively, it should satisfy the following first-order condition for welfare maximization:

$$
\begin{aligned}
0 = \frac{\partial \hat{w}^{iT}}{\partial t_i} &= \frac{\partial \tilde{w}^i}{\partial t_i} + \frac{\partial \tilde{w}^i}{\partial r}\hat{r}_i \\
&= (t_i - \theta_i D')z_t^i + \left\{(t_i - \theta_i D')z_r^i - (f_i + \theta_i D' z_r^j)\right\}\hat{r}_i \\
&= (t_i - \theta_i D')\hat{z}_i^i - f_i \hat{r}_i - \theta_i D' z_r^j \hat{r}_i,
\end{aligned} \tag{17}
$$

where use was made of (7). Letting t_i^T represent the solution of the above first-order condition for welfare maximization, i.e., country i's emission tax rate at the non-cooperative tax-tax policy game equilibrium, we have

$$t_i^T = \theta_i D' + f_i\left(\frac{\hat{r}_i}{\hat{z}_i^i}\right) + \theta_i D'\left(\frac{\hat{z}_i^j}{\hat{z}_i^i}\right), \tag{18}$$

or alternatively,

$$t_i^T = f_i\left(\frac{\hat{r}_i}{\hat{z}_i^i}\right) + \theta_i D'\left(\frac{\hat{z}_i^W}{\hat{z}_i^i}\right) \tag{19}$$

$$= \frac{f_i}{\Delta_r e_i(1 - \zeta_i)} + \left(1 - \frac{e_j \zeta_j}{e_i(1 - \zeta_i)}\right)\theta_i D', \tag{20}$$

where use was made of (12) and (14).

In (18), each term represents different determinant of emission tax. The first term represents the well-known basic motive for internalizing negative externalities caused by emissions. This term is obviously positive. The second term is related to the TOT for fuel. As a result of an emission tax, the fuel-consuming country can improve the TOT for fuel and hence welfare. This effect works to raise the emission tax rate. Finally, the last term arises because of carbon leakage. Since an increase in the emission tax rate lowers the fuel price, the other fuel-consuming country's demand for the fossil fuel is boosted, which worsens the global environment quality through an increase in GHG emissions. This carbon-leakage effect works to reduce the emission tax rate. If this carbon-leakage effect is sufficiently large, then the optimal policy would in fact be to impose a negative, rather

than a positive, emission tax rate. This case occurs only when an increase in the emission tax rate increases world total GHG emissions (i.e., $\hat{z}_i^W > 0$), as is shown in (19). Since $\hat{z}_2^W < 0$ always holds with $e_1 \leq e_2$, the optimal emission tax could be negative only in country 1.

Therefore, we obtain the following proposition.

Proposition 2   *1. Given the emission tax rate of the other country, the TOT effect makes the optimal emission tax rate for a fuel-consuming country higher but the carbon-leakage effect makes it lower.*

    2. Given the emission tax rate of the other country, each fuel-consuming country sets a strictly positive rate of emission tax if an increase in its own emission tax rate decreases world total GHG emissions. A negative emission tax rate is optimal only in country 1. This is the case only if an increase in country 1's emission tax rate increases world total GHG emissions.

Note that the carbon-leakage effect vanishes when a fuel-consuming country is a price-taker in the world fuel market, so that its optimal emission tax rate is given by

$$t_i^T = \theta_i D' \left(\sum_k z_k \right). \tag{21}$$

The emission tax rate should be set equal to the perceived marginal environment damage. This result is the same with the standard result obtained in a closed-economy model where neither the TOT effect nor the carbon-leakage effect exists.

We should mention that the effect of an increase in the emission coefficient on the optimal emission tax rate is ambiguous. It increases the marginal environment damage, D'. It is straightforward from (21) that an increase in D' induces the country to raise the optimal emission tax rate without carbon leakage. However, this is not necessary the case with carbon leakage (see (19)). That is, an increase in the emission coefficient raises the country's optimal emission tax rate without carbon leakage, but may not raise country 1's optimal emission tax rate with carbon leakage.

3.2   Shapes of the Reaction Curves

When we solve (17) for the own emission tax rate, the solution gives country i's reaction function, which we denote by $R^{iT}(t_j)$. In this subsection, we examine its shape.

As has been made clear in the previous literature, when each fuel-consuming country is a price-taker in the world fuel market, the optimal emission tax rate formula (21) implies that the optimal emission tax of one country decreases as that of the other country increases. This is because an

emission tax increase by the other country decreases the own GHG emissions as well as the world total, which decreases the marginal environment damage. This leads the first country to lower its emission tax rate. For this reason, each country's reaction curve is downward-sloping in the tax-tax policy game in the absence of the carbon-leakage effect.

However, as is implied by (18), once the carbon-leakage effect occurs, the shape of the reaction function may change and it is possible that it becomes upward-sloping.

Lemma 4 *In the presence of carbon leakage through fuel trade, each country's emission tax rate is not necessarily a strategic substitute to the other's tax rate in the tax-tax policy game.*

3.3   A Tax Increase by the Other Country

We next consider whether a fuel-consuming country gains or loses if the other fuel-consuming country raises its emission tax rate. Specifically, we evaluate this effect when the country initially employs the optimal-response emission tax rate.

It is proved in Appendix B that even in the presence of carbon leakage, one finds that a tax increase by either fuel-consuming country benefits the other country. That is, $\partial \hat{w}^{iT}/\partial t_j > 0$ holds.

Proposition 3 *Given the individually optimal emission tax rate, the welfare of either of the fuel-consuming countries improves as the other country increases the emission tax rate.*

Thus, as in the standard literature, emission taxation by a fuel-consuming country gives rise to pecuniary external economies to the other fuel-consuming country. Using this result, it is straightforward to depict each country's iso-welfare contour at the non-cooperative equilibrium, as shown in Figure 2. In the figure, point T_1 is the non-cooperative equilibrium. Country i's iso-welfare contour is given by w_i^T. Thus, the two fuel-consuming countries are better off by raising their tax rates above those at the non-cooperative equilibrium. Note that this result holds regardless of whether the emission tax rates are strategic substitutes or complements.

4   The Equivalence between Taxes and Quotas

As a preliminary analysis for the later discussion as to equilibria under emission quota, we examine in the present section whether equivalence between emission taxes and quotas holds. By emission quota, we mean a country-wide cap of total GHG emissions. To exclude any possible distortion other than replacement of the tax with a quota, we assume that the government

issues a certain number of GHG emission permits and establishes a perfectly competitive market for the domestic trade in such permits.

4.1 Unilateral Equivalence

From the viewpoint of an individual country, taxes and quotas, given the policy instrument of the other country, can be shown to be equivalent in the sense that they achieve the same world resource allocation. We call this result <u>unilateral equivalence</u> between emission taxes and quotas.

First, as in the preceding discussion, suppose that country j employs emission taxes. Then in view of (13), given country i's emission quota q_i, the equilibrium permit price t_i should satisfy

$$q_i = \hat{z}^i(t_i, t_j).$$

Thus, given country j's emission tax rate, there is a one-to-one relationship between the emission quota q_i and the emission tax rate or permit price t_i. This establishes that emission taxes and quotas are equivalent for country i given country j's emission tax rate.

Next consider the case in which country j sets the emission quota q_j. Then, given q_j, when country i chooses the emission quota q_i, the resulting permit prices, t_i and t_j, should satisfy

$$q_i = \hat{z}^i(t_i, t_j), q_j = \hat{z}^j(t_j, t_i).$$

Since

$$\Delta_z \overset{\text{def}}{=} \hat{z}_1^1 \hat{z}_2^2 - \hat{z}_2^1 \hat{z}_1^2 > 0 \tag{22}$$

holds,[14] the implicit function theorem can be applied to ensure a one-to-one relationship between the permit-price profile $\boldsymbol{t}$ and the emission-quota profile $\boldsymbol{q} \overset{\text{def}}{=} (q_1, q_2)$. This implies that emission taxes and quotas are equivalent for country i given country j's emission quota.[15]

The above discussion leads to the following unilateral equivalence result.

Proposition 4 *Given the environmental policy instrument of the other fuel-consuming country, emission taxes and quotas are equivalent for each individual country.*

This proposition implies that given the other country's environmental policy instrument, a country's reaction curves are the same regardless of its choice between taxes and quotas once they are transformed and depicted over the tax-tax space.

---

[14]This result is obtained as follows:

$$\Delta_z = (z_t^1 + z_r^1 \hat{r}_1)(z_t^2 + z_r^2 \hat{r}_2) - z_r^1 z_r^2 \hat{r}_1 \hat{r}_2 = z_t^1 z_t^2 + z_t^1 z_r^2 \hat{r}_2 + z_r^1 z_t^2 \hat{r}_1$$
$$= e_1 e_2 (f_t^1 f_t^2 + f_t^1 f_r^2 \hat{r}_2 + f_r^1 f_t^2 \hat{r}_1) = e_1^2 e_2^2 f_r^1 f_r^2 \zeta_s > 0.$$

[15]A more rigorous proof is provided in Appendix C.

4.2 Strategic Non-equivalence

Even when emission taxes and quotas are equivalent given the other country's environmental policy instrument, they are no longer equivalent once the other country changes its policy instrument. In fact, once the other country switches from emission taxes to quotas, each country has an incentive to strengthen its own environmental regulation. Let us demonstrate this result, which we call the strategic non-equivalence result.

We assume that the two countries initially employ emission taxes. In Figure 2, the equilibrium is given by point T_1 where the reaction curves (which are not shown in the figure to avoid it getting too complex) intersect with each other. Now suppose that country 2 switches from emission taxes to quotas. Given the associated tax profile, draw a curve showing the tax pairs keeping country 2's GHG emissions constant. This iso-GHG-emissions curve is given by z_2^T. In view of (14), such a curve should be upward-sloping. Then, since country 1's iso-welfare contours are U-shaped as shown in Figure 2 and its welfare improves in the higher country 2's emission tax rate, country 1 becomes better off by choosing point Q_1 along the iso-GHG-emissions curve z_2^T.

The result is that country 1's emission tax rate becomes higher as well as country 2's. The reason is as follows. Since country 2's GHG emissions are held constant, its fuel demand is also kept constant under the emission quota. This implies that country 1's tax increase results in no carbon leakages, leading to an increase in the emission tax rate.

How do the GHG emissions by country 1 change after such a change in the emission tax policy? The figure also shows the iso-GHG-emissions curves for country 1, z_1^T and z_1^Q. They are also upward-sloping and their slopes are greater than country 2's by virtue of the following relation:

$$\frac{dt_2}{dt_1}\bigg|_{z_1=const} - \frac{dt_2}{dt_1}\bigg|_{z_2=const} = \frac{\hat{z}_1^2}{\hat{z}_2^2} - \frac{\hat{z}_1^1}{\hat{z}_2^1} = \frac{1}{\hat{z}_2^2 \hat{z}_2^1}\left(\hat{z}_2^1 \hat{z}_1^2 - \hat{z}_1^1 \hat{z}_2^2\right) > 0,$$

where use was made of (22).

Since $\hat{z}_1^1 < 0$, GHG emissions on the iso-GHG-emissions curve z_1^Q are smaller than those on the curve z_1^T. This is consistent with the result for the case above when country 1 employs more stringent environmental regulations.

Thus, we obtain:

Proposition 5 *If a country switches from an emission tax to an individually equivalent emission quota, then the other country has an incentive to raise its emission tax rate or to reduce its emission quota level.*

As the above proposition implies, one country's reaction curve (which is not shown in the figure) shifts rightward on the tax-tax plane when the

other country switches from an emission tax to a quota. One should note that the resulting new reaction curve does not necessarily have the same shape as the original curve. That is, even when, for example, the original reaction curve is downward-sloping given the other country's emission tax rate, the new curve may become upward-sloping given the other country's quota. The next subsection demonstrates this result.

4.3 Reaction Curves in the Quota Game

Consider now a policy game in which both fuel-consuming countries employ emission quotas. We call this the quota-quota policy game. Let q_i denote country i's quota and $\boldsymbol{q} \stackrel{\text{def}}{=} (q_1, q_2)$ the quota profile. In view of (2)-(6), each fuel-consuming country's welfare is now described by

$$\widetilde{w}^{iQ}(t_i, r) \stackrel{\text{def}}{=} v^i(p_i) + t_i q_i - \theta_i D\left(\sum_k q_k\right) \tag{23}$$

subject to

$$v^{i\prime}(p_i) = -x^i(p_i) \tag{3}$$

$$p_i = c^i(r, t_i) \tag{4}$$

$$f_i = f^i(r, t_i) \tag{5}$$

$$q_i = z^i(r, t_i) = e_i f^i(r, t_i) \tag{24}$$

$$s(r) = \sum_k \frac{q_i}{e_i} \tag{25}$$

where t_i now represents the price of the tradable emission permit in country i. The last equation (25) determines the equilibrium fuel price as a function of the quota profile, which we express by $\widehat{r}^Q(\boldsymbol{q})$. Simple calculation yields

$$\frac{\partial \widehat{r}^Q(\boldsymbol{q})}{\partial q_i} = \frac{1}{e_i s'(r)} > 0.$$

We insert this into (24), and solve for t_i. We then obtain the price of the tradable permit as a function of the quota profile, which we express by $\widehat{t}^i(\boldsymbol{q})$. From $\widehat{r}^Q(\boldsymbol{q})$ and $\widehat{t}^i(\boldsymbol{q})$, the country's welfare is represented as a function of the quota profile:

$$\widehat{w}^{iQ}(\boldsymbol{q}) \stackrel{\text{def}}{=} \widetilde{w}^{iQ}(t^i(\boldsymbol{q}), r^Q(\boldsymbol{q})).$$

In the quota-quota policy game, each country sets the quota so as to maximize its welfare given by (23), so that the following first-order condition holds:

$$\begin{aligned} 0 = \frac{\partial \widehat{w}^{iQ}}{\partial q_i} &= \left(-x_i c_t^i + q_i\right) \frac{\partial \widehat{t}^i(\boldsymbol{q})}{\partial q_i} + \left(-x_i c_r^i\right) \frac{\partial \widehat{r}^Q(\boldsymbol{q})}{\partial q_i} + (t_i - \theta_i D') \\ &= -\frac{f_i}{e_i s'(r)} + (t_i - \theta_i D') \end{aligned} \tag{26}$$

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where use was made of (24) and $f_i = c_r^i x_i$.

Solving the above equation for the permit price, we obtain

$$t_i^Q = \frac{f_i}{e_i s'(r)} + \theta_i D',\tag{27}$$

which, compared with (18), shows that there are no carbon-leakage effects. This means, as is implied by Proposition 5, that each fuel-consuming country has an incentive to strengthen its environmental regulation by setting a higher emission tax rate (or, a higher price for emission permits).

The following proposition is established.

Proposition 6 *If both fuel-consuming countries employ emission quotas, then there are no carbon-leakage effects, and hence each country has an incentive to strengthen its environmental regulation compared with the case of emission taxes.*

In general, however, the shape of the associated reaction curve is ambiguous. In the absence of fuel trade, (27) is rewritten as $t_i^Q = \theta_i D'$. Since the domestic permit price is independent of the other country's quota, it is straightforward to see that each country's emission quota is a strategic substitute to the other's. In the presence of fuel trade, however, this is not necessarily the case.

Let us now examine the relationship between the original reaction functions in terms of emission quota levels and the corresponding reaction curve in terms of emission tax rates. Let $\Gamma^i(q_j) \overset{\text{def}}{=} \arg\max_{q_i} \widehat{w}^{iQ}(\boldsymbol{q})$. Since $q_k = \hat{z}^k(\boldsymbol{t})$ holds for $k \in \{1, 2\}$, the reaction function in terms of emission tax rates, $t_i = R^{iQ}(t_j)$, should satisfy

$$\hat{z}^i(\boldsymbol{t}) = \Gamma^i\left(\hat{z}^j(\boldsymbol{t})\right).$$

Thus, the transformed reaction function, $R^{iQ}(t_j)$, should satisfy:

$$\frac{dR^{iQ}(t_j)}{dt_j} = \frac{\frac{d\Gamma^i(q_j)}{dq_j}\hat{z}_j^j - \hat{z}_j^i}{\hat{z}_i^i - \frac{d\Gamma^i(q_j)}{dq_j}\hat{z}_i^j},$$

Since

$$\frac{\hat{z}_i^i}{\hat{z}_i^j} = -\frac{e_j(1-\zeta_i)}{e_i\zeta_j}\tag{28}$$

holds by virtue of (14), we can rewrite the slope of the transformed reaction function as follows:

$$\frac{dR^{iQ}(t_j)}{dt_j} = -\frac{\hat{z}_j^j \frac{d\Gamma^i(q_j)}{dq_j} + \frac{e_j(1-\zeta_j)}{e_i\zeta_i}}{\hat{z}_i^j \frac{d\Gamma^i(q_j)}{dq_j} + \frac{e_j\zeta_j}{e_i(1-\zeta_i)}}.$$

Since $e_j\zeta_j/e_i(1-\zeta_i) < e_j(1-\zeta_j)/e_i\zeta_i$ always holds, it is straightforward to obtain the following lemma from the above equation:

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Lemma 5

$$\frac{dR^{iQ}(t_j)}{dt_j} < 0 \iff \begin{cases} (i) & \frac{d\Gamma^i(q_j)}{dq_j} < 0 \\ (ii) & \frac{e_j\zeta_j}{e_i(1-\zeta_i)} < \left| \frac{d\Gamma^i(q_j)}{dq_j} \right| < \frac{e_j(1-\zeta_j)}{e_i\zeta_i} \end{cases}$$

As the above lemma shows, under the quota-quota policy game, the reaction curve in terms of emission tax rates becomes upward-sloping even when the corresponding reaction curve in terms of emission quota levels is downward-sloping. Moreover, when the original reaction curve in the quota-quota policy game over the quota-quota space is upward-sloping, the corresponding transformed reaction curve should always be upward-sloping.

4.4 A Quota Decrease by the Other Country

What if the other country reduces its emission quota level in the quota-quota policy game? The following shows that if a country optimizes its emission quota in response to the quota set by the other country, such a decrease in the other country's quote unambiguously improves the welfare of the first country:

$$\begin{aligned} \frac{d\widehat{w}^{iQ}\left(\Gamma^i(q_j), q_j\right)}{dq_j} &= \frac{\partial\widehat{w}^{iQ}\left(\Gamma^i(q_j), q_j\right)}{\partial q_j} \text{ (by virtue of the envelope theorem)} \\ &= -\theta_i D' - f_i \widehat{r}_j^Q < 0. \end{aligned} \tag{29}$$

Thus, in the quota-quota policy game, each country's choice of the emission quota level generates external diseconomies for the other country. This means that the incentive for each country to reduce GHG emissions through quotas is not enough from the viewpoint of the joint welfare of both fuel-consuming countries. Thus, we have established:

Proposition 7 *If both fuel-consuming countries further reduce their GHG emissions through quotas, then both can be better off than at the non-cooperative quota-quota policy game equilibrium.*

5 Strategic Interdependence

5.1 Policy Instrument Choices and Subgame Equilibria

The result of the strategic non-equivalence of emission taxes and quotas implies that the quality of the global environment will differ depending on each country's choice of policy instrument. These differences are shown in Figures 3 (a) and (b). Figure 3(a) shows the case in which the reaction curves of both fuel-consuming countries are downward-sloping, while Figure 3 (b) shows the case in which they are upward-sloping.

In the figures, each intersection of the reaction curves of the two countries represent a non-cooperative environmental policy equilibrium for each possible combination of instrument choices. Thus, for example, point E_{TQ} shows the equilibrium when country 1 chooses emission taxes and country 2 emission quotas.

5.2 Welfare Comparison

As already discussed in Section 4.3, in the quota-quota policy game, both countries tend to strengthen their environmental regulation compared with the tax-tax policy game. Moreover, in view of Proposition 3, one may be tempted to conclude that both countries would be better off at the quota-quota policy game equilibrium E_{QQ} than at the tax-tax policy game equilibrium E_{TT}. In general, however, this is not correct. The reason is that E_{QQ} does not always lie within the set of the tax profiles dominating E_{TT} for both countries.

For a more specific welfare comparison among the possible equilibria, let us compare E_{QQ} with the equilibrium in which country i chooses emission taxes but country j chooses emission quotas. Movement from the latter to the former requires changes in the tax profile along country i's transformed reaction curve $R^{iQ}(t_j)$ (see Figures 3 (a) and (b)). This is because when country i switches to emission quotas, country j has an incentive to alter its emission quota so as to raise the price of domestic emission permits, or, effectively, the emission tax rate.

The associated effect on country i's welfare is given by:

$$
\frac{d\widehat{w}^{iQ}\left(\hat{z}^i\left(R^{iQ}(t_j), t_j\right), \hat{z}^j\left(R^{iQ}(t_j), t_j\right)\right)}{dt_j}
$$

$$
= \frac{\partial \widehat{w}^{iQ}\left(\Gamma^i\left(\hat{z}^j\left(R^{iQ}(t_j), t_j\right)\right), \hat{z}^j\left(R^{iQ}(t_j), t_j\right)\right)}{\partial q_i} \frac{d\hat{z}^i\left(R^{iQ}(t_j), t_j\right)}{dt_j}
$$

$$
+ \frac{\partial \widehat{w}^{iQ}\left(\Gamma^i\left(\hat{z}^j\left(R^{iQ}(t_j), t_j\right)\right), \hat{z}^j\left(R^{iQ}(t_j), t_j\right)\right)}{\partial q_j} \frac{d\hat{z}^j\left(R^{iQ}(t_j), t_j\right)}{dt_j}
$$

$$
= -\left(f_i \hat{r}^Q_j + \theta_i D'\right) \frac{d\hat{z}^j\left(R^{iQ}(t_j), t_j\right)}{dt_j} = -\left(f_i \hat{r}^Q_j + \theta_i D'\right) \hat{z}^j_i \left\{ \frac{dR^{iQ}(t_j)}{dt_j} - \frac{e_j(1-\zeta_j)}{e_i \zeta_i} \right\},
$$

where use was made of the envelope theorem, (29), (28) and (14). Thus, country i is better off by switching to emission quotas given country j's choice of emission quotas if and only if country j's GHG emissions decrease with an increase in its emission tax rate along country i's transformed reaction curve, or alternatively if and only if $dR^{iQ}(t_j)/dt_j < e_j(1-\zeta_j)/e_i\zeta_i$.

Let $E_{T_i Q_j}$ denote the equilibrium in which country i chooses emission taxes and country j emission quotas, and $E_{T_i Q_j} \succ_i E_{QQ}$ means that country i's welfare is strictly higher at $E_{T_i Q_j}$ than at E_{QQ}. Then the above discussion can be summed up in the following proposition.

Proposition 8   1. $E_{QQ} \succ_i E_{T_i Q_j} \iff \dfrac{dR^{iQ}(t_j)}{dt_j} < \dfrac{e_j(1-\zeta_j)}{e_i \zeta_i}$

2. $E_{QQ} \succ_j E_{T_i Q_j} \iff \dfrac{dR^{iQ}(t_j)}{dt_j} > \dfrac{e_j \zeta_j}{e_i(1-\zeta_i)}$

These results, based on Proposition 3 (i.e., $E_{Q_i T_j} \succ_i E_{TT}$), are summarized in Figure 4. Noting $e_i(1-\zeta_i)/e_j\zeta_j > e_i\zeta_i/e_j(1-\zeta_j)$, we have four regions in the figure. We can easily confirm in the figure that the quota-quota policy game equilibrium E_{QQ} may not be the best for both countries.

We are now ready to determine which combination of the environment regulation instruments emerges as a subgame perfect Nash equilibrium for our full game. Noting Figure 4, we can draw Figure 5 that illustrates possible equilibria when both countries simultaneously choose a policy instrument. In *Region QQ*, a quota policy is the dominant strategy for both countries, so that E_{QQ} arises.[16] In *Region QT (TQ)*, the choice of a quota policy dominates that of a tax policy for country 1 (2) but country 2 (1) prefers emission taxes when country 1 (2) chooses quotas, so that E_{QT} (E_{TQ}) arises. Lastly, in *Region U*, each country is better off by choosing a policy instrument different from the other's choice, so that there are at least three equilibria; two are pure-strategy equilibria, E_{TQ} and E_{QT}, and the last is a mixed-strategy equilibrium.[17]

Thus, we obtain:

Proposition 9 *Both countries choose emission quotas if both $dR^{1Q}(t_2)/dt_2 < e_2(1-\zeta_2)/e_1\zeta_1$ and $dR^{2Q}(t_1)/dt_1 < e_1(1-\zeta_1)/e_2\zeta_2$ hold. Countries 1 and 2, respectively, choose an emission tax and an emission quota if both $dR^{1Q}(t_2)/dt_2 > e_2(1-\zeta_2)/e_1\zeta_1$ and $dR^{2Q}(t_1)/dt_1 < e_1(1-\zeta_1)/e_2\zeta_2$ hold, and vice versa if both $dR^{1Q}(t_2)/dt_2 < e_2(1-\zeta_2)/e_1\zeta_1$ and $dR^{2Q}(t_1)/dt_1 > e_1(1-\zeta_1)/e_2\zeta_2$ hold.*

This proposition suggests a reason why employed policy instruments are different across countries.

6   The Welfare Implications of Creating an International Market for Emission Permits

In this section, on the basis of the analysis above, we explore the welfare effects of creating an international market for emission permit market. To

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[16] When $e_1\zeta_1/e_2(1-\zeta_2) < dR^{2Q}/dt_1 < e_1(1-\zeta_1)/e_2\zeta_2$ and $dR^{1Q}/dt_2 < e_2(1-\zeta_2)/e_1\zeta_1$, $E_{QT} \succ_1 E_{QQ}$ holds. Since country 2 chooses quotas in that region, however, E_{QT} is not realized. Similarly, E_{TQ} is not realized when $e_2\zeta_2/e_1(1-\zeta_1) < dR^{1Q}/dt_2 < e_2(1-\zeta_2)/e_1\zeta_1$ and $dR^{2Q}/dt_1 < e_1(1-\zeta_1)/e_1\zeta_1$.

[17] A mixed-strategy equilibrium is easily obtained. See Appendix D.

exclude any possible problems in choosing the world total volume of tradable permits, we assume that its volume is set equal to the GHG emissions chosen at a non-cooperative environmental regulation equilibrium before the market creation. More specifically, we assume that the amount of tradable emission permits each country is endowed with is the same as the country would choose before the creation of an international permit market.

Let q_i^e denote the size of country i's GHG emissions at an equilibrium and t_i^e its associated emission tax rate or permit price. Since each country is endowed with q_i^e units of emission permit, world total GHG emissions are kept constant at $q_c \overset{\text{def}}{=} \sum_k q_k^e$. Free permit trade leads to equalization of the permit price between the two countries.

Noting Lemma 2 and Proposition 1, we examine two possible cases. The first is Case N of $\hat{z}_1^W < 0$ and $\hat{z}_2^W < 0$ (i.e., when e_1/e_2 lies in *Region N* in Figure 1). The iso-GHG-emissions curve for this case is shown in Figure 6(a). Along the curve, when t_1 rises, t_2 must fall. Otherwise, world total GHG emissions would increase. Thus, the iso-GHG-emissions curve is downward-sloping.[18] The second is Case A of $\hat{z}_1^W > 0$ and $\hat{z}_2^W < 0$ (i.e., when e_1/e_2 lies in *Region A* in Figure 1). The iso-GHG-emissions curve is upward-sloping, as shown in Figure 6(b). Note that in the second case, the iso-GHG-emissions curve has a slope of less than unity by virtue of Lemma 3.

The critical difference between the two cases is as follows. In the first case, the equilibrium permit price under international trade in emission permits, denoted by t_m, lies between the initial permit prices of both countries. In the second case, however, t_m is either greater or less than the initial domestic prices. If the starting tax-profile is located above (below) the equal-tax-rate line (i.e., the 45° line) as shown in Figure 6 (b), t_m is greater (less) than the initial domestic prices.

We now examine the welfare effects of allowing international trade in emission permits. For this purpose, we consider the relationship between the domestic permit prices in the two countries. This can be obtained by solving the following equation:

$$q_c - \sum_k \hat{z}^i(t_1, t_2) = 0. \tag{30}$$

Country 2's permit price is then determined as a function of country 1's permit price, which we express by $t_{2m}(t_1)$. This satisfies:

$$t'_{2m}(t_1) = -\frac{\hat{z}_1^W}{\hat{z}_2^W}, \tag{31}$$

where one should note that the assumption of $e_1 \leq e_2$ assures $\hat{z}_2^W < 0$ but $\hat{z}_1^W < 0$ may not hold (recall Figure 1). By construction, the function $t_{2m}(t_1)$

---

[18]See (31) below.

satisfies:
$$t_{2m}(t_1^e) = t_2^e, \quad t_{2m}(t_m) = t_m.$$

The associated equilibrium fuel price, denoted by $r = r_m(t_1)$, satisfies:

$$s(r) - f^1(r, t_1) - f^2(r, t_{2m}(t_1)) = 0.$$

It is straightforward to verify that

$$r'_m(t_1) = \frac{e_1 e_2 \zeta_1 \zeta_2 \Delta_r}{\widehat{z}_2^W}(e_2 - e_1) \leq 0, \tag{32}$$

where use was made of $e_1 \leq e_2$. This implies that an increase in t_1 as a result of country 1's exports of emission permits decreases the equilibrium fuel price if $e_1 < e_2$ holds. The intuition is as follows. If country 1 exports emission permits to country 2, then emissions decrease in country 1 but increase in country 2. Since world total GHG emissions are kept constant, the world demand for fuel decreases with $e_1 < e_2$ and hence the fuel price falls.

The welfare of country i is given by:

$$w^{iM}(t_1) \stackrel{\text{def}}{=} v^i(p_i) + t_i q_i^e - \theta_i D\left(\sum_k q_k\right), \tag{33}$$

where

$$p_i = c^i\left(r_m(t_i), t_i\right),$$
$$t_i = \begin{cases} t_1 & \text{for } i = 1 \\ t_{2m}(t_1) & \text{for } i = 2 \end{cases}.$$

Thus, noting that world total GHG emissions are constant, we have the following expressions for the change in each country's welfare resulting from an increase in country 1's permit price:

$$\frac{dw^{1M}}{dt_1} = (q_1^e - z_1) - f_1 r'_m(t_1), \tag{34}$$

$$\frac{dw^{2M}}{dt_1} = (q_2^e - z_2)t'_{2m}(t_1) - f_2 r'_m(t_1). \tag{35}$$

The first term corresponds to the standard gains from trade in emission permits. There are gains from trade for the permit-exporting (the permit-importing) country if the permit price rises (falls) as a result of permit trade. The second term stems from the change in the TOT for fuel. If country 1 exports emission permits to country 2, then the world demand for fuel decreases with $e_1 < e_2$ and hence the TOT for fuel improve for both fuel-consuming countries.

Since we have

$$\frac{d\hat{z}^1\left(t_1, t_{2m}(t_1)\right)}{dt_1} = -\frac{\Delta_z}{\hat{z}_2^W} < 0,$$

$q_1^e > z_1$ and $q_2^e < z_2$ hold for $\forall t_1 > t_1^e$. By virtue of $r'_m \leq 0$ and (31), the right-hand side of (34) is strictly positive for $\forall t_1 > t_1^e$, while the right-hand side of (35) is strictly positive for $\forall t_1 > t_1^e$ if $\hat{z}_1^W \leq 0$, which holds when carbon leakage is not very strong. Thus, if the autarky emission permit price is lower in country 1, where the emission coefficient is smaller, and carbon leakage is weak, then both countries become better off by creating an international market for emission permits. As mentioned above, there are two sources for the gains from permit trade here. The first is the standard gains from trade, while the second is the gains from the improvement in the TOT for fossil fuel.

In Figure 6(a), both countries gain if the permit prices without international trade in permits satisfy $t_1^e < t_2^e$ (say, N_2). However, the welfare effect of creating a world market for permit trade is ambiguous for both countries if $t_1^e > t_2^e$ (say, N_1). This is because emission trading worsens the TOT for fossil fuel. In Figure 6 (b), if $t_1^e < t_2^e$ (say, point A_2), then country 1 gains but country 2 may or may not gain. If $t_1^e > t_2^e$ (say, point A_1), on the other hand, then country 2 loses but country 1 may or may not lose.

The following should be noted in the case of Figure 6 (b). First, only country 1 can realize the standard gains from trade. At point A_1 (A_2), country 2 exports (imports) the emission permits, but the permit price falls (rises) in country 2. Second, the effect of emission trading on country 2's welfare is ambiguous at point A_2, though the total welfare of the two fuel-consuming countries increases. Given $e_1 \leq e_2$ and $t_1 > t_1^e$, the change in the total welfare of the two fuel-consuming countries is expressed by

$$\begin{aligned}
\frac{dw^{1M}}{dt_1} + \frac{dw^{2M}}{dt_1} &= (q_1^e - z_1)(1 - t'_{2m}(t_1)) - (f_1 + f_2)r'_m(t_1) \\
&= (q_1^e - z_1)\frac{(\hat{z}_1^W + \hat{z}_2^W)}{\hat{z}_2^W} - (f_1 + f_2)r'_m(t_1) > 0,
\end{aligned}$$

where use was made of $\hat{z}_1^W + \hat{z}_2^W < 0$.

Therefore, we have obtained the following proposition.

Proposition 10 *Given $e_1 \leq e_2$, when $t_1^e < t_m$, the creation of a world market for permit trade unambiguously makes country 1 better off and makes country 2 better off if $\hat{z}_1^W \leq 0$.*

Thus, mutually welfare-enhancing permit trade necessarily arises if the autarky emission permit price is lower in country 1 with the smaller emission coefficient and carbon leakage is not be very strong. However, one should note that, unlike Copeland and Taylor (2005), improvement in the TOT here

does not always assure that both countries become better off. In Figure 6 (b), a shift from point A_2 to M entails the TOT improvement for both fuel-consuming countries, but country 2 may lose from international emission trading.

7   Conclusion

In this paper, we explored environmental policy choices in the presence of international carbon leakage caused by fuel price changes, explicitly taking into account international trade in fossil fuel. We considered a world consisting of two fuel-consuming countries emitting GHG and a fuel-producing country. The fuel-consuming countries non-cooperatively regulate GHG emissions through emission taxes or quotas. The two policy instruments are equivalent for each country if the other country's choice of policy instrument is given. However, the presence of the carbon-leakage effect affects each country's policy stance on global warming once the other country switches its policy instrument. That is, non-equivalence between emission taxes and quotas could arise. Such strategic non-equivalence affects the subgame perfect equilibrium when the countries commit to either emission taxes or quotas before determining their specific level. The results of, and tools for, the analysis were then applied to discuss the welfare effects of creating an international market for the trade in emission permits. We found that the creation of such a market improves the welfare of each participant when (i) there is an increase in the emission permit price for the country with the smaller emission coefficient (i.e., the more efficient environmental technology) and (ii) the difference in the level of environmental technology is not large between the two participants.

As was shown, the presence of carbon leakage and its size critically affect the optimal environmental policy of each country. As an illustration of the implications of the results obtained here, we may regard country 1 as the North (advanced countries with better environmental technologies) and country 2 as the South. Doing so, the following two policy implications can be derived.

First, when only the North tightens environmental regulations, there is a danger that world total GHG emissions may increase, rather than decrease, thus aggravating global warming. In this sense, what would be required is to call on the South to cooperate with the North in dealing with global warming. Second, when initially the North is tougher against global warming, the creation of an international market to trade emission permits may not benefit both North and South. This is likely to be the case when carbon leakage is strong. A necessary condition for both North and South to gain from international emission trading is that their emission coefficients are not different too much. Thus, technology transfers from North to South

may play an important role when creating an international market to trade emission permits.

The purpose of this paper was to present a simple, stylized model in order to focus on the international carbon leakage caused by changes in the fuel price. To do so, we assumed that the production of the non-tradable good alone is responsible for GHG emissions and that the fuel-producing country does not emit GHG. However, it would be worthwhile to examine the implications of this approach in more generalized models.

References

[1] Böringer, C., A. Lange and T. F. Rutherford (2010). "Optimal Emission Pricing in the Presence of International Spillovers: Decomposing Leakage and Terms-of-Trade Motives," NBER Working Paper Series 15899, National Bureau of Economic Research..

[2] Burniaux, J. and J. O. Martins (2000) "Carbon Emission Leakages: A General Equilibrium View," OECD Economics Department Working Papers, No. 242, OECD Publishing.

[3] Copeland, B. R. and M. S. Taylor (1994) "North-South Trade and Environment," *Quarterly Journal of Economics* 109: 755-787.

[4] Copeland, B. R. and M. S. Taylor (2005) "Free Trade and Global Warming: A Trade Theory View of the Kyoto Protocol," *Journal of Environmental Economics and Management* 49, 205–234.

[5] Felder, S. and T. F. Rutherford, (1993). "Unilateral CO Reductions and Carbon Leakage: The Consequences of International Trade in Oil and Basic Materials," *Journal of Environmental Economics and Management*, 25, 162-176.

[6] Ishikawa, J. and K. Kiyono (2000) "International Trade and Global Warming," CIRJE Discussion Paper Series CIRJE-F-78, Faculty of Economics, University of Tokyo.

[7] Ishikawa, J. and K. Kiyono (2006) "Greenhouse-gas Emission Controls in an Open Economy", *International Economic Review* 47, 431-450.

[8] Ishikawa, J., K. Kiyono, and M. Yomogida (2011) "Is Emission Trading Beneficial?," CCES Discussion Paper Series No. 41, Center for Research on Contemporary Economic Systems, Graduate School of Economics, Hitotsubashi University <http://hermes-ir.lib.hit-u.ac.jp/rs/handle/10086/18961>, forthcoming in *Japanese Economic Review*.

[9] Ishikawa, J. and T. Okubo (2008) "Greenhouse-gas Emission Controls and International Carbon Leakage Through Trade Liberalization," CCES Discussion Paper Series No.3, Hitotsubashi University <http://hdl.handle.net/10086/16318 >.

[10] Kiyono, K. (1985) "Trade-policy Games – An Inquiry Into Tariff-quota Equivalence (Boueki-seisaku geimu – Kanzei to suryo wariate no douchi meidai ni kansuru ichi kousatsu–)," *Studies on Trade and Industrial Policies* (*Tsusho-Seisaku Kenkyu*), 10, 1-16 (in Japanese).

[11] Kiyono, K. and J. Ishikawa (2004) "Strategic Emission Tax-quota Non-equivalence Under International Carbon Leakage," in H. Ursprung and S. Katayama (eds.) *International Economic Policies in a Globalized World*, Springer Verlag, 133–150.

[12] Lahiri, S. and Y. Ono (2007) "Relative Emission Standard versus Tax under Oligopoly: The Role of Free Entry," *Journal of Economics* 91, 107-128.

[13] Markusen, J. R., E. R. Morey and N. D. Olewiler (1993) "Environmental Policy When Market Structure and Plant Locations are Endogenous," *Journal of Environmental Economics and Management* 24, 69–86.

[14] Markusen, J. R., J, E. Morey and N. Olewiler (1995) "Competition in Regional Environmental Policies When Plant Locations are Endogenous," *Journal of Public Economics* 56, 55–77.

[15] Mead, J. E. (1952) "External Economies and Diseconomies in a Competitive Situation, " *Economic Journal* 62, 54-67.

[16] Ulph, A. (1996) "Environmental Policy Instruments and Imperfectly Competitive International Trade," *Environmental and Resource Economics* 7, 333-355.

[17] Ulph, A. and L. Valentini (2001) "Is Environmental Dumping Greater When Plants Are Footloose?" *Scandinavian Journal of Economics* 103, 673–688.

[18] Xepapadeas, A. (1997) *Advanced Principles in Environmental Policy*, Edward Elgar Publishing Inc.

Appendix

A. Proof of $\hat{z}_1^W + \hat{z}_2^W < 0$

This appendix proves Lemma 3. Equation (14) shows

$$\hat{z}_i^W = \Delta_r e_i \zeta_i \left\{ e_j \zeta_j - e_i (1 - \zeta_i) \right\},$$

which yields

$$\frac{1}{\Delta_r} \left(\hat{z}_1^W + \hat{z}_2^W \right) = 2 e_1 e_2 \zeta_1 \zeta_2 - e_1^2 \zeta_1 (1 - \zeta_1) - e_2^2 \zeta_2 (1 - \zeta_2).$$

Consider the right-hand side as a quadratic equation in e_1. Then, the associated determinant is equal to

$$\zeta_1^2 \zeta_2^2 e_2^2 - \zeta_1 \zeta_2 (1 - \zeta_1)(1 - \zeta_2) e_2^2 = e_2^2 \zeta_1 \zeta_2 (\zeta_1 + \zeta_2 - 1) < 0,$$

which implies that the given equation never becomes non-negative given $e_1 e_2 \neq 0$. This establishes

$$\hat{z}_1^W + \hat{z}_2^W < 0.$$

B. Proof of $\partial \hat{w}^{iT} / \partial t_j > 0$

In this appendix, we prove Proposition 3. By construction of the welfare function, one can derive

$$\frac{\partial \hat{w}^{iT}}{\partial t_j} = \frac{\partial \tilde{w}^i}{\partial t_j} + \frac{\partial \tilde{w}^i}{\partial r} \hat{r}_j = \frac{\partial \tilde{w}^i}{\partial t_j} - \frac{\hat{r}_j}{\hat{r}_i} \frac{\partial \tilde{w}^i}{\partial t_i}$$

$$= -\theta_i D' z_t^j - \frac{f_t^j}{f_t^i} (t_i - \theta_i D') z_t^i = -f_t^j \left\{ \theta_i D' e_j + (t_i - \theta_i D') e_i \right\}$$

$$= -f_t^j \left\{ \theta_i D' e_j + e_i \left\{ f_i \left(\frac{\hat{r}_i}{\hat{z}_i^i} \right) + \theta_i D' \left(\frac{\hat{z}_i^j}{\hat{z}_i^i} \right) \right\} \right\},$$

or alternatively

$$-\frac{\hat{z}_i^i}{f_t^j} \frac{\partial \hat{w}^{iT}}{\partial t_j} = e_i f_i \hat{r}_i + e_j \theta_i D' \hat{z}_i^i + e_i \theta_i D' \hat{z}_i^j$$

$$= e_i f_i (-e_i \zeta_i) + e_j \theta_i D' \times e_i^2 (1 - \zeta_i) f_r^i + e_i \theta_i D' \left(-e_i e_j \zeta_i f_r^j \right)$$

$$= -e_i^2 f_i \zeta_i + e_i^2 e_j \theta_i D' (1 - \zeta_i) f_r^i - e_i^2 e_j \theta_j D' \zeta_i f_r^j.$$

Thus,

$$-\frac{1}{e_i^2} \frac{\hat{z}_i^i}{f_t^j} \frac{\partial \hat{w}^{iT}}{\partial t_j} = -f_i \zeta_i + \Delta_r e_j \theta_i D' \left(\zeta_i \zeta_j - \zeta_i (1 - \zeta_i) \right) \qquad \text{(B-1)}$$

$$= -f_i \zeta_i - \Delta_r e_j \theta_i D' \zeta_i \zeta_s < 0, \qquad \text{(B-2)}$$

which establishes

$$\frac{\partial \hat{w}^{iT}}{\partial t_j} > 0.$$

C. Proof of Unilateral Equivalence

To prove the unilateral equivalence between emission taxes and quotas, we must show that there is a one-to-one relationship for each fuel-consuming country between the emission tax rate and the emission quota given the other. Let us prove this first for the case in which the other country chooses emission taxes.

Given country j's emission tax rate t_j, let q_i denote the emission quota or GHG emissions by country i. The equilibrium condition requires:

$$q_i = e_i f^i(r, t_i), s(r) = \frac{q_i}{e_i} + z^j(r, t_i).$$

Solving the second equation for the fuel price and denoting the solution by $r^T(q_i, t_j)$, the latter satisfies:

$$\frac{\partial r^T(q_i, t_j)}{\partial q_i} = \frac{1}{e_i(s'(r) - e_j f_r^j)} > 0.$$

Insert this relation into the first equation and solve the latter for the equilibrium emission tax rate or emission permit price t_i. Let $t^{iT}(q_i, t_j)$ express the solution. It satisfies:

$$\frac{\partial t^{iT}(q_i, t_j)}{\partial q_i} = \frac{e_i f_t^i}{1 - e_i f_r^i r_q^T} < 0,$$

by virtue of (8). This establishes the result.

Next, consider the case in which the other country chooses emission quotas. Let q_j denote country j's emission quota. Then again the equilibrium requires:

$$q_k = e_k f^k(r, t_k), s(r) = \sum_k \frac{q_k}{e_k}$$

The equilibrium fuel price depends on the quota profile $\boldsymbol{q}$. We express this relation by $r^Q(\boldsymbol{q})$. It satisfies:

$$\frac{\partial \widehat{r}^Q(\boldsymbol{q})}{\partial q_i} = \frac{1}{e_i s'(r)} > 0.$$

Insert this into the first equation. Then the emission tax rate is determined by the quota profile, the relation of which we express by $\widehat{t^i}(\boldsymbol{q})$. It satisfies

$$\frac{\partial \widehat{t^i}(\boldsymbol{q})}{\partial q_i} = \frac{1 - e_i f_r^i \frac{\partial \widehat{r}^Q(\boldsymbol{q})}{\partial q_i}}{e_i f_t^i} < 0,$$

which establishes the result.

D. Mixed-strategy Equilibrium

A mixed-strategy equilibrium in Section 5 is easily obtained. Let ρ_j^T denote the probability that country j chooses emission taxes. Then country i is indifferent between taxes and quotas if and only if

$$\rho_j^T w_{Q_i T_j}^i + (1 - \rho_j^T) w_{QQ}^i = \rho_j^T w_{TT}^i + (1 - \rho_j^T) w_{T_i Q_j}^i,$$

where $w_{T_i Q_j}^i$ for example represents country i's equilibrium welfare when country i chooses emission taxes and country j emission quotas. The above equation shows that the equilibrium probability ρ_j^T satisfies

$$\rho_j^T = \frac{w_{T_i Q_j}^i - w_{QQ}^i}{(w_{Q_i T_j}^i - w_{TT}^i) + (w_{T_i Q_j}^i - w_{QQ}^i)}.$$

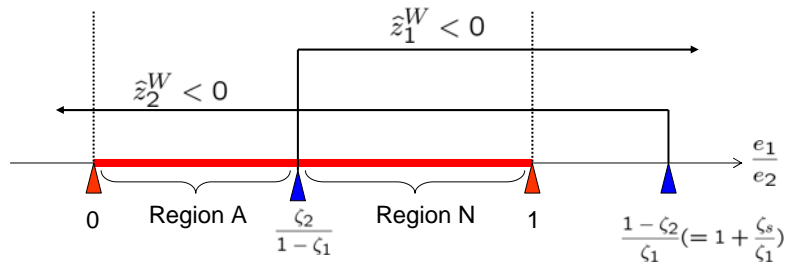Figure 1: Changes in emission taxes and world total GHG emissions

$\hat{z}_1^W < 0$

$\hat{z}_2^W < 0$

Region A

$\dfrac{\zeta_2}{1 - \zeta_1}$

Region N

$\dfrac{e_1}{e_2}$

0

1

$\dfrac{1 - \zeta_2}{\zeta_1}\left(= 1 + \dfrac{\zeta_s}{\zeta_1}\right)$

Figure 2: Jointly better tax profiles for the fuel-consuming countries

t_2

$w_1^T \quad w_1^Q$

$z_1^T \quad z_1^Q$

z_2^T

Q_1

t_2^T

T_1
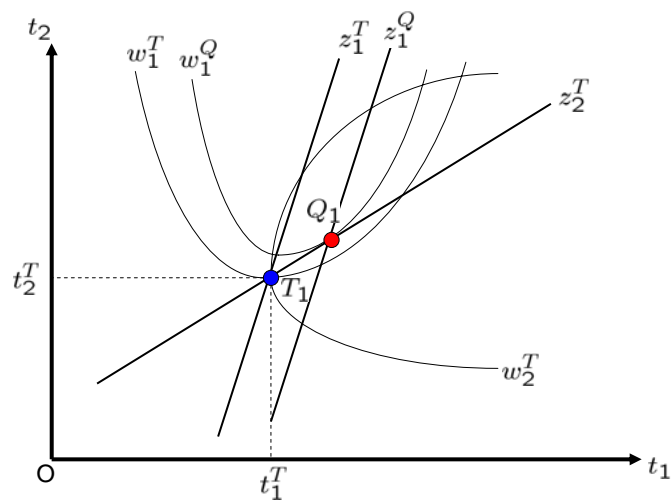
w_2^T

O

t_1^T

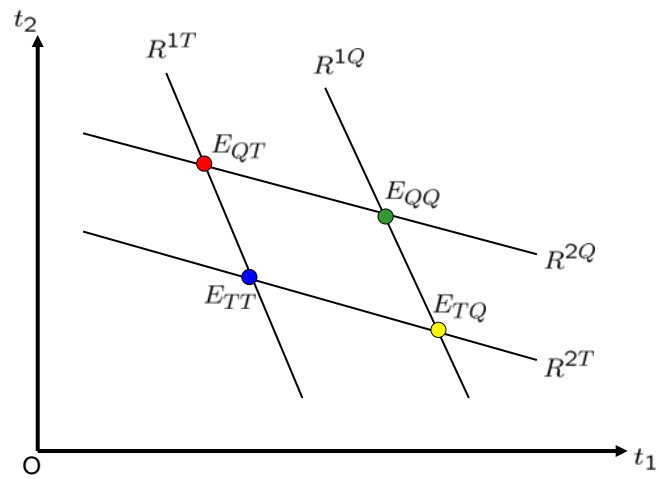t_1

Figure 3 (a): Reaction curves: The case of strategic substitutes

Figure 3 (b): Reaction curves: The case of strategic complements

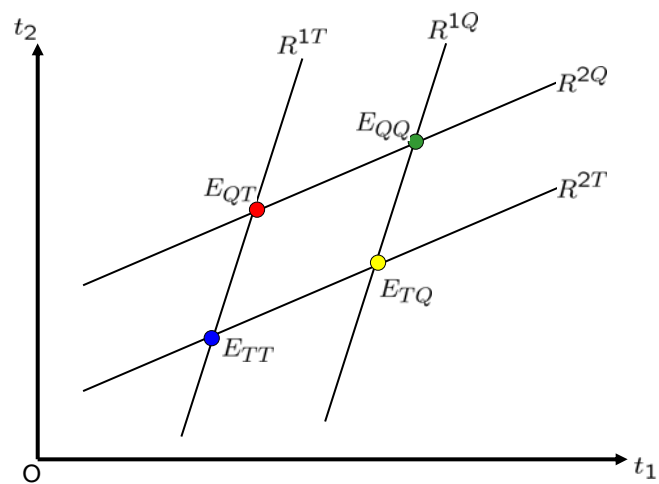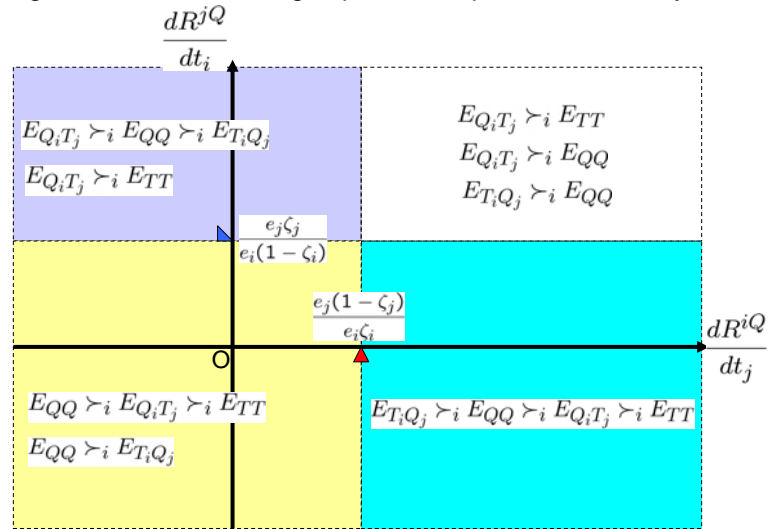Figure 4: Welfare ranking of possible equilibria for country i

$E_{Q_i T_j} \succ_i E_{QQ} \succ_i E_{T_i Q_j}$

$E_{Q_i T_j} \succ_i E_{TT}$

$E_{Q_i T_j} \succ_i E_{TT}$

$E_{Q_i T_j} \succ_i E_{QQ}$

$E_{T_i Q_j} \succ_i E_{QQ}$

$\dfrac{e_j \zeta_j}{e_i(1-\zeta_i)}$

$\dfrac{e_j(1-\zeta_j)}{e_i \zeta_i}$

$E_{QQ} \succ_i E_{Q_i T_j} \succ_i E_{TT}$

$E_{QQ} \succ_i E_{T_i Q_j}$

$E_{T_i Q_j} \succ_i E_{QQ} \succ_i E_{Q_i T_j} \succ_i E_{TT}$

$\dfrac{dR^{jQ}}{dt_i}$

$\dfrac{dR^{iQ}}{dt_j}$

Figure 5: Possible equilibria

Region QT

Region U

$\dfrac{e_1(1-\zeta_1)}{e_2 \zeta_2}$

$\dfrac{e_1 \zeta_1}{e_2(1-\zeta_2)}$

$\dfrac{e_2(1-\zeta_2)}{e_1 \zeta_1}$

Region QQ

$\dfrac{e_2 \zeta_2}{e_1(1-\zeta_1)}$

Region TQ

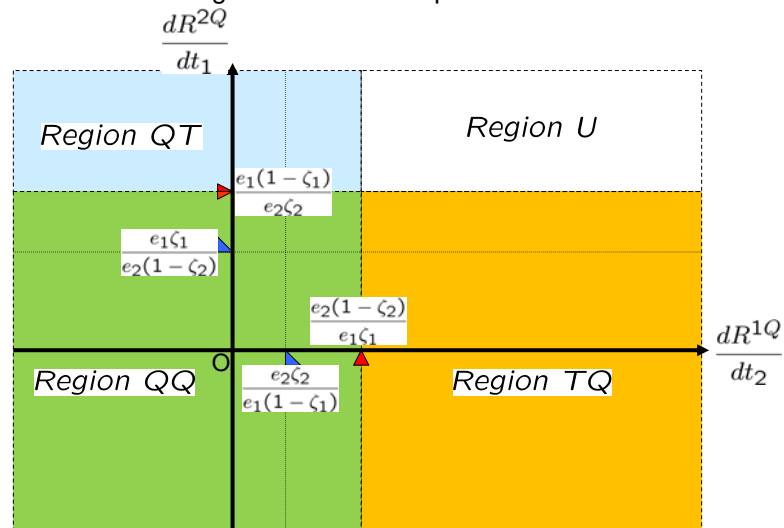$\dfrac{dR^{2Q}}{dt_1}$

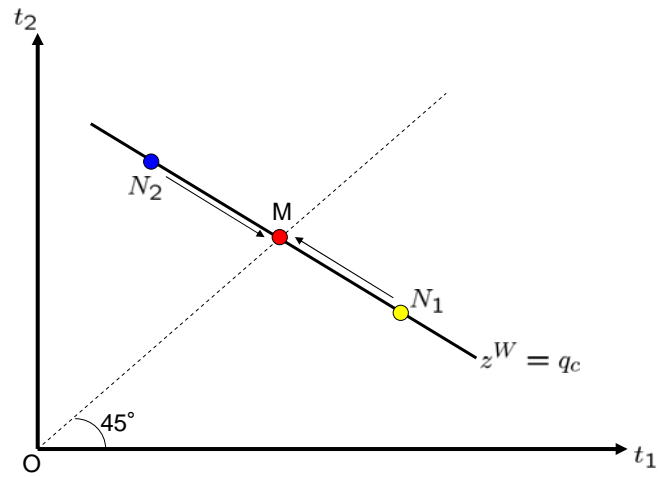$\dfrac{dR^{1Q}}{dt_2}$

Figure 6 (a): International trade in permits: Case N

Figure 6 (b): International trade in permits: Case A