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Greenhouse Gas Emission Controls and Firm Locations in North-South Trade

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Abstract

This paper studies greenhouse gas (GHG) emission controls in the presence of international carbon leakage through international firm relocation. In a trade and geography framework with two countries ("North" and "South"), only North sets a target for GHG emissions. We compare the consequences of emission quotas, emission taxes, and emission standards under trade liberalization for the location of pollution-intensive and less pollution-intensive sectors and the degree of carbon leakage. With low trade costs, further trade liberalization increases global emissions by facilitating carbon leakage. Regulation by quotas leads to spatial sorting with less carbon leakage and less global emissions than regulation by taxes and standards.

Keywords: Global warming, Emission tax, Emission quota, Emission standard, Carbon leakage, Firm relocation, Trade liberalization
JEL classification: F18, Q54

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1. INTRODUCTION

Global warming caused by greenhouse-gas (GHG) emissions has been a central issue among global environmental problems. To cope with global warming, an international environmental treaty, the United Nations Framework Convention on Climate Change (UNFCCC), was negotiated at the Earth Summit held in Rio de Janeiro in 1992. The Kyoto Protocol was then adopted at the third session of the Conference of Parties to the UNFCCC (COP3) in December 1997. In the protocol, the industrialized countries, which are called Annex I Parties, made a commitment to decrease their GHG emissions by 5.2% compared to their 1990 baseline levels over the 2008 to 2012 period. Under the protocol, however, large emitters such as the United States, China, and India had no obligation to undertake the reduction.[1] Moreover, when the Kyoto Protocol was provisionally extended in COP17 in 2011, Canada and Japan were against the extension and announced their secession from the protocol. In these circumstances, in which some countries have pledged to reduce emissions but some have not, a serious concern is international carbon leakage. That is, the reduction in GHG emissions in some countries may increase GHG emissions in other countries. In fact, worldwide emissions may even rise as a result of international carbon leakage.

International carbon leakage may occur through a number of channels. For example, it may occur through fuel price changes (e.g., Felder and Rutherford, 1993; Burniaux and Martins, 2000; Ishikawa and Kiyono, 2000; Kiyono and Ishikawa, 2004, 2012). This is because when a country adopts policies to reduce GHG emissions, its demand for fossil fuels is likely to decrease. For example, if the world prices of fossil fuels fall as a result of this decrease in demand in a country attempting to reduce its GHG emissions, the demand for fossil fuels rises in other countries with weak regulations. Carbon leakage may also arise through changes in a country's industrial structures (e.g., Copeland and Taylor 2005; Ishikawa and Kiyono, 2006). For example, with stringent GHG emission regulations in a country, the comparative advantage of an emission-intensive industry in the highly regulated country may shift abroad. This is the so-called 'pollution haven hypothesis', in which, in response to environmental

[1] China was the largest CO_2 emitter in 2011. Its share of CO_2 emissions in the world is 27.1%. The second and the third largest emitters of CO_2 (when considered as a single country) are the US (15.9%) and India (5.5%).

policy differences across countries, firms may relocate from countries with stringent regulations to countries with lax environmental regulations (e.g., Markusen et al., 1993, 1995; Rauscher, 1995; Ulph and Valentini, 2001). This problem may be exacerbated because recent improvements in transportation and communications technology as well as trade liberalization allow firms to relocate their plants more easily (Forslid, Okubo and Sanctuary, 2013).

In this paper, we explore GHG emission controls in the presence of carbon leakage through international firm relocation in a North-South model in which there are two countries: 'North' and 'South'. Specifically, we examine the relationship between trade liberalization and international carbon leakage when only North sets a target for GHG emissions and when there are pollution-intensive and less intensive industries. We also compare the consequences of emission quotas (including the creation of a competitive emission-permit market), taxes, and emission standards under trade liberalization for the location of industry and the degree of carbon leakage. To investigate the impact of trade liberalization on firm location, we adopt the simplest new economic geography (NEG) model of Martin and Rogers (1995), which is called "the footloose capital (FC) model."[2]

In our model, in addition to the two countries (North and South), there are three sectors (agriculture and two manufacturing sectors with high pollution intensity and low pollution intensity respectively), and three factors (labor, physical capital, and human capital). The agricultural product, which perfectly competitive firms produce from labor alone with constant-returns-scale (CRS) technology, is freely traded internationally. The manufactured products are subject to the Dixit–Stiglitz (1977) type of monopolistic competition, are costly to ship internationally, and generate GHG emissions in the process of production. Human and physical capital move between countries and determine plant location, although capital owners are not mobile and labor is only mobile between sectors and not countries. To make our point as clearly as possible, we assume that North, which is larger than South in population, unilaterally adopts an environmental policy, which might be an emission tax, an emission quota, or an emission standard. Then, we consider the effects of these policies when trade costs fall and firms are free to relocate to South.

[2] See Baldwin et al. (2003, Ch. 3).

There are many papers that examine the pollution haven hypothesis. In the framework of an open economy, the first theoretical analysis of the hypothesis is Pethig (1976). Subsequently, Markusen et al. (1993, 1995) investigated the hypothesis in the presence of foreign direct investment (FDI). In Markusen et al. (1993), two polluting firms (one is local to the home country and the other is foreign) choose the number of plants and plant locations when only the home country adopts emission taxes. They are primarily concerned with market structures induced by taxes. In Markusen et al. (1995), a single firm decides the plant number and locations when both countries adopt environmental policies non-cooperatively. The governments have an incentive to lower (raise) environmental standards to attract (deter) investment if the benefit from investment is greater (less) than the loss (i.e., the environmental damage).[3]

Although evidence on the pollution haven hypothesis is mixed,[4] recent empirical studies investigating sectoral level impacts provide striking evidence for the hypothesis. Since pollution intensities are largely different between sectors, environmental costs due to emission reduction policies are accordingly substantially different among sectors. Ederington et al. (2005) investigate the pollution haven hypothesis using US sectoral data and find that a pollution haven occurs in some pollution-intensive and footloose sectors. In this vein, Cole et al. (2010) explore Japanese industries and find that the pollution haven effect is stronger in trade with non-OECD countries in pollution-intensive sectors. In this sense, it is worthwhile to model two sectors with different emission intensities in order to argue about different policy impacts between sectors. Thus, our model includes, in addition to an agricultural sector, two manufacturing sectors with different emission intensities.

[3] When a country adopts exceedingly lax environmental policies in order to keep its competitive advantage, its strategy is sometimes called “environmental (or ecological) dumping.” On the other hand, when a country adopts too stringent environmental policies in order to reduce local pollution, this strategy is called “Not in my back yard (NIMBY).” There are a number of studies which, following Markusen et al. (1995), analyze environmental dumping and NIMBY strategies; see, for example, Rauscher (1995) and Ulph and Valentini (2001).

[4] According to Jaffe et al. (1995), differences in environmental policies have little or no effect on trade patterns, investment, or firm location. However, Henderson (1996), Becker and Henderson (2000), Greenstone (2002), and List et al. (2003) find that pollution-intensive plants are responding to environmental regulations. Smarzynska and Wei (2004) discuss factors that may make the evidence of the hypothesis weak. Levinson and Taylor (2008) point out that the pollution haven effect has been underestimated.

A few NEG studies investigate environmental policies (Pflueger, 2001; Venables, 2001; Elbers and Withagen, 2004; Ishikawa and Okubo, 2011).[5] Pflueger (2001) considers Pigouvian emission taxes in an NEG model similar to ours. However, his analysis is along the line of Markusen et al. (1995). Thus, environmental damage is local and governments can detect emitters, estimate the damage, and impose optimal emission taxes. In contrast, emissions in our model are global and hence it is hard to identify polluters and estimate emissions damage. This makes it impossible to levy a tax on each polluter and compensate the public through tax reimbursement. In our paper, global warming is an impending issue and North is required to reduce total emissions by a certain amount. In addition, unlike Pflueger (2001), in addition to an agricultural sector, our model has two manufacturing sectors with different emission intensities. The manufacturing sectors are both footloose and thus different emission policies lead to different impacts on location choices between sectors due to different emission intensities.

Turning to the environment and trade literature, Ishikawa and Kiyono (2006) analyze the potential effects of choices about emission controls in an open economy. They specifically compare emission taxes, quotas, and standards in a perfectly competitive general equilibrium trade model. Our analysis is somewhat similar to theirs in the sense that one of two countries unilaterally employs an environmental policy, which generates cross-border carbon leakage,[6] and that in the sense that North's emission level is endogenously determined under emission taxes. However, their model is based on traditional trade models (i.e., both the Ricardian and the Heckscher–Ohlin (HO) models) and does not take firm relocation into account.

Copeland and Taylor (1995) briefly compare the welfare implications of inflexible (exogenously determined) taxes and permits in the model from Pethig (1976). They do not, however, explicitly demonstrate that regulation by permits results in less relocation of production than regulation by taxes. In an analysis of the

[5] Venables (2001) studies the impact of an ad valorem tax on equilibrium in a vertical linkage model. In the case of energy taxes that are unilaterally introduced in one country, he discusses hysteresis in location but does not investigate quotas. Elbers and Withagen (2004) study the impact of an emission tax on agglomeration in the presence of labor migration. Using an FC model, Ishikawa and Okubo (2011) explore the effect of environmental product standards on the environment.

[6] Ishikawa et al. (2012) extend the analysis of emission quotas in Ishikawa and Kiyono (2006) by incorporating South's emission quotas into the model. Kiyono and Ishikawa (2004, 2012) focus on international interdependence of environmental management policies in the presence of international carbon leakage.

Kyoto Protocol, Copeland and Taylor (2005) explore the relationship between international trade in goods and emission permits using an HO framework. Interestingly, they show that unilateral emission reductions in North can induce the unconstrained South to reduce emissions. This implies that, in contrast to our analysis, international carbon leakage may not be a serious issue even without universal participation in the protocol. This contrast basically stems from the presence of an income effect as well as from the absence of firm relocation in their analysis. Here, the income effect means that higher income results in lower pollution.[7]

The rest of the paper is organized as follows. In Section 2, we present our basic model. Emission taxes, quotas, and standards are investigated in Sections 3, 4, and 5, respectively. Then, in Sections 6 and 7, we investigate the mechanism of spatial sorting and compare emission policies in terms of firm share and global emissions. Section 8 concludes the paper.

2. BASIC MODEL

2.1. *Two-country, three-sector, three-factor model without environmental policies*

To investigate environmental issues, we extend the FC model developed by Martin and Rogers (1995) to two manufacturing sectors with GHG emissions. There are two countries (North and South), three production factors (labor, L, physical capital, K, and human capital, H), and three sectors (agriculture, which is called the A-sector, and also two manufacturing sectors). The two manufacturing sectors are footloose in firm locations and emit GHGs. In order to highlight the different impacts of environmental policies on location choice between sectors, the two manufacturing sectors involve different emission intensity. One manufacturing sector is low-tech and pollution-intensive and the other is a high-tech sector and is less pollution-intensive. More precisely, the low-tech sector uses labor and physical capital with high emission intensity, making it a so-called dirty sector (hereinafter called the D-sector) and the high-tech sector uses labor and human capital with low emission intensity, making it a so-called clean sector (hereinafter called the C-sector). The only difference between

[7] Evidence of the income effect is also mixed. See, for example, Barbier (1997).

the two manufacturing sectors is that there are different emission intensities due to different types of capital, although all other sectoral characteristics are identical.

North is bigger than South in terms of population size. The agricultural product is produced from labor alone by perfectly competitive firms under CRS technology and is traded without any trade costs. Specifically, one unit of labor is required to produce one unit of the agricultural product. This product serves as a numéraire.

The manufactured goods in the C- and D- sectors are subject to the Dixit–Stiglitz type of monopolistic competition and are traded with trade costs. Firms in both manufacturing sectors can move between countries, but there is no entry and exit.[8] The C- and D- sectors use labor and exclusively employ physical and human capital (K and H), respectively. Specifically, each firm is required to use one unit of capital (K or H), which represents fixed costs, and a units of labor per unit of production. The cost function for firm j is given by the same structure in both sectors as $TC_{j,C} = \pi_C + awx_{j,C}$ for the C-sector and $TC_{j,D} = \pi_D + awx_{j,D}$ for the D-sector, where π_D and π_C, i.e., the fixed cost part of total cost, represent the capital return of physical capital and human capital, respectively; w is the wage rate; and x_j is the output of firm j. The C- and D-sectors emit GHGs in the process of production and firms in the D-sector emit more units of GHGs per unit of production than do those in the C-sector. Without loss of generality, we assume a=1. Trade costs, $\tau(\geq 1)$, are of the iceberg type. When x units of a good are exported, only x/τ units arrive because of iceberg trade costs. The freeness of trade, ϕ, can be defined as $\phi \equiv \tau^{1-\sigma}$ (where σ >1). This implies that free trade, $\tau = 1$, can be expressed as $\phi = 1$ whereas $\phi = 0$ represents autarky ($\tau = \infty$). For the sake of simplicity, we assume that the same production technology is used in both North and South under quota, emission tax, and emission standard policies.[9]

Turning to the demand side, a representative consumer in North has the following quasi-linear utility function:

[8] Due to no entry and exit the only margin of adjustment in this model is firm size.

[9] Even in the presence of different technologies including abatement, the essence of our results would not change. With lower costs in South, leading to an increased cost advantage in South, the impact of North taxes and quotas will be magnified, and vice versa.

$$U = \mu \ln C + \mu \ln D + A - f(\chi + \chi^*),$$
(1)
$$C \equiv \left(nc^{1-1/\sigma} + n^* c_S^{1-1/\sigma}\right)^{1/(1-1/\sigma)}, \quad D \equiv \left(md^{1-1/\sigma} + m^* d_S^{1-1/\sigma}\right)^{1/(1-1/\sigma)}, \quad 1 > \mu > 0, \quad \sigma > 1$$

where *C, D*, and *A* stand for consumption of C- and D-sectors and A-sector, respectively, and μ is the intensity of preference towards M-sector goods. "*" indicates variables and parameters in South. *n* and *m* are the numbers of differentiated varieties in the C- and D-sectors. *c* and *d* are the quantities of North consumption for each variety in each manufacturing sector produced in North, while c_S d_S are the quantities of North consumption for each variety in each manufacturing sector produced in South.[10] We note that, without loss of generality, the C- and D-sectors are symmetric in the demand side. σ in the constant elasticity of substitution (CES) function for differentiated varieties denotes the constant elasticity of substitution between the two C- and D-sector varieties. The disutility is expressed as an increasingly monotonic function of GHG emissions, $f(\chi + \chi^*)$, where χ is GHG emissions. Each consumer has one unit of physical capital and human capital as well as labor and gets income from all factors, $w + \pi_D + \pi_C$. However, the quasi-linear utility function has no income effect and thus each consumer buys a certain number of units of C- and D-sector goods regardless of her income.

Labor is mobile between sectors but immobile between countries. While human and physical capital are both mobile between North and South, capital owners are immobile and thus capital rewards are repatriated to the country of origin. Because capital endowment is initially allocated in proportion to labor endowment (i.e., market size), North's share of initial capital and labor endowments is given by $s_K \equiv K / K^W = s_H \equiv H / H^W = L / L^W \equiv s_L$, where *W* stands for values pertaining to the world. However, after firms relocate, capital shares are generally not equal to population share, whereas population share always corresponds to labor share. Capital shares are always identical to firm shares, $s_H = n / n^W$ and $s_K = m / m^W$. This is because each footloose firm needs one unit of capital. Because no income effect exists, the quasi-linear utility function ensures $s \equiv s_L = s_E$, where the share of North expenditure, *E*, in the world is defined as $s_E \equiv E / E^W$. For simplicity, total

[10] c_S should be distinguished from c^* in equation (3) ,which is the quantity of South consumption for each product variety produced in North.

expenditure, E^W, and total labor and capital endowments, L^W, H^W, and K^W (thus the total number of firms, n^W and m^W), are normalized to one. Thus, *n* (*m*) is North's share of C-sector firms (D-sector firms).[11]

2.2. *Initial equilibrium*

Since the A-sector good is freely traded internationally, wage rates in both North and South are equalized: $w = w^* = 1$. Utility maximization results in the well-known CES demand function. As a result of maximization, the local and export prices of the product varieties of the North-based C- and D-sector firms are given by:

$$(2)\quad p = \frac{1}{1-1/\sigma}, \quad p^* = \frac{\tau}{1-1/\sigma}.$$

The local and export prices of the product varieties of the South-based C- and D-sector firms, p_S^* and p_S, are isomorphic. Consumption per product variety for the North-based C-sector firms in North and South are given by:

$$(3)\quad c = \frac{\mu p^{-\sigma} s}{np^{1-\sigma} + (1-n)p^{*1-\sigma}}, \quad c^* = \frac{\mu p^{*-\sigma}(1-s)}{np^{1-\sigma} + (1-n)p^{*1-\sigma}}$$

where c^* is the quantity of South consumption for each product variety produced in North. Consumption in the D-sector, *d* and *d**, are isomorphic. Similarly, consumption per product variety for the South-based C- or D-sector firm is isomorphic.

The quantity produced by each North-based firm for the North market is identical to consumption, i.e., $x=c$ for the C-sector and $y=d$ for the D-sector. Turning to the export market, when *x* (*y*) units are exported, only x/τ (y/τ) units reach the foreign market because of iceberg trade costs. It follows that the total quantity produced by a North-based firm, firm *j*, in the C-sector is given by: $x + x^* = \mu\left(\frac{s}{np^{1-\sigma}+(1-n)p^{*1-\sigma}} + \phi\frac{1-s}{np^{1-\sigma}+(1-n)p^{*1-\sigma}}\right)p^{-\sigma}$. The total quantity produced by a North-based firm, firm *j*, in the D-sector, $y+y^*$, is isomorphic.

[11] Importantly, we use a quasi-linear utility function. The income effect is eliminated. The total number of households (population) is one in the world, because each individual has one unit of labor and capital. The level of demand depends on population size rather than income.

Now turning to GHG emissions, the C- and D- sectors have different emission intensities, regardless of the same formulation of the cost function. Producing one unit of C-sector goods entails one unit of GHG emissions, whereas producing one unit of D-sector goods entails $\gamma(>1)$ units of emissions.

The amount of local emissions in each country is proportional to each country's total quantity produced. Thus, local emission levels in North and South are, respectively:

$$\chi \equiv n(x+x^*) + m\gamma(y+y^*) = n\beta\left(\frac{s}{\Delta_C} + \phi\frac{1-s}{\Delta_C^*}\right) + m\beta\gamma\left(\frac{s}{\Delta_D} + \phi\frac{1-s}{\Delta_D^*}\right) \quad \text{and}$$

$$\chi^* \equiv (1-n)\beta\left(\phi\frac{s}{\Delta_C} + \frac{1-s}{\Delta_C^*}\right) + (1-m)\beta\gamma\left(\phi\frac{s}{\Delta_D} + \frac{1-s}{\Delta_D^*}\right),$$

where the first term in each local emission level stems from the C-sector and the second term stems from the D-sector, $\beta \equiv \dfrac{\mu}{(1-1/\sigma)}$, $\Delta_C \equiv n + \phi(1-n)$, $\Delta_C^* \equiv \phi n + (1-n)$, $\Delta_D \equiv m + \phi(1-m)$ and $\Delta_D^* \equiv \phi m + (1-m)$. Since β is exogenously given and constant, without loss of generality, we can normalize $\beta = 1$ by an appropriate choice of units.[12] Note that GHG emissions in North and South correspond to quantities produced in each country. In sum, global emissions are given by $\chi^W \equiv \chi + \chi^*$.

By using (2)-(3), pure profits for a representative firm in North and South are, respectively, given by:[13]

$$\pi_C = \left(\frac{s}{\Delta_C}s + \frac{\phi(1-s)}{\Delta_C^*}\right)\frac{\mu}{\sigma} \quad \text{and} \quad \pi_C^* = \left(\frac{\phi s}{\Delta_C} + \frac{1-s}{\Delta_C^*}\right)\frac{\mu}{\sigma}.$$

Expressions for profits in the D-sector are isomorphic. Because our model has asymmetric market size, $s > 1 - s$ (i.e., $s > 1/2$), the pure profit of a North-based firm is higher than that of a South-based firm with positive trade costs. Therefore, allowing for

[12] This normalization is not crucial for our main results, though the value of σ is bound to μ and vice versa. Even if we do not employ this normalization, all main results remain valid.

[13] Note that each firm's profit is $1/\sigma$ times firm revenue. The $(1 - 1/\sigma)$ terms cancel out in the price of a product variety and in CES composition.

free relocation, the pure profits are equalized and then firm shares, n, are determined as locational equilibrium:

$$(4)\quad \pi_C - \pi_C^* = \frac{\mu(1-\phi)}{\sigma}\left(\frac{s}{\Delta_C} - \frac{1-s}{\Delta_C^*}\right) = 0 .$$

Solving (4) for n and its isomorphic expression for m, we obtain:

$$(5)\quad n = m = \frac{1}{2} + \left(\frac{1+\phi}{1-\phi}\right)(s - \frac{1}{2}) .$$

As trade costs fall (as ϕ rises), n and m increase and more South firms move to North in a so-called gradual agglomeration. Then, below a certain trade cost, called the sustain point ($\phi_0^S = \frac{1-s}{s}$), all firms concentrate in North, i.e., full agglomeration. That is, trade costs measured in terms of ϕ, which are above the sustain point, create full agglomeration in North as a stable equilibrium.

In spite of different emission intensities, both manufacturing sectors are identical locational equilibrium and correspond to the standard FC model. In other words, emission intensities never affect location choice without environmental policies.

Lemma 1: Without environmental policies, emission intensities have no impact on location patterns. In spite of different emission intensities between manufacturing sectors, location patterns are always identical to those of the standard FC model.

Using firm shares (5), local and global emissions in equilibrium are written as:

$$(6)\quad \chi_0 = \frac{(1+\gamma)(s-(1-s)\phi)}{1-\phi},\ \ \chi_0^* = \frac{(1+\gamma)(1-s-s\phi)}{1-\phi} \ \text{ and }\ \chi_0^W = 1+\gamma .$$

As trade costs decrease, North emissions rise and South emissions fall through relocation from South to North. On the other hand, global emissions are always independent of trade costs.

Lemma 2: Without environmental policies, local emissions depend on trade costs in gradual agglomeration, while global emissions are always independent of trade costs and location of firms.

In the following analysis, we set a certain level of North emissions as a policy target to make comparison of policy impacts. For simplicity, we assume that full agglomeration in both manufacturing sectors arises in North and then the North government introduces environmental policies:

(7) $$\bar{\chi} \equiv \frac{1}{1+t} + \frac{\gamma}{1+\gamma t} = 1 + \frac{1}{b}$$

In the following sections, t is employed as the notation for tax rates (section 3) and $\bar{\chi}$ is set as the North emission constraint in a quota policy (section 4). The permit price, which is, under $\bar{\chi}$ with full agglomeration in North, equivalent to the tax rate, i.e., $\bar{q} \equiv t$. In an emission standard policy, b reflects abatement activity in the D-sector, which will be discussed in detail in section 5.[14] Under all policies, North emissions in policy targets are equivalent if all firms in both sectors locate in North, i.e., full agglomeration in both manufacturing sectors. In this setting, the North government presupposes no relocation due to all policies and thus can keep full agglomeration in both manufacturing sectors. However, once firm relocation is allowed under the policies, emission levels in North are not equivalent any more. This is aimed at measuring how carbon leakage is likely to occur through firm relocation.

3. EMISSION TAX

3.1. *Taxation without relocation*

Now we introduce environmental policies. Because of an international environmental agreement such as the Kyoto Protocol, an industrialized country, which has manufacturing agglomeration, namely North, sets a maximum level of emissions as (7). To decrease emissions to the level specified by the international agreement, we assume that North introduces an emission tax, quota, or emission standard. In this section, we examine emission taxes.

North imposes an emission tax so as to reduce emissions and implement the international agreement. Because one and $\gamma(>1)$ units of GHG emissions for the C-

[14] Although government regulates a maximum level of per-unit of emissions, b is not a policy variable in the emission standard policy. Without loss of generality, however, we exogenously set b so as to make comparisons in location impacts under the same level of policy target.

and D- sectors correspond to one unit of quantity produced in our model, an emission tax needs to be levied on each unit of emission that stems from each unit of production rather than being levied on prices, pure profits, or sales. Thus, the emission tax is equivalent to a specific production tax, *t*. Then, the total costs and prices in the C-sector in North are expressed as $TC_{j,C} = \pi + (1+t)x_j$ and $p = \frac{1+t}{1-1/\sigma}$; $p^* = \frac{\tau(1+t)}{1-1/\sigma}$. Firms in the D-sector in North emit γ units of GHGs per unit of production and thus $TC_{j,D} = \pi + (1+\gamma t)x_j$ and $p = \frac{1+\gamma t}{1-1/\sigma}$; $p^* = \frac{\tau(1+\gamma t)}{1-1/\sigma}$.

The tax increases total costs and prices. Thus, the pure profit of a North-based firm and North's emissions without relocation are given by:

$$(8)\quad \pi_C = \left(\frac{s}{\Delta_C} + \frac{\phi(1-s)}{\Delta_C^*} \right) \frac{\mu(1+t)^{1-\sigma}}{\sigma},$$

$$(9)\quad \pi_D = \left(\frac{s}{\Delta_D} + \frac{\phi(1-s)}{\Delta_D^*} \right) \frac{\mu(1+\gamma t)^{1-\sigma}}{\sigma},$$

where $\Delta_C = n(1+t)^{1-\sigma} + \phi(1-n)$, $\Delta_C^* = \phi n(1+t)^{1-\sigma} + (1-n)$, $\Delta_D = m(1+\gamma t)^{1-\sigma} + \phi(1-m)$ and $\Delta_D^* = \phi m(1+\gamma t)^{1-\sigma} + (1-m)$.

3.2. *Equilibrium with free relocation*

We now allow for free firm relocation. Because taxation decreases profits in North, firms may have an incentive to move to the non-taxed country, i.e., South, regardless of the South's small market size. Firm shares, *n* and *m*, are determined so as to equalize pure profits between countries:

$$(10)\quad \pi_C - \pi_C^* = \frac{\mu}{\sigma}\left(\frac{s}{\Delta_C} + \frac{\phi(1-s)}{\Delta_C^*} \right)(1+t)^{1-\sigma} - \frac{\mu}{\sigma}\left(\phi\frac{s}{\Delta_C} + \frac{1-s}{\Delta_C^*} \right) = 0 \quad \text{and}$$

$$(11)\quad \pi_D - \pi_D^* = \frac{\mu}{\sigma}\left(\frac{s}{\Delta_D} + \frac{\phi(1-s)}{\Delta_D^*} \right)(1+\gamma t)^{1-\sigma} - \frac{\mu}{\sigma}\left(\phi\frac{s}{\Delta_D} + \frac{1-s}{\Delta_D^*} \right) = 0.$$

Solving these equations, firm shares are derived as:

(12) $n=\dfrac{(1+t)^{1-\sigma}(s+\phi^2-s\phi^2)-\phi}{(1-\phi(1+t)^{1-\sigma})((1+t)^{1-\sigma}-\phi)}$ and $m=\dfrac{(1+\gamma t)^{1-\sigma}(s+\phi^2-s\phi^2)-\phi}{(1-\phi(1+\gamma t)^{1-\sigma})((1+\gamma t)^{1-\sigma}-\phi)}$.

Figure 1 plots firm shares, *n* and *m,* in terms of freeness of trade ϕ and small tax rates. Given a fixed, low tax rate, the firm share locus is hump-shaped. Taxation causes international carbon leakage: firm relocation occurs from North (the taxed country) to South (the non-taxed country). Stated differently, it is necessary to have intermediate levels of trade costs to keep full agglomeration, $\phi^{NL}<\phi<\phi^{NU}$, which can be written as:

(13) $\phi_C^{NU}=\dfrac{(1+t)^{1-\sigma}+\sqrt{(1+t)^{2(1-\sigma)}-4s(1-s)}}{2s}$, $\phi_C^{NL}=\dfrac{(1+t)^{1-\sigma}-\sqrt{(1+t)^{2(1-\sigma)}-4s(1-s)}}{2s}$,

$\phi_D^{NU}=\dfrac{(1+\gamma t)^{1-\sigma}+\sqrt{(1+\gamma t)^{2(1-\sigma)}-4s(1-s)}}{2s}$ and $\phi_D^{NL}=\dfrac{(1+\gamma t)^{1-\sigma}-\sqrt{(1+\gamma t)^{2(1-\sigma)}-4s(1-s)}}{2s}$.

Note that the sustain point under the tax is always higher than in the standard model, i.e., $\phi_C^{NL}>\phi_0^S$.

<Figure 1>

In reverse, given a fixed ϕ, a low tax rate can sustain full agglomeration. The condition for the low tax rate is given by:

$(1+t)^{2(1-\sigma)}-4s(1-s)>0\Leftrightarrow t<\tilde{t}_C\equiv(4s(1-s))^{1/(2(1-\sigma))}-1$ in the C-sector and similarly

$t>\tilde{t}_D\equiv\dfrac{1}{\gamma}(4s(1-s))^{1/(2(1-\sigma))}-1$ is the condition for the D-sector. When the tax rate is above $\tilde{t}$, North never sustains full agglomeration for any trade cost and instead at least one firm locates in South. Figure 2-a illustrates the case of moderate (or high) tax rates without North's full agglomeration.[15] The D-sector is more likely to experience non-full agglomeration in North than is the C-sector. In addition, as the D-sector is pollution-intensive (higher γ), non-full agglomeration is more likely to happen.

[15] See Appendix for parameter values.

<Figure 2-a, Figure 2-b>

As shown in Figures 1 and 2-a, all firms relocate to South with a sufficiently small trade cost, that is, complete carbon leakage arises. The critical values of trade costs, ϕ^S, are analytically given by:

(14) $\phi_C^S = \dfrac{1-\sqrt{1-4s(1-s)(1+t)^{2(1-\sigma)}}}{2(1-s)}$ and $\phi_D^S = \dfrac{1-\sqrt{1-4s(1-s)(1+\gamma t)^{2(1-\sigma)}}}{2(1-s)}$.

As the tax rate, *t,* rises, the critical values, ϕ_C^S and ϕ_D^S, decrease and full agglomeration in South is more likely to occur. A sufficiently small trade cost coupled with a high tax rate accelerates international carbon leakage, with all firms relocating to the country without environmental regulation. Note that $\phi^S > \phi^{NU} > \phi^{NL}$ is always ensured in each sector. ϕ^S in each sector is a real number, because $1-4s(1-s)(1+t)^{2(1-\sigma)} > 0$ and $1-4s(1-s)(1+\gamma t)^{2(1-\sigma)} > 0$ always hold.[16]

Then, the D-sector is more likely to relocate and this makes full agglomeration in South, i.e., $\phi_C^S > \phi_D^S$, and it is less likely to make agglomeration in North, i.e., $\phi_C^{NU} > \phi_D^{NU} > \phi_D^{NL} > \phi_C^{NL}$. Furthermore, as the D-sector is more pollution-intensive (a rise in γ), full agglomeration is more (less) likely to occur in South (North).

Proposition 1: When $t \leq \tilde{t}$, an emission tax leads to full agglomeration for a certain trade cost, i.e., $\phi^{NL} < \phi < \phi^{NU}$ and to satisfaction of the policy target ($\bar{\chi}$). When $t > \tilde{t}$, an emission tax necessarily results in full agglomeration in South without Northern agglomeration and thus international carbon leakage. The pollution-intensive sector is more (less) likely to make full agglomeration in South (North).

Turning to emission levels, local emissions are given by:

$$\chi = n\left(\frac{s}{\Delta_C} + \phi\frac{1-s}{\Delta_C^*}\right)(1+t)^{-\sigma} + m\gamma\left(\frac{s}{\Delta_D} + \phi\frac{1-s}{\Delta_D^*}\right)(1+\gamma t)^{-\sigma},$$

[16] This is because $4(1-s)s < 1$ for $s > 1/2$ and $1 > (1+t)^{2(1-\sigma)} > (1+\gamma t)^{2(1-\sigma)}$.

$\chi^* = (1-n)\left(\phi\dfrac{s}{\Delta_C}+\dfrac{1-s}{\Delta_C^*}\right)+(1-m)\gamma\left(\phi\dfrac{s}{\Delta_D}+\dfrac{1-s}{\Delta_D^*}\right)$ and global emissions are expressed as the sum of Northern and Southern emissions: $\chi^W = \chi + \chi^*$.

Figure 2-b plots global emissions in terms of ϕ. As firms relocate to South in both manufacturing sectors, global emissions increase, which is international carbon leakage through firm relocation.

In autarky, emissions are written as $\chi = \dfrac{s}{1+t}+\dfrac{s\gamma}{1+\gamma t}$ and $\chi^* = (1-s)(1+\gamma)$ and thus global emissions are $\chi^W < \chi_0^W$. With intermediate trade costs such as $\phi_D^{NL} < \phi < \phi_D^{NU}$, all firms in both sectors locate in North. In this case, emissions are correspondent to the target emission level, $\chi^W = \chi = \dfrac{1}{1+t}+\dfrac{\gamma}{1+\gamma t} = \overline{\chi}$. Note that emissions are independent of trade costs and global emissions are reduced only by emission taxation.

Because small and large trade costs allow more relocation to the non-taxed country, global emissions increase. In particular, above ϕ_C^S all firms in both sectors concentrate in South and no firms pay tax, and hence the emission level becomes $1+\gamma$, which is identical to the initial non-policy level (recall Lemma 1). North's emission policy is nullified and the global amount of emissions returns to the initial equilibrium (without environmental policy). We can say that the only impact of taxation with small trade costs is to transfer GHG emissions from North to South through the relocation of all firms in both manufacturing sectors. With small trade costs, unilateral emission taxation results in complete carbon leakage (full agglomeration in both sectors in South) and taxation cannot control pollution any longer: $\chi^W = \chi^* = 1+\gamma = \chi_0^W$.

Proposition 2: With emission taxation, the global emission level generally increases in trade freeness. Emission taxation has no impact on the global emission level when trade costs are small (i.e., $\chi^W = \chi_0^W$ for $\phi > \phi_C^S$).

4. EMISSION QUOTA

4.1. *Quota without relocation*

Next we discuss an emission quota. North unilaterally introduces an emission quota so as to satisfy the international environmental agreement. To make a strict comparison with the policy impact on carbon leakage in the tax case, the quota is set so that the emission level under the quota is the same as that under taxation given a certain tax rate when both sectors create full agglomeration in North, i.e., $\overline{\chi} \equiv \frac{1}{1+t} + \frac{\gamma}{1+\gamma t}$. Moreover, the quota is assumed to be accompanied by creation of a competitive emission-permit market in North. The quota is implemented by the North government via a fee. Purchasing one unit of the permit allows one unit of production for a North firm. Importantly, firms in the D-sector are required to purchase γ(>1) units of the permit per unit of production, albeit one unit of purchase in the C-sector.

The following should be noted. Although tax rates are exogenously determined by an international agreement, the price of a permit, q, is endogenously determined by the number of firms located in North and trade costs so as to clear North's emission-permit market:

$$(15) \qquad n\left(\frac{s}{\Delta_C} + \frac{\phi(1-s)}{\Delta_C^*}\right)(1+q)^{-\sigma} + \gamma m\left(\frac{s}{\Delta_D} + \frac{\phi(1-s)}{\Delta_D^*}\right)(1+\gamma q)^{-\sigma} - \overline{\chi} = 0,$$

where $\Delta_C = n + (1-n)\phi(1+q)^{1-\sigma}$ and $\Delta_C^* = n\phi + (1-n)(1+q)^{1-\sigma}$

$\Delta_D = m + (1-m)\phi(1+\gamma q)^{1-\sigma}$ and $\Delta_D^* = m\phi^{1-\sigma} + (1-m)(1+\gamma q)^{1-\sigma}$.

This results in different impacts on firm location and emission level. Total costs and price for North firms are given by: $TC_C = \pi_C + (1+q)x$, $p = \frac{1+q}{1-1/\sigma}$, $p^* = \frac{\tau(1+q)}{1-1/\sigma}$, $TC_D = \pi_D + (1+\gamma q)x$, $p = \frac{1+\gamma q}{1-1/\sigma}$ and $p^* = \frac{\tau(1+\gamma q)}{1-1/\sigma}$. Firm location is determined by profit equalization and the quota constraint.

4.2. *Equilibrium with free relocation*

In the equilibrium with free relocation, *n, m*, and q are determined by pure profit equalizations:

(16) $\pi_C - \pi_C^* = \frac{\mu}{\sigma}\left(\frac{s}{\Delta_C} + \frac{\phi(1-s)}{\Delta_C^*}\right)(1+q)^{1-\sigma} - \frac{\mu}{\sigma}\left(\phi\frac{s}{\Delta_C} + \frac{1-s}{\Delta_C^*}\right) = 0$,

(17) $\pi_D - \pi_D^* = \frac{\mu}{\sigma}\left(\frac{s}{\Delta_D} + \frac{\phi(1-s)}{\Delta_D^*}\right)(1+\gamma q)^{1-\sigma} - \frac{\mu}{\sigma}\left(\phi\frac{s}{\Delta_D} + \frac{1-s}{\Delta_D^*}\right) = 0$.

as well as the emission constraint (15). In general, it is not possible to derive closed form solutions for *n* and *m* due to the endogenous permit price. Although *q* is endogenously determined and thus not amenable to explicit form solutions, *n* and *m* are given as $n = \frac{(1+q)^{1-\sigma}(s+\phi^2 - s\phi^2) - \phi}{(1-\phi(1+q)^{1-\sigma})((1+q)^{1-\sigma} - \phi)}$ and

$m = \frac{(1+\gamma q)^{1-\sigma}(s+\phi^2 - s\phi^2) - \phi}{(1-\phi(1+\gamma q)^{1-\sigma})((1+\gamma q)^{1-\sigma} - \phi)}$.

Figure 3-a plots firm shares, *n* and *m*, in terms of freeness of trade, ϕ . The permit price is not analytically solvable and is thus derived by numerical simulation. Figure 3-c plots permit prices in terms of ϕ , which is hump-shaped.

<Figure 3-a,3-b,3-c>

Once we set up a moderate level of emission constraint, Northern emissions are not binding when trade costs are large enough. Starting from autarky, as trade costs decline, C- and D- sector firms gradually relocate to North. The C- and D-sectors have the same equilibrium as discussed in Section 2 under no environmental policies. As trade costs decline more, total North production increases through firm relocation and thus the level of Northern emissions rise. At a certain level of trade costs, the quota is finally binding. Below the critical level of trade costs, locational equilibrium is determined by profit equalization as well as the quota constraint. With $q>0$, C- and D-sector firms have totally different location patterns. The bifurcation point of the binding quota constraint is derived as: $\phi^B = \frac{\Gamma - s}{\Gamma - (1-s)}$ where $\Gamma \equiv \frac{\chi}{\mu(1+\gamma)}$. Above the bifurcation point ($\phi > \phi^B$), the C- and D-sectors have totally different equilibrium paths, i.e., spatial sorting. C-sector firms move to North, while D-sector firms move to South. Finally, all C-sector firms locate in North at the sustain point. Since the total quota is more than all production by C-sector firms in North, D-sector firms are still accommodated in South. As a result of trade liberalisation, all C-sector firms locate in North, while D-sector firms locate in both countries.

Proposition 3: In the case of emission quotas, when the quota is binding, spatial sorting occurs. North attracts C-sector firms while South attracts D-sector firms. Trade liberalization promotes the spatial sorting.

Emission levels in North, in South, and in the world are, respectively, given by:

(18) $\chi = n\left(\frac{s}{\Delta_C} + \phi\frac{1-s}{\Delta_C^*}\right)(1+q)^{-\sigma} + m\gamma\left(\frac{s}{\Delta_D} + \phi\frac{1-s}{\Delta_D^*}\right)(1+\gamma q)^{-\sigma} = \bar{\chi}$, (constant)

(19) $\chi^* = (1-n)\left(\phi\frac{s}{\Delta_C} + \frac{1-s}{\Delta_C^*}\right) + (1-m)\gamma\left(\phi\frac{s}{\Delta_D} + \frac{1-s}{\Delta_D^*}\right)$

(20) $\chi^W = \chi + \chi^*$.

Figure 3-b plots global emissions in terms of trade costs. With $q>0$, a quota leads to U-shaped global emissions in terms of trade costs. More generally, when the quota is binding, some firms locate and emit GHGs in South, though North's emissions are at $\bar{\chi}$ because of the emission constraint. However, unlike the effect of taxation, global emissions never return to the level without emission regulations, $1+\gamma$, for any strictly positive trade costs. Because South never creates full agglomeration and the quota is still binding in North, this diversification of firm location results in less global emissions than the case without any policy as well as the case of taxation.

Below the bifurcation point, firm share and pricing in both sectors, $n=m$, are the same and correspond to the case of non-environmental policies, i.e., (5). Thus, local emissions in North and South and global emissions at the bifurcation point are the same as they are in the non-environmental policy case.

Proposition 4: In the case of emission quotas, North's GHG emissions are constant, which are at the target level, though trade liberalization decreases South's emissions if trade costs are large but increases South's emissions if trade costs are small.

5. Emission Standard

5.1. *Emission standard without relocation*

In an emission standard policy, the North government sets a maximum emission level per output. If a firm emits more than the maximum level, the firm is required to reduce its per-output emission level by abatement. In our model, we assume for simplicity that North sets the maximum level equal to γ/z ($1 \leq \boldsymbol{\gamma/z < \gamma}$), where z is exogenously given as z>1. Since a D-sector firm emits $\gamma(>\gamma/z)$ units per output, it has to engage in abatement activity. On the other hand, a C-sector firm satisfies the standard without any abatement.

Regarding abatement of D-sector firms, we specifically assume that z units of labor are required to reduce the per-output emission level from γ to γ/z. We also assume that this abatement technology is not used in the case of an emission tax and quota because it is too costly. That is, firms would pay an emission tax or purchase emission permits rather than engage in abatement.

To make comparisons among impacts of environmental policies on emission levels, we set the level of emission standard so that North emissions under the emission standard are equal to those under two other policies in the case of North's full agglomeration in both sectors, i.e. $\overline{\chi} = 1 + \frac{1}{b} = \frac{1}{1+t} + \frac{\gamma}{1+\gamma t}$, where $b \equiv (1+z)z/\gamma$.[17]

Profit gap equations are written as:

$$(21)\quad \pi_C - \pi_C^* = \frac{\mu}{\sigma}\left(\frac{s}{\Delta_C} + \frac{\phi(1-s)}{\Delta_C^*}\right) - \frac{\mu}{\sigma}\left(\phi\frac{s}{\Delta_C} + \frac{1-s}{\Delta_C^*}\right) = 0,$$

$$(22)\quad \pi_D - \pi_D^* = \frac{\mu}{\sigma}\left(\frac{s}{\Delta_D} + \frac{\phi(1-s)}{\Delta_D^*}\right)b^{1-\sigma} - \frac{\mu}{\sigma}\left(\phi\frac{s}{\Delta_D} + \frac{1-s}{\Delta_D^*}\right) = 0,$$

$\Delta_C \equiv n + \phi(1-n)$, $\Delta_C^* \equiv \phi n + (1-n)$, $\Delta_D \equiv mb^{1-\sigma} + \phi(1-m)$ and $\Delta_D^* \equiv \phi mb^{1-\sigma} + (1-m)$.

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[17] b is re-written in terms of tax rates as: $b = \dfrac{(1+t)(1+\gamma t)}{-t(1+\gamma t) + \gamma(1+t)}$.

5.2. *Equilibrium with free relocation*

In equilibrium, the C-sector is just like a sector in the standard FC model due to non-regulation. On the other hand, the D-sector is similar to a sector in the case of an emission tax in the sense of a rise in marginal cost in North (i.e., $b>1$ and $1+t>1$). Solving (21) and (22), the firm shares in equilibrium are given by:

$n = \frac{1}{2} + \left(\frac{1+\phi}{1-\phi}\right)(s - \frac{1}{2})$ and $m = \frac{b^{1-\sigma}(s+\phi^2 - s\phi^2) - \phi}{(1-\phi b^{1-\sigma})(b^{1-\sigma} - \phi)}$. Figure 4-a plots n and m in equilibrium. Compared with an emission tax and quota, firm share of the C-sector, n, is always larger for a given ϕ, because it corresponds to the case of t=0 and q=0. The firm share of the D-sector, m, is always larger for a given ϕ than under a tax policy if $1+\gamma t>b$, i.e., when there is a small b and/or a large γ.

All C-sector firms locate in North and all D-sector firms locate in South above the sustain points, $\phi^S < \phi$, which are given as $\phi_D^S = \frac{1-\sqrt{1-4s(1-s)b^{2(1-\sigma)}}}{2(1-s)}$ and $\phi_C^N = \frac{1-s}{s}$. Compared with a tax, ϕ_C^N is always smaller while ϕ_D^S is smaller when $1+\gamma t<b$. For instance, large abatement costs (large b) are more likely to make full agglomeration in South than under a tax policy.

<Figure 4-a, 4-b>

Proposition 5: An emission standard leads to perfect spatial sorting, in which all D-sector firms locate in South and all C-sector firms locate in North.

Next, local and global emissions are written as:

(23) $\chi = \frac{s-(1-s)\phi}{1-\phi} + m\left(\frac{s}{\Delta_D} + \phi\frac{1-s}{\Delta_D^*}\right)b^{-\sigma}$,

(24) $\chi^* = \frac{1-s-s\phi}{1-\phi} + (1-m)\gamma\left(\phi\frac{s}{\Delta_D} + \frac{1-s}{\Delta_D^*}\right)$ and

(25) $\chi^W = 1 + \frac{s(b^{1-\sigma} - \gamma)(1-\phi^2)}{(1-b^{1-\sigma}\phi)(b^{1-\sigma} - \phi)} + \frac{\gamma - \phi}{b^{1-\sigma} - \phi}$.

Figure 4-b plots global emissions in terms of trade freeness. Similar to the emission tax policy, global emissions increase in terms of trade freeness below the sustain point.

With small trade costs, all C-sector firms locate in North, while all D-sector firms locate in South. This is perfect spatial sorting due to different emission intensities. The emissions with small trade costs are written as $\chi = 1$, $\chi^* = \gamma$ and $\chi^W = 1 + \gamma = \chi_0^W$, which means complete carbon leakage. Compared with a tax, complete carbon leakage is more likely to occur in the emission standard policy (ϕ_D^S is smaller in the emission standard) when $1+\gamma t<b$.

Proposition 6: With an emission standard, the global emission level generally increases with trade freeness. An emission standard has no impact on the global emission level when trade costs are small (i.e., $\chi^W = \chi_0^W$ for $\phi > \phi_C^S$).

6. MECHANISM OF SPATIAL SORTING

A key result is different location patterns across policies. In particular, the quota and emission standards drive spatial sorting due to different emission intensities. Thus, this section investigates the mechanism of spatial sorting in more detail. Now, in order to explain the mechanism in a simple manner, we consider a case of a marginal decrease in trade costs (a marginal rise in trade freeness, i.e., $d\phi>0$). As in the standard FC model, North, the bigger market, is marginally more profitable and South, the smaller market, is marginally less profitable. The marginal decline in trade costs drives relocation from South to North.

First of all, Figure 5 plots the profit gap curve (i.e., North-South) in terms of *q* and *t* for C-sector firms and D-sector firms. Through firm relocation (change in *n* and *m*), profit curves shift down and then the profit gap goes to zero for a certain *q* or *t*, where the profit curves of C- and D-sector firms converge. This is the new equilibrium as a result of a marginal decline in trade costs.

<Figure 5>

Next, Figure 6 shows the case of a quota. To be clear, we omit the change of profit gap curves (see Figure 5). Starting from point a, for instance, profit curves in both manufacturing sectors are positive, and thus q rises through more demand for emission permits associated with a rise in n and m. Then, when point b is reached, the profit gap of D-sector firms is zero but that of C-sector firms is positive. Thus, the relocation to North continues and then q rises more. However, the profit gap turns to be negative for D-sector firms, thus D-sector firms' relocation is now from North to South (i.e., a fall in m). On the other hand, C-sector firms still relocate to North due to a positive gap (a rise in n). This is the mechanism of spatial sorting. Thus, the profit curves of D-sector firms move upward and those of C-sector firms move downward. Then, both curves finally converge and q stops at point d, which is the new equilibrium.

<Figure 6>

On the other hand, Figure 7 shows the case of a tax. Since tax rates are fixed, only profit curves shift as a response to a marginal fall in trade costs. For example, when tax rates are high enough (t=Z), the profit gap curves in both sectors are negative. Thus, C-sector firms and D-sector firms relocate to South (i.e., a fall in n and m) and then shift down the profit curves until the point of zero-profit gap. The equilibrium is at point Z. Next, when tax rates are low enough (t=X), both curves are positive. C- and D-sector firms relocate to North (i.e., a rise in n and m) and profit curves move down. The new equilibrium is given by point X. Finally, the case of an intermediate tax rate is given by point Y. Note that the case of an emission standard is similar to the emission tax. However, only D-sector firms' profit gap curves move through firm relocation. In sum, a key device of spatial sorting is permit prices, which are endogenously determined through firm relocation, although tax rates are fixed.

<Figure 7>

7. Comparison in Location and Global Emissions

7.1. *Social welfare implications*

A social planner adopts environmental policies so as to maximize social welfare. Social welfare is defined as the sum of per-capita welfare including the disutility of global emissions in the world. Using a quasi-linear utility function, (1), social welfare is given by:

(26) $$V \equiv Y^W + s\frac{\mu}{\sigma-1}(\ln\Delta_C + \ln\Delta_D) + (1-s)\frac{\mu}{\sigma-1}(\ln\Delta_C^* + \ln\Delta_D^*) - f(\chi+\chi^*).$$ [18]

where Y^W denotes total income in the world. As discussed in Baldwin et al. (2003), the market equilibrium path is always optimal if our model excludes disutility from global emissions and any environmental policies. In essence, socially optimal equilibrium in the standard FC model is that the bigger market (North) should attract more firms and make full agglomeration with small trade costs. In other words, social welfare is higher when North attracts more firms. However, our model involves emissions. Apart from location patterns, global emissions in our model have a negative impact on social welfare. In this respect, North takes environmental policies to reduce emissions while preventing firm relocation to South as much as possible. More stringent policy with less carbon leakage improves social welfare.

However, the crux of our difficulty is simulation-dependent, which makes it impossible to rigorously compare across policies (in particular, *q*). Thus, the following sub-sections separately discuss two crucial factors in social welfare. One is location patterns, *n* and *m* in Δ, and the other is global emissions as disutility.

[18] Here, we assume tax and quota revenues are repatriated to individuals.

7.2. *Location patterns*

Here, we assume away the disutility of emissions. Without environmental policies, location patterns are equivalent to the standard FC model (as shown in Lemma 1). Thus, the equilibrium under no environmental policies is always socially optimal. However, once environmental policies are introduced, equilibrium is not socially optimal and location patterns are totally different from the standard model as well as across environmental policies. In the case of an emission tax, when trade costs are small, both sectors create agglomeration in South. Smaller trade costs improve market access and thus firms prefer to locate in South to escape from Northern tax payment. Thus, trade liberalization promotes both firms' relocation to South and no firms stay in North. In the aspect of social welfare, North loses all firms in both sectors with small trade costs. This is a loss of social welfare in terms of location patterns.

Next, an emission quota involves endogenous permit prices, in other words, an endogenous tax rate. Since the quota is not binding with high trade costs, locational equilibrium is the same as it is for the non-environmental policy case. Below a certain level of trade costs, spatial sorting occurs. C-sector firms relocate to North, while D-sector firms relocate to South. With smaller trade costs, when C-sector firms concentrate in North, sorting is moderate. Some D-sector firms stay because the emission quota is larger than C-sector firms' total emissions. North can keep all C-sector firms and some D-sector firms. Thus, an emission quota results in a smaller social welfare loss than in the case of an emission tax.

Finally, an emission standard in our model influences only D-sector firms. While C-sector firms involve the same locational equilibrium as the standard model, D-sector firms gradually relocate to South. With small trade costs, North has only C-sector firms while South has only D-sector firms. Hence, welfare loss due to the policy is less than it is with a tax but more than it is for a quota.

In sum, without taking into account the negative impact of global emissions, trade liberalization leads a quota policy to be closer to a socially optimal equilibrium than the other policies with respect to location patterns. This is because North can keep all C-sector firms and, in addition, can accommodate some of the D-sector firms. On the other hand, the tax is the worst policy of the three, because all C- and D-sector firms locate in South.

7.3. *Global emissions*

Now we turn to global emissions. To maximize social welfare, global emissions should be minimized. In this sense, North should keep as many firms as possible with stringent emission policies. A crucial difference between a quota and the other policies is that permit prices are endogenously determined and thus are affected by location patterns and trade costs. This results in q being less than t for any ϕ.[19] The tax rate is fixed, but the price of the emission permit is endogenously determined by the number of North firms. As more firms relocate to South, the emission constraint can be more easily attained and the permit price decreases, which hampers firm relocation. To summarize: [20]

Proposition 7: The price of the emission permit under a quota is always lower than the per-unit emission tax rate.

In other words, the emission quota could be a weaker relocation force than for a tax and a standard. As is clear in Figures 2-b, 3-b, and 4-b, carbon leakage is moderate under the quota. Because a tax and a standard have a stronger relocation effect, a tax always leads to more carbon leakage and full agglomerations in both manufacturing sectors in South are possible. This implies that in the presence of carbon leakage, the emissions in North are larger with a quota than with taxation for a given ϕ. Turning to global emissions, however, the emissions are smaller with a quota than with taxation and a standard for a given ϕ.

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[19] Our model sets the same level of emissions in all policies as (7). As derived in the target emission level as (7), we assume that all firms locate in North without relocation and thus the permit price is given as: $\bar{q}$: $\bar{\chi} \equiv \frac{1}{1+t} + \frac{\gamma}{1+\gamma t} = \frac{1}{1+\bar{q}} + \frac{\gamma}{1+\gamma\bar{q}}$,where tax rates are set as t in section 3. However, as discussed in the locational equilibrium in section 4, all firms in the D-sector never have full agglomeration in North in the case of quota, while a tax has full agglomeration for some trade costs. This indicates that the permit price is always lower than t (and $\bar{q}$) in equilibrium. In other words, while a tax policy sets t as the tax rate, permit prices are endogenously determined and $\bar{q}$ is not set in the market equilibrium.

[20] This finding is somewhat similar to Krishna and Tan (2009), who studied whether tariffs and quotas are equivalent under free entry and exit in a competitive setting. They find that a tariff (tax) and a quota are not equivalent, because a quota discourages entry less than a tariff (tax) through the adjustment of permit prices. However, their model is completely different from ours.

Thus, taking into account location patterns and global emissions in social welfare, we can conclude that a quota is a better policy than the others in reducing global emissions.

Proposition 8: Compared with taxation and standards, a quota can mitigate international carbon leakage. In the presence of carbon leakage, the global emissions are lower with a quota than with a tax and standard policies with low trade costs.

One of our key assumptions is a fixed tax rate and an endogenous permit price influenced by firm location patterns and trade costs. This leads to contrasting results in trade liberalization. One may think that the North government may revise tax rates as trade costs fall. If this is the case, the North government can set tax rates equal to permit prices and the two instruments become equivalent. However, a government is less likely to revise tax rates so frequently. From the viewpoint of global emissions, therefore, an emission tax compares unfavourably with an emission quota based on the market mechanism.

8. CONCLUSION

This paper has studied the impact of environmental policies on firm location and carbon leakage when an international agreement such as the Kyoto Protocol requires the ratified countries (in our study represented by the country North) to reduce emissions by a certain amount. We have specifically compared three environmental policy tools, an emission tax, an emission quota, and an emission standard, under trade liberalization.

All environmental policies could lead firms to relocate to countries without any environmental regulation (i.e., to South), which causes international carbon leakage and a socially suboptimal equilibrium path. An interesting result is that the leakage is U-shaped in trade freeness in the case of a quota. In the presence of firm relocation, a fall in trade costs reduces the leakage when trade costs are relatively high and vice versa when trade costs are relatively low. Therefore, when an environmental agreement is ratified by North alone, trade liberalization could initially decrease global emissions, but eventually increase them. The relationship between trade liberalization and global emissions is non-monotonic. This implies that, under trade liberalization, both North and South should commit themselves to reducing their GHG emissions to deal with global warming.

It has also been shown that an emission tax (with a fixed rate) and an emission standard result in more firm relocation than an emission quota based on the market mechanism. Therefore, an emission tax causes more international carbon leakage, increasing global emissions. This implies that when South hesitates to regulate its emissions (which is currently observed), endogenizing environmental policy in North is a more plausible approach to considering the environmental consequences of trade liberalization.

In concluding this paper, four final remarks are in order. First, to focus on firm relocation, we have adopted the NEG framework in which firm locations and trade costs are central issues. Also, the agglomeration force by large market size plays a crucial role in our results. However, it is certainly worthwhile to examine the robustness of our verdicts within other frameworks. One may naturally think that an alternative is the HO framework. Without firm relocation, we can construct and analyze a two-factor, two-good HO model where two factors are labor and emissions (e.g., Copeland and Taylor, 2005; Ishikawa and Kiyono, 2006; Ishikawa et al., 2011). However, we need another factor, capital, when exploring firm relocation. As is well known, it is messy to handle capital movements in a three-factor, two-good HO model.

Second, the policy target in this paper is to reduce GHG emissions to highlight the different policy effects of a tax and a quota. Of course, it is plausible to think that governments maximize social welfare. Welfare analysis and socially optimal policies are left for future research. Because our model assumes one unit of emissions per unit of quantity produced, production and emissions are subject to a perfect trade-off: more production (consumption) positively affects welfare but simultaneously has a negative effect through increased emissions. There may exist an optimal level of emissions and production, which hinges on the specification of a social welfare function. To conduct welfare analysis formally, we have to specify disutility in the utility function more rigorously, taking account of accumulation of emissions over time. Furthermore, it would be worthwhile to consider the negative impact of emissions on

A-sector productivity. The A-sector may be subject to decreasing returns to scale by serious emissions.

Third, although our model considers unilateral environmental policies (i.e., Northern policies), it might be more suggestive and realistic to investigate bilateral environmental policies. In particular, emission tax rates will be determined in the strategic relationship of both governments and in a game framework (e.g., a sequential game). However, our monopolistic competition model might not be appropriate to study them. A generalized oligopolistic model with trade and location is the most appropriate for addressing the issue (Gaigné and Wooton, 2011; Haufler and Wooton, 2010; Exbrayat, Gaigné and Riou, 2012). This might create room for future research.

Last, we have assumed a quasi-linear utility function that excludes an income effect. The total demand for manufactured goods remains constant even if firms relocate and prices change through the absence of taxation or a quota in South. The constant total demand implies constant total production and hence the global emission level without any environmental policy is independent of trade costs. This has the advantage of highlighting the different effects of the policies. We can get analytical solutions allowing us to easily compare the relocation effects of a tax and a quota. Furthermore, even if we take into account tax/quota revenue reimbursement, because we can ignore its impact, we can narrow our focus on the effects of each policy scheme to include only firm location and carbon leakage.[21]

APPENDIX: PARAMETER VALUES IN FIGURES

We use the following values for Figure 1: $s = 0.6$, $\sigma = 1.5$, $\gamma = 1.2$, $t = 0.02$ and $\mu = 1/3$. The target emissions are derived as $\overline{\chi} = 2.1522$. Then, we use the following

[21] However, it is certainly worthwhile examining the robustness of our results in the presence of an income effect. The presence of an income effect caused by relocation may cause complete specialization in manufacturing in South and in agriculture in North, though it is an extreme and unrealistic case. In this case, factor prices are determined by the trade balance and factor markets, and market size and factor prices may determine emission levels.

values for Figures 2 to 4: $s = 0.6$, $\sigma = 2$, $b = 1.5$, $\gamma = 1.2$, $t = 0.5$ and $\mu = 0.45$.

Thus, target emissions are derived as $\bar{\chi} = \frac{17}{12}$.

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Figure 1: Locational Equilibrium (Low Tax rates)

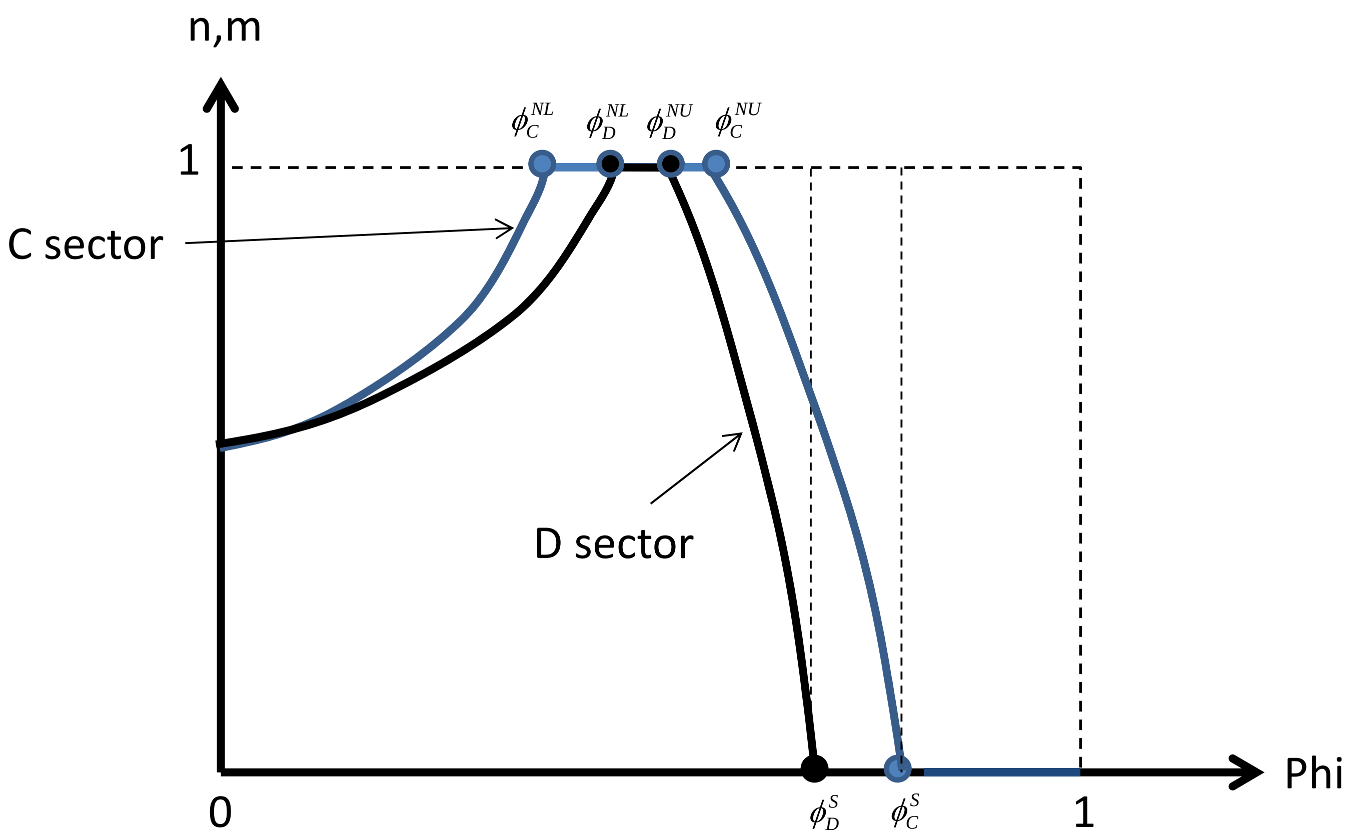

Figure 2-a: Locational Equilibrium

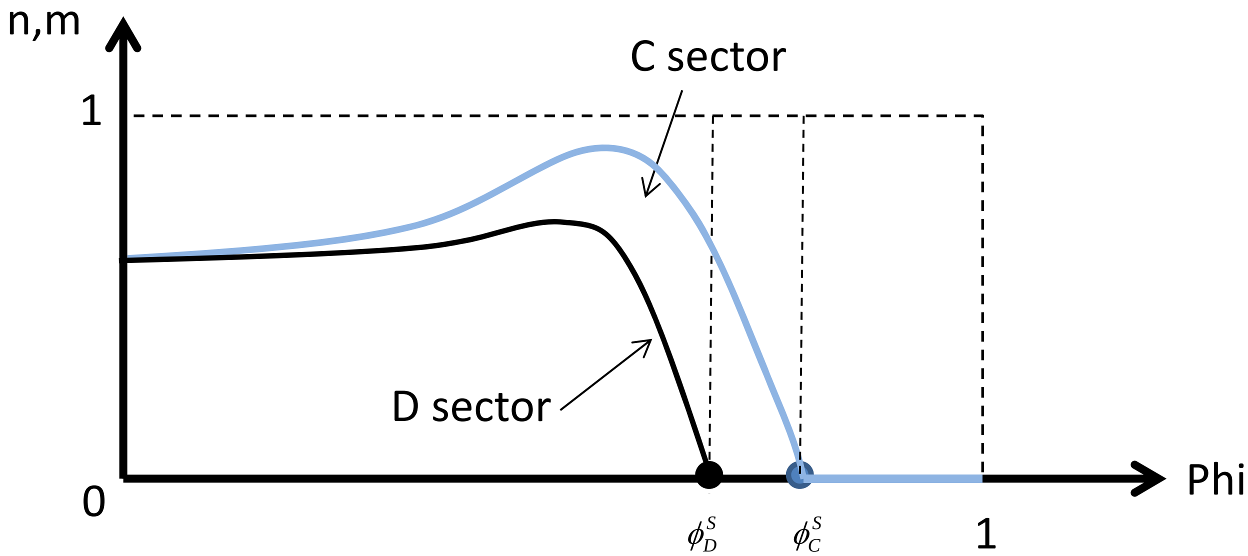

Figure 2-b: Global Emission

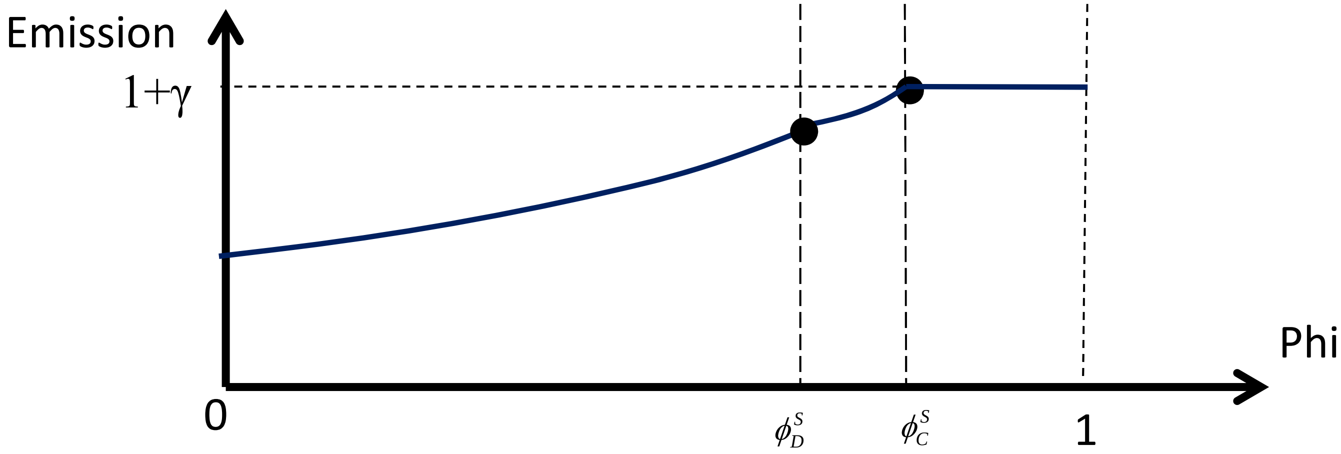

Figure 3-a: Locational Equilibrium (Quota)

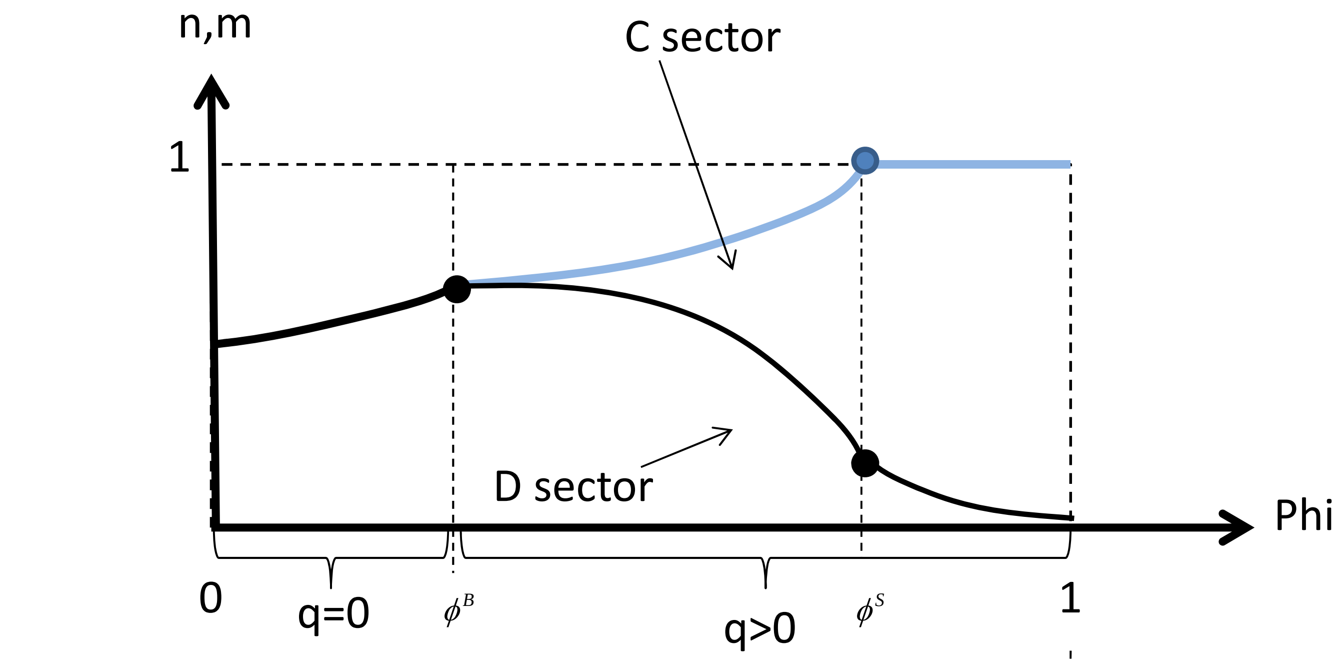

Figure 3-b: Global Emission

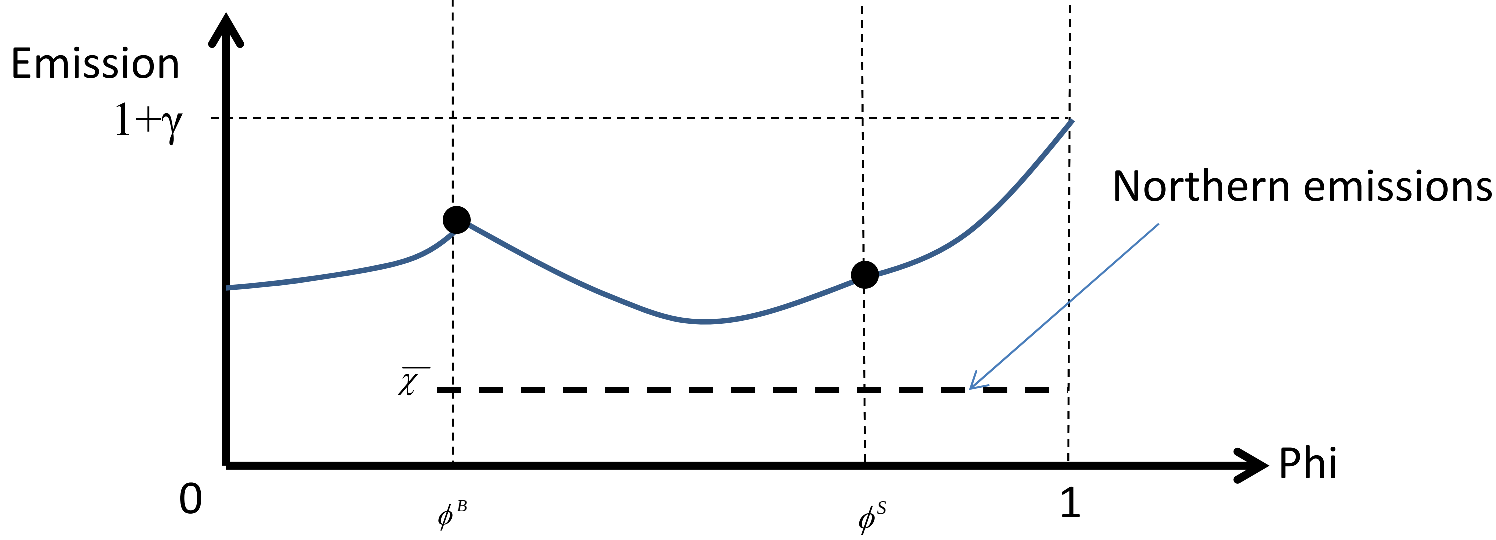

Figure 3-c: Quota prices

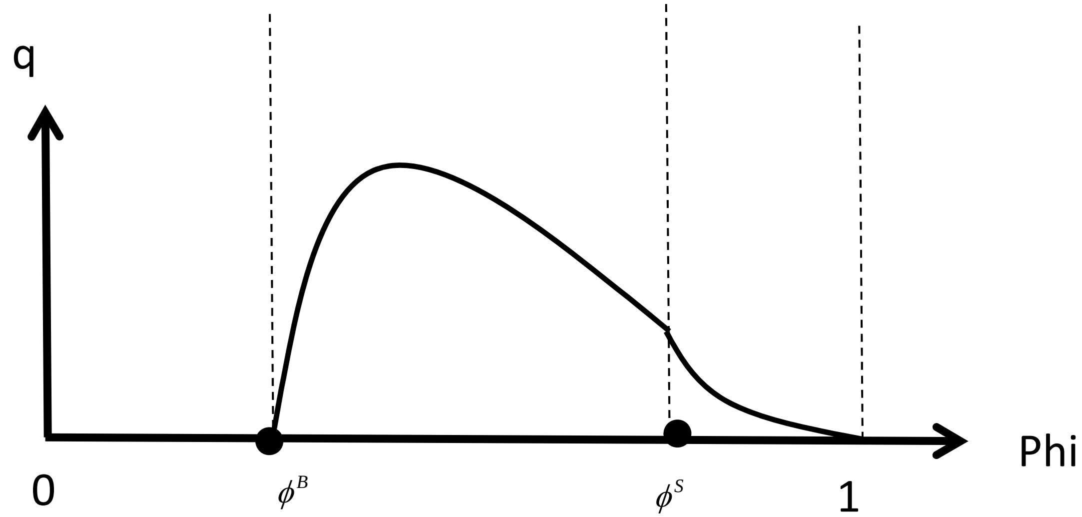

Figure 4-a: Locational Equilibrium (Emission standard)

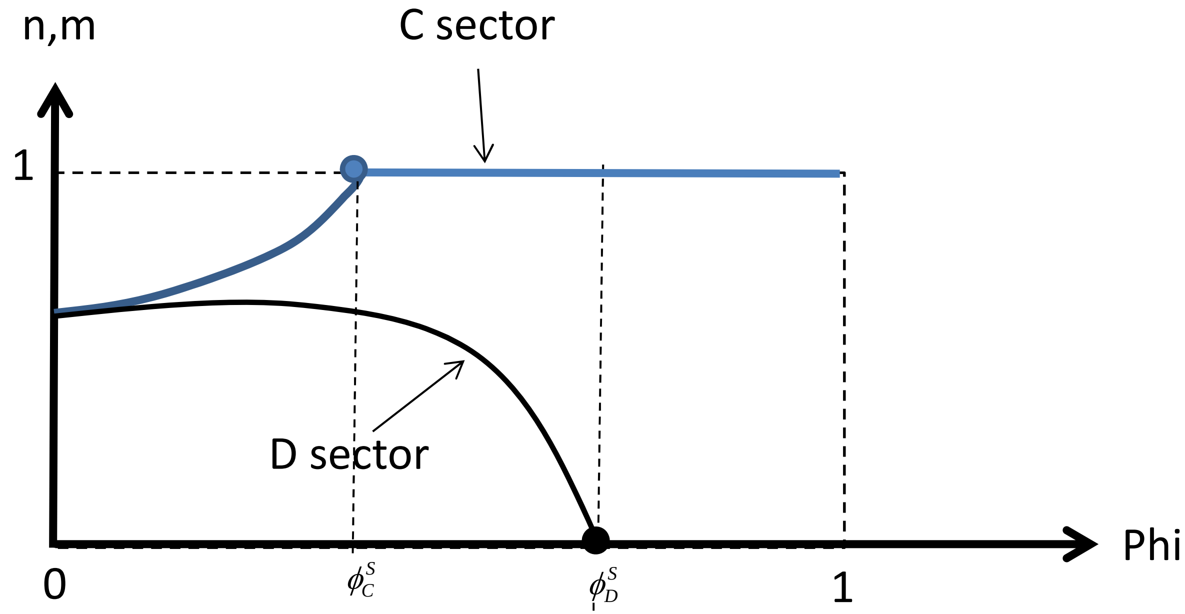

Figure 4-b: Global Emissions

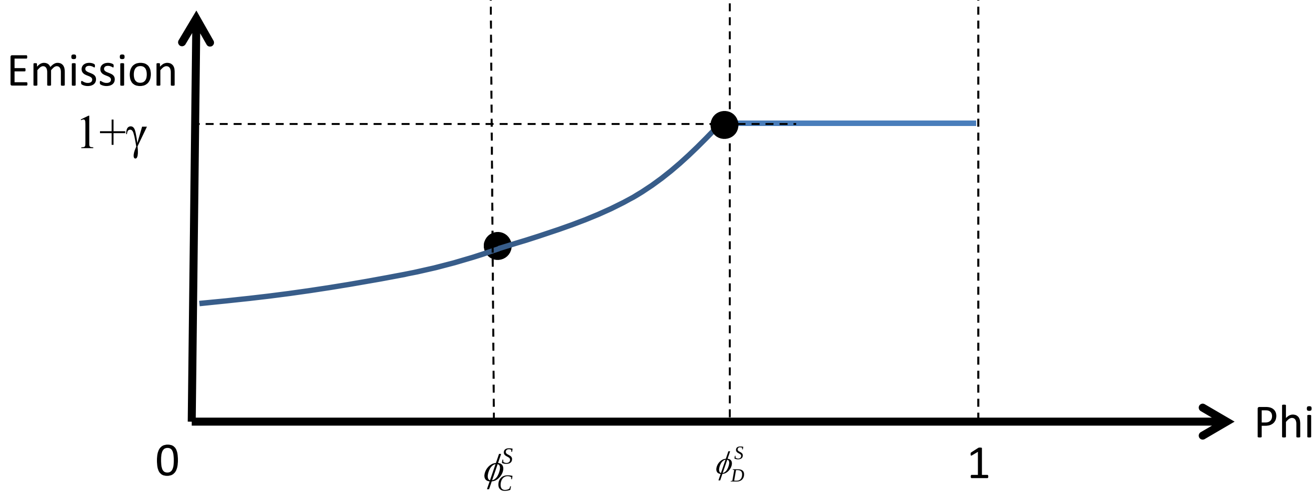

Figure 5: Profit gap curves

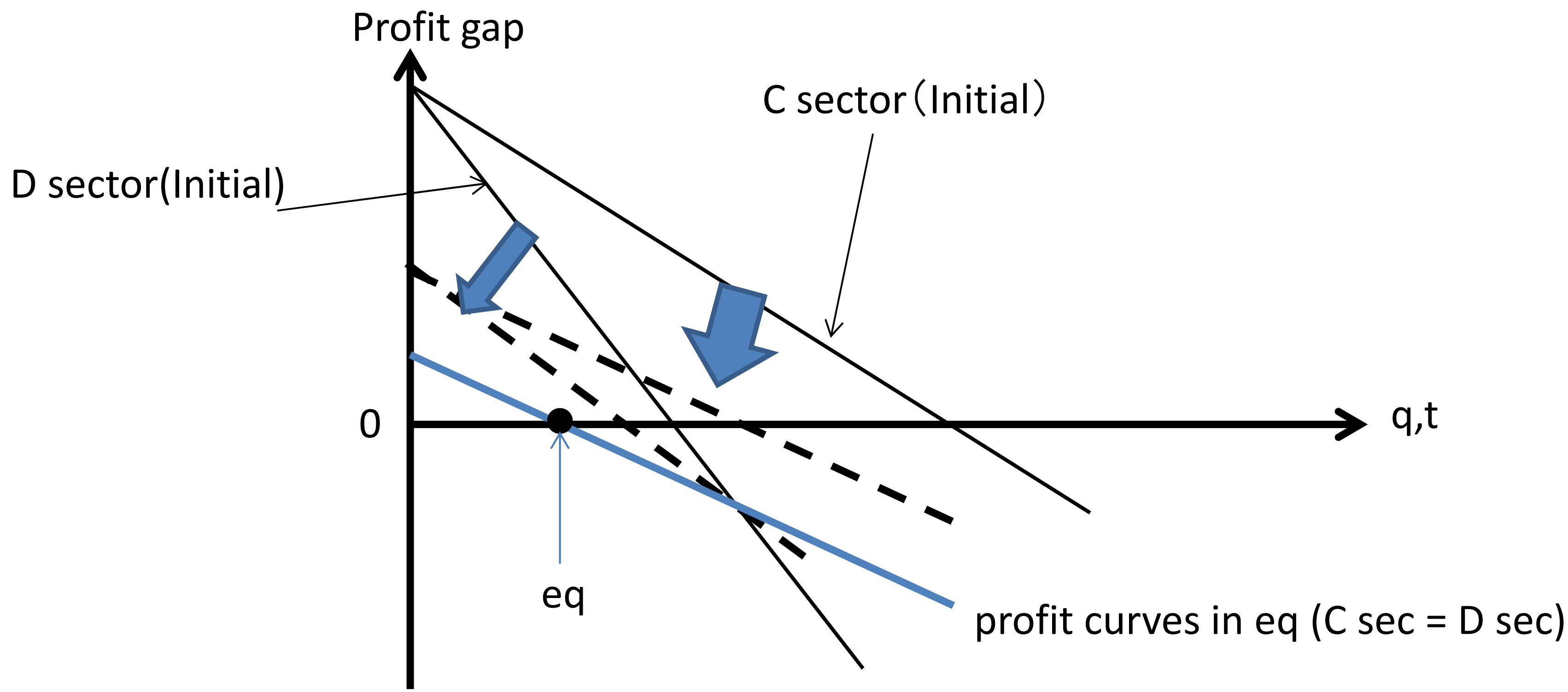

Figure 6: Quota and equilibrium

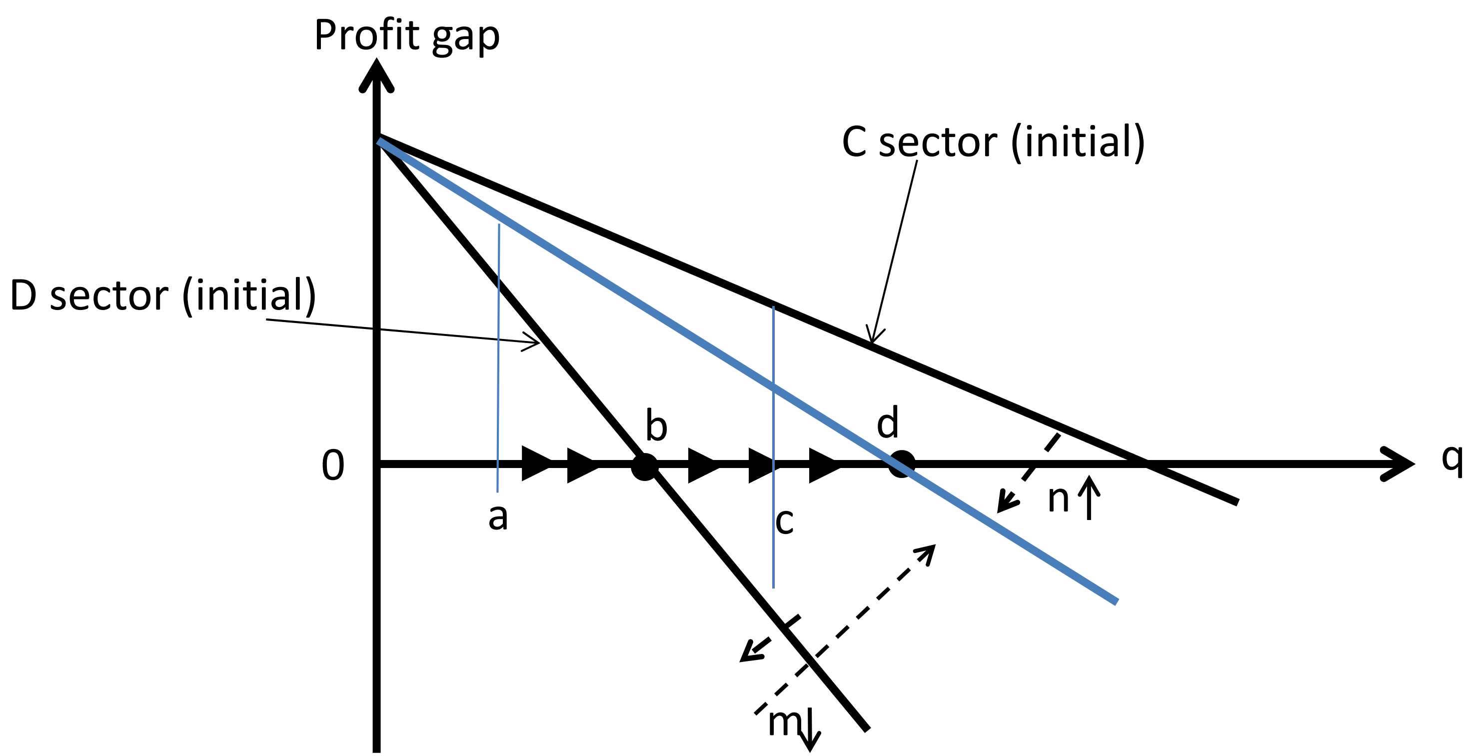

Figure 7: Tax and equilibrium