Essays on Trade and the Environment

by

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Preface

The relationship between trade and the environment has been explored over several decades. There are three key questions in the literature. The first is whether free trade or trade liberalization is good for the environment (e.g., Copeland and Taylor, 2005b); the second is how environmental policies affect firms' locations, production and abatement activities (e.g., Markusen et al., 1995); the third is how to design environmental policies under different market structures in trade (e.g., Carraro et al., 2013). We aim to answer the old questions from new perspectives.

The dissertation consists of six chapters, including four essays. Chapter 1 introduces the background of environmental issues in trade and sketches out the basic structure of the dissertation.

In Chapter 2, we consider socially optimal environmental taxes in a two-country model of global value chains in which the location of both parts and assembly can differ. When unbundling costs are so high, harmonizing environmental taxes maximizes global welfare. In contrast, with low unbundling costs, harmonization fails to maximize global welfare. Similar results hold when the two countries non-cooperatively choose their environmental taxes. In Chapter 3, we investigate how trade liberalization and consumption taxes affect firm locations and GHG emissions from consumption. We find that an increase in the consumption tax always decreases global emissions; however, trade liberalization affects global emissions non-monotonically. The welfare analysis indicates that trade costs and market sizes matter a lot for the policy decisions of global and national optima.

Chapters 4 and 5 both examine border carbon-tax adjustments in trade. We specifically explore three policy regimes: i) emission taxes alone, ii) emission taxes accompanied by carbon-content tariffs, and iii) emission taxes coupled with emission-tax refunds and carbon-content tariffs. In Chapter 4, we examine how home emission taxes with border tax adjustments (BTAs) affect outputs, emissions and firm locations when an emission-abatement technology is available. We show that BTAs can eliminate or mitigate carbon leakage and discourage firms from producing in the non-taxing country. In Chapter 5, we re-investigate the effectiveness of BTAs in the presence of intermediate goods and endogenous assembly location. Strikingly, BTAs may not be more effective than an emission tax alone to avoid carbon leakage and decrease global emissions.

Chapter 6 makes concluding remarks and suggests directions for future research.

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Chapter 1

General Introduction

1.1 Background and Related Literature

Over the past century, both consumers and producers around the world benefited a lot from international trade. They enjoyed an increasing diversity and quantity of goods and a decreasing production cost. However, the concern was also raised that trade may deteriorate the environment. In fact, the same century also saw an increase in industrial pollution, a depletion of ocean resources, a decline in stocks of the forest, a rise in soil desertification and climate change, etc. All these environmental disasters provoke us into considering the nexus between trade and the environment.

The literature has not achieved a consensus on whether trade is good for the environment. Grossman and Krueger (1991) investigate empirically how a reduction in trade barriers affects the environment by decomposing the total effect into the scale effect, composition effect and technique effect. They find that pollution concentrations increase initially and then decrease as per capita GDP increases, which is known as the environmental Kuznets curve (EKC). Copeland and Taylor (1994, 1995b) develop a theoretical model for the decomposition method in Grossman and Krueger (1991) and show that free trade can increase world pollution. However, Antweiler et al. (2001) find that if trade liberalization raises per capita GDP by one percent, then pollution concentrations decline by about one percent, which implies that openness to international goods market appears to be good for the environment. Cherniwchan (2017) employs plant-level data and also suggests that trade liberalization led to significant reductions of PM_{10} and SO_2 emissions from the U.S. manufacturing sector between 1994 and 1998.

To deal with environmental issues, governments and international organizations have worked a lot. China implemented the Environmental Protection Law on 1st, January 2015 and the Law on the Protection and Control of Air Pollution on 1st, January 2016. The EU set up the world's first international emissions trading system (ETS) in 2005 which covers around 45 percent of the

EU's greenhouse gas (GHG) emissions. Another example is the Paris Agreement which entered into force on 4th, November 2016. It is the first environmental agreement that brings both developing and developed countries into a common cause. Until now, 189 parties have ratified the agreement including China and India.

Environmental policy analyses in the literature on trade and the environment can be traced back to the pioneering works of Markusen (1975a,b). Markusen (1975a) extends the model in the generalized theory of distortions and welfare by involving global pollution and common property resources and derives the necessary conditions for an optimal tax structure in the national optimum, international optimum and joint optimum. Markusen (1975b) employs the same model to examine and compare the necessary conditions for an optimal tax structure in three policy regimes of a consumption subsidy, a production tax and a tariff. From the 1990s, the analyses shifted the focus of market structure from perfect competition into imperfect competition. The researchers began to explore how environmental policies affect producers' strategic variables and how countries design their policies in the presence of monopolistic and oligopolistic market structures (e.g., Markusen et al., 1993, 1995; Ulph, 1996; Ulph and Ulph, 1996, 2007; Ishikawa and Okubo, 2016, 2017). Markusen et al. (1993, 1995) employ the multinational model to endogenize firms' choices of plant numbers and locations. Markusen et al. (1993) study a unilateral environmental policy; however, Markusen et al. (1995) investigate bilateral environmental tax competition where countries choose their pollution taxes non-cooperatively. Ulph (1996), Ulph and Ulph (1996, 2007) extend the strategic trade policy model to examine the strategic issues of environmental policies. Compared to Markusen et al. (1993, 1995), they emphasize R&D of production and (or) environmental technologies while ignoring endogenous firm locations. Ishikawa and Okubo (2016, 2017) use the footloose capital model to study carbon leakage through firm relocation under different kinds of environmental policies.

1.2 Preview of the Dissertation

Based on the background and previous literature, we are going to explore the effect of trade liberalization on the environment and examine environmental policies from new perspectives. The dissertation consists of four essays. Chapter 2 and Chapter 3 study the strategic behaviors of both producers and countries in a specific policy regime, with a focus on global value chains in Chapter 2 and on consumption pollution in Chapter 3. Chapter 4 and Chapter 5 examine producers' strategic variables in different policy regimes of border tax adjustments (BTAs). Chapter 4 concentrates more on policy distortions, while Chapter 5's interest lies in tax avoidance in vertically related markets. A common feature of the four essays is that they all consider endogenous firm locations under environmental regulation. Therefore, the dissertation also has a foothold in the literature on the pollution haven effect which implies that a more stringent environmental regulation in a country induces its firms to locate in other countries with laxer regulations. In the following, we briefly introduce the four essays.

Chapter 2 is motivated by the facts that the spatial unbundling of parts production and assembly leads to the worldwide dispersion of pollution under current globalization and that harmonized environmental regulations among countries are treated as one measure against the harmful impacts of unbundling. The harmonization may mitigate the divergence of environmental quality. However, it may be difficult to address local environmental impacts given the heterogeneity of countries. To evaluate the effectiveness of environmental tax harmonization in global value chains, we extend the model in Baldwin and Venables (2013) where a final-good producer produces final goods through assembling the chain of many parts. Specifically, we characterize the socially optimal (cooperative) environmental taxes that maximize global welfare and compare them with harmonized taxes. When unbundling costs are so high that parts and assembly must colocate in the pre-globalized world, pollution is spatially concentrated, and harmonizing environmental taxes maximizes global welfare. In contrast, with low unbundling costs triggering the dispersion of parts and thus pollution throughout the world as today, harmonization fails to maximize global welfare. Similar results hold when the two countries choose their environmental taxes non-cooperatively.

In Chapter 3, we turn our attention to consumption pollution instead of production pollution. Consumption is an essential source of GHG emissions, e.g., fossil fuel combustion of heating and cooking need, leaks from refrigerants in homes and business. Countries like Norway and the UK impose fuel tax to control consumption emissions. Therefore, in this chapter, we are going to theoretically analyzes how trade liberalization and consumption tax affect the GHG emissions originated from consumption and firm locations across countries. Introducing consumption-originated emissions in a standard footloose capital model, we find several novel results from previous analyses on production-originated GHG emissions. First, trade liberalization has a non-monotonic effect on the global emissions: that is, as trade costs decline, the global emissions initially decrease and then rise. Second, the consumption tax causes carbon leakage: that is, the tax on one country reduces the emissions in one country while increasing them in the rest of the world. Third, the optimal consumption tax maximizing the global welfare must be neutral about firm location decisions. In particular, even if firms are asymmetrically distributed across countries in the absence of the consumption tax, the optimal tax level must be identical across countries.

The motivations of Chapter 4 are shown as follows. A country's ambition to cope with climate change may be ruined by international carbon leakage. Therefore, more and more policymakers are appealing for carbon adjustments at the borders. They believe that border tax adjustments

(BTAs) can internalize the environmental costs of production and therefore can be more effective than an emission tax alone to eliminate carbon leakage and deal with climate change. However, there is little consensus about what BTAs should involve. Some proposals only include environmental regulation on imports, e.g., the American Clean Energy and Security Act of 2009, the European Green Deal. On the other hand, BTAs may also include exemptions on exports to eliminate the cost disadvantages of them in other markets, e.g., the SB 775 California Global Warming Solutions Act of 2006. Although the effectiveness of BTAs has been demonstrated by many previous papers, there is still a concern for the strategic behaviors of firms under BTAs. To investigate firms' responses to BTAs, we develop a simple international duopoly model with endogenous firm locations and abatement activities. We specifically explore three policy regimes: i) emission taxes alone (regime without BTAs); ii) emission taxes accompanied by carbon-content tariffs (regime with partial BTAs); and iii) emission taxes coupled with emission-tax refunds for exports and carbon-content tariffs (regime with full BTAs). According to our findings, emission taxes are not effective in decreasing global emissions in certain circumstances. Interestingly, an increase in the emission tax rate can increase global emissions. High tax rates may discourage adopting the clean technology. When firm locations are fixed, full BTAs completely eliminate cross-border carbon leakage. However, partial BTAs can be more effective in reducing global emissions than full BTAs. When firm locations are endogenous, firms tend to produce in the foreign country to avoid the home emission tax. BTAs discourage in producing in the foreign country. This effect is stronger with full BTAs than with partial BTAs.

In Chapter 5, we continue to study BTAs. BTAs have been demonstrated to be more effective to deal with carbon leakage and control global emissions. However, vertical linkages of production have not been considered in this issue regardless of the following two facts. First, the production of intermediate goods can be dirtier than the production of final goods. Second, a country may feel easier to regulate direct emissions than indirect emissions due to high administration costs of data collection for emissions embedded in the whole production process. The two points may induce firms to change their production and location patterns to avoid or mitigate environmental regulations under BTAs. For instance, firms may have an incentive to produce clean final goods in a non-taxing country by assembling polluting inputs and then export the final goods to the taxing country, which may lead to carbon leakage and more global emissions under BTAs. Regarding this concern, we develop a two-country model to examine whether BTAs still work in the presence of intermediate goods and endogenous assembly location. We explore the same three policy regimes as in Chapter 4. We find that the effectiveness of BTAs depends on whether assembly relocation happens. If the assembly is always located in the taxing country, carbon leakage is prevented and global emissions decrease under BTAs; however, if the assembly is relocated to the non-taxing country, carbon leakage can occur with partial BTAs and global emissions can be higher with full BTAs.

Chapter 2

Is Environmental Tax Harmonization Desirable in Global Value Chains?

This chapter is based on a joint work with Professors Hayato Kato and Ayako Obashi (Cheng et al., 2020).

2.1 Introduction

Globalization since the late twentieth century features not just declining barriers to trade and factor mobility, but also the lowering of costs for coordinating activities within organizations. This spatial separation of production stages, which Baldwin (2016) refers to as the *second unbundling*, has significant implications for the environment as well as trade.[1] This is because it may promote the relocation of polluting industries to countries with lax environmental standards, an issue known as the pollution haven hypothesis (Markusen et al., 1995; Levinson and Taylor, 2008).

One measure taken to act against the harmful impact of unbundling production processes could be the harmonization of environmental standards among countries (Sterner and Köhlin, 2003). Equalizing regulations among countries does not distort the location decisions of firms and may mitigate the divergence of environmental quality. However, harmonization may be too naive a policy to address individual environmental impacts given country heterogeneity and the extent of globalization.

From the 1970s onward, the EU sought to harmonize environmental policies among its member states. Holzinger et al. (2008) find that some 40 environmental measures converged across 24 advanced economies, including the EU 15, between 1970 and 2000. In addition, Arbolino et al.

[1] The first unbundling refers to the spatial separation of consumption and production owing to the development of the steam engine in the Industrial Revolution.

(2018) analyze the diffusion process of environmental policies and find that achievements of the environmental policy objectives of one country converged to the corresponding performance of the other country within the EU 15 from 2000 to 2014. These studies suggest that harmonization was dominant between member states with similar characteristics (EU 15) and/or in periods covering years prior to the second unbundling (1970-1990).[2]

On the other hand, it would be difficult to achieve a common goal through harmonized policies if there are significant disparities in social and economic status among countries. In this regard, Andonova and VanDeveer (2012) examine environmental policies in the Central and Eastern European (CEE) countries in the process of EU accession and show that considerable divergence in environmental practices and institutions persists. Furthermore, as international fragmentation of production or offshoring expands, less developed nations would be reluctant to raise environmental standards to the stringency level closer to those of the advanced economies because in a world of liberalized trade and investment they fear losing the interest of foreign investors. Although environmental policy is not a sole determinant of comparative advantage, it does matter at the margin, particularly for countries whose competitiveness depends on low-cost production (World Bank, 2020b, Ch.5).

Against the background, we aim to evaluate the effectiveness of environmental tax harmonization using a two-country model of global value chains à la Baldwin and Venables (2013), where firms produce a final good through assembling the chain of many parts. Specifically, we characterize the socially optimal environmental taxes (or cooperative equilibrium) that maximize global welfare and compare them with harmonized taxes. In the pre-globalized world where all production processes colocate, i.e., before the second unbundling, environmental taxes do nothing to improve the global environment. Setting an equal tax between countries maximizes the global welfare by not distorting efficient locations. However, in the globalized world where assembly and parts can be spatially unbundled, i.e., after the second unbundling, environmental taxes can reduce global environmental damage by avoiding the concentration of polluting processes. The simple harmonization is almost never desirable and more careful coordination is necessary.

This result is about whether socially optimal and harmonized taxes coincide. One interested in the need for policy coordination (not just simple harmonization) may also question whether socially optimal taxes coincide with noncooperative taxes. We show that this is more likely to hold before the second unbundling than in the globalized world. This is because prior to the second unbundling, there is little scope for governments to manipulate the location of parts through environmental taxes. Each government then lacks a strong incentive to set specific tax rates so that it realizes the socially optimal taxes in the noncooperative equilibria. As a result, the equilibrium tax rates chosen by each

[2] According to Baldwin (2016), the second unbundling accelerated from around 1990 (p.5).

country do not differ much from the socially optimal tax rates. The second unbundling, however, makes the location of parts more sensitive to environmental taxes and thus tax competition leads to equilibrium tax rates different to the socially optimal tax rates.

2.1.1 Related Literature

Some studies have investigated the environmental impact of mobile firms, but the production structure in their models is generally too simple to cover fragmentation (Pfluger, 2001; Zeng and Zhao, 2009; Ishikawa and Okubo, 2017; Forslid et al., 2017; Ikefuji et al., 2016; Birg and Voßwinkel, 2018).[3] Pfluger (2001), for example, examines the effect of pollution taxes on the international relocation of monopolistically competitive firms. By extending Pfluger's model to incorporate transboundary pollution, Ishikawa and Okubo (2017) reveal that trade liberalization may increase global pollution through firm relocation from a country with stringent regulation to a country with lax regulation. Birg and Voßwinkel (2018) examine non/cooperative environmental policies in an oligopolistic competition setting with a specific focus on the quality difference of goods. In contrast to these studies where the vertical linkages between sectors are ignored, we consider a so-called *spider* structure, comprising multiple limbs (parts) coming together to make up a body (assembly).

The studies closest to ours are Hamilton and Requate (2004) and Wan et al. (2018), which examine unilaterally optimal taxes and Nash equilibrium taxes in two-country models with vertically linked sectors.[4] Both these studies assume that upstream firms produce polluting inputs and are taxed/subsidized by their local government, as do we. However, unlike the current chapter, they only consider international trade in final goods, which corresponds to the pre-globalized situation in our analysis. To describe the global value chains in the present world, we allow for trade in both inputs and assembly relocation.

Using Baldwin and Venables (2013)'s framework, Obashi (2019) characterizes optimal combinations of trade instruments and finds that policy prescriptions proposed by traditional trade models are not sufficient to achieve the social optimum. Although environmental issues were outside the scope of Obashi (2019), her study and ours should be seen as complements as both emphasize that the evolution of global value chains significantly changes policy design.

The remainder of the chapter is structured as follows. Section 2.2 presents the model and analyzes the location patterns of parts given assembly location and environmental taxes. Section 2.3 allows for endogenous assembly location and examines socially optimal taxes in the pre-globalized

[3] Using an evolutionary game approach, Dijkstra and De Vries (2006) conclude that environmental taxation may induce polluting firms to stay away from consumers. However, in contrast to our analysis, their focus is on the spatial unbundling of consumption and production, not the spatial unbundling of production itself.

[4] See also Wan and Wen (2017). Some studies consider a wider variety of policy tools, including border tax adjustments as well as emission taxes, although they do not allow for vertical linkages (Lai and Hu, 2008; Yomogida and Tarui, 2013; Keen and Kotsogiannis, 2014; Sanctuary, 2018; Ogawa et al., 2019).

world and Section 2.4 does this for the globalized world. Section 2.5 confirms that our main result holds in different settings. The final section discusses implications for the real world.

2.2 The Basic Model

Consider a world with two countries, N and S. The two countries have equal population with unit mass. Each individual inelastically supplies one unit of labor. There are three types of goods: a final good, a range of parts (intermediate inputs), and a numéraire good. The numéraire good is produced using labor and is costlessly traded, which equalizes its international price. With choice of units, the wage rates in both countries are equal to unity. Each part can be produced using labor in both countries and can be internationally traded. Parts production generates local pollution and is thus taxed by the domestic government. A single final good producer (assembler) locates in N or S and assembles the range of parts into one unit of the good. As in Baldwin and Venables (2013), the two countries differ in two ways: (i) only N consumes the final good and (ii) the average cost of producing parts is lower in S than in N.

To describe the second unbundling, we distinguish between two types of frictions. If the assembler is located in S, it must pay *trade costs* to export the final good to N. If the locations of parts and assembly differ, the assembler must pay additional *unbundling costs* to import parts from abroad. Unbundling costs include communication costs between headquarters and foreign suppliers as well as physical transportation costs.[5]

2.2.1 Preferences

The utility of the representative consumer in $i \in \{N, S\}$ is

$$U_i = \widetilde{u}\mathbf{1}_i + \Lambda_i - D(e_i), \tag{1}$$

where Λ_i is the consumption of the numéraire good, and e_i is the pollution level. $\mathbf{1}_i$ takes one if $i = N$ and zero if $i = S$. The consumer in N obtains $\widetilde{u}$ from consuming one unit of the final good.

[5] As discussed shortly, we assume that both trade costs and unbundling/communication costs increase proportionally to quantity. There is no general agreement about how to model communication costs (Gokan et al., 2019). Whether communication costs affect the fixed or variable costs of trade depends on the role of communications in transactions. The increased use of the Internet (e.g., Freund and Weinhold, 2004), for example, facilitates the search for trading partners and thus solely affects the fixed costs. However, in the manufacturing activities, the downstream and upstream production processes need to interact to coordinate the specification of a customized product and the timing of delivery, which would primarily affect variable costs. Considering these interactions between headquarters and distant plants, some studies model communication costs as an iceberg cost proportional to the firm's output (Duranton and Puga, 2005; Fujita and Thisse, 2006). Indeed, Fink et al. (2005) find that communication costs exert a significant impact on the variable costs of trade, thereby affecting trade patterns, especially for differentiated goods. We follow the latter modeling strategy for communication costs.

The disutility from pollution is expressed as $D(e_i) = \gamma e_i^2/2$ with $\gamma > 0$. The budget constraint is

$$p\mathbf{1}_i + \varLambda_i = 1 + t_i e_i + \overline{\varLambda}, \tag{2}$$

where p is the final good's price and t_i is the environmental tax by i per unit of pollution. The income consists of wage ($w_i = 1$), the redistribution of tax revenues ($t_i e_i$), and the initial endowment of the numéraire ($\overline{\varLambda}$). $\overline{\varLambda}$ ensures positive consumption of the numéraire. Substituting (2) into (1) yields the indirect utility V_i.

2.2.2 Sourcing Decision

The assembler first chooses where to locate and then from which country to source parts. Here, we consider the sourcing decision of the assembler given its location.

Letting z be the index of parts from the set $Z = [\underline{b}, \overline{b}]$, the unit cost of any part $z \in Z$ is unity if it is produced in N. If a part $z \in Z$ is produced in S, on the other, its unit cost is $b(z) = z$ with $0 < \underline{b} < 1 < \overline{b}$. Thus N has a comparative advantage in parts $b \in [1, \overline{b}]$, while S has it in parts $b \in [\underline{b}, 1)$. S has an average cost advantage over N, i.e., $\beta \equiv 1 - (\underline{b} + \overline{b})/2 > 0$.[6] Producing one unit of each part generates one unit of local pollution.[7]

The assembler produces one unit of the final good by assembling one unit of each part. When parts cross the border, additional unbundling costs θ arise. The sourcing decision is on a parts basis by comparing the international cost difference. Supposing the assembler is in N, a part z is sourced there if

$$\begin{aligned} &\underbrace{1 + t_N}_{\text{Cost in } N} < \underbrace{b(z) + \theta + t_S}_{\text{Cost in } S}, \\ &\to b(z) > b_N \equiv \min[\max\{\underline{b}, 1 - \theta + \Delta t\}, \overline{b}], \\ &\text{where} \quad \Delta t \equiv t_N - t_S. \end{aligned}$$

The inequality is likely to hold if S's cost is high (high $b(z)$), N's tax compared with S's is low (low Δt), and unbundling costs are high (high θ).

Supposing the assembler is in S, a part z is produced there if

$$\begin{aligned} &\underbrace{1 + \theta + t_N}_{\text{Cost in } N} > \underbrace{b(z) + t_S}_{\text{Cost in } S}, \\ &\to b(z) < b_S \equiv \max[\min\{\overline{b}, 1 + \theta + \Delta t\}, \underline{b}], \end{aligned}$$

[6] The average cost of parts in S is $\frac{1}{\overline{b}-\underline{b}} \int_{\underline{b}}^{\overline{b}} \tilde{b} d\tilde{b} = \frac{1}{\overline{b}-\underline{b}} \cdot \frac{\overline{b}^2 - \underline{b}^2}{2} = \frac{\overline{b}+\underline{b}}{2}$, while that in N is $\frac{1}{\overline{b}-\underline{b}} \int_{\underline{b}}^{\overline{b}} 1 d\tilde{b} = 1$.

[7] See Appendix 2.A.5 for a discussion about global pollution.

which can be interpreted analogously.

When unbundling costs are sufficiently high, the two *unbundling thresholds* degenerate, i.e., $b_N = \underline{b}$ and $b_S = \overline{b}$, and all parts colocate with assembly. Specifically, supposing $\theta > \overline{\theta} \equiv \max\{1 - \underline{b} + \Delta t, \overline{b} - 1 - \Delta t\}$, Figure 2.1 draws such a region ($\mathcal{NS}$ in the figure) given assembly location and taxes.[8] The co-location motive of the assembler to save unbundling costs is so strong that neither comparative advantage nor environmental taxes matter. The parts and assembly are spatially bundled in the pre-globalized world.

When unbundling costs are sufficiently low, the two unbundling thresholds do not degenerate. The location of some parts is dictated by comparative advantage and taxes, not by the colocation motive. Supposing $\theta < \underline{\theta} \equiv \min\{1 - \underline{b} + \Delta t, \overline{b} - 1 - \Delta t\}$, Figure 2.2 depicts the sourcing pattern.[9] Unlike Figure 2.1, there are two other regions in Figure 2.2, $\mathcal{N}$ and $\mathcal{S}$. Parts in $\mathcal{N}$, for example, are those in which N has a very strong comparative advantage, and are always produced in N. As low unbundling costs also make the assembler aware of taxes, the tax difference now matters for its sourcing decision. The spatial unbundling captures the current globalization. In what follows, we separately present the analysis of the two cases.

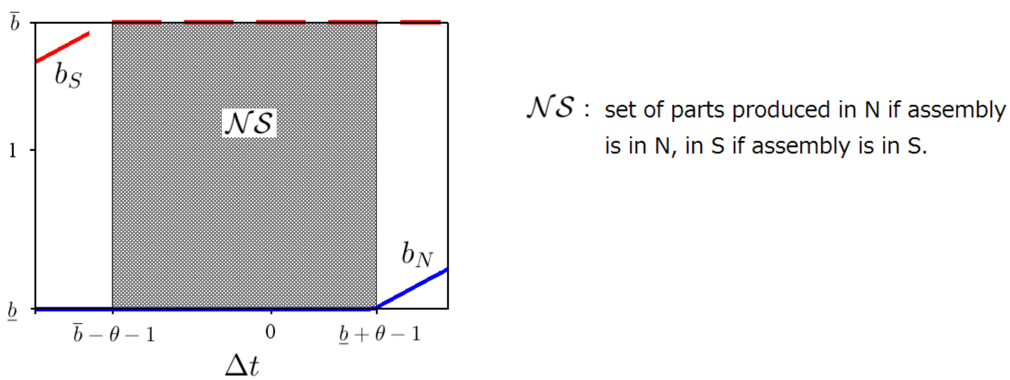

Figure 2.1: Sourcing pattern under high unbundling costs.

2.3 High Unbundling Costs: Colocation of Parts and Assembly

We consider here the case where unbundling costs are high: $\theta > \overline{\theta}$ so that parts and assembly are spatially bundled. We first characterize the assembly location for the given taxes and then derive the socially optimal taxes.

[8]Note that $b_N = \underline{b}$ holds if $\underline{b} > 1 - \theta + \Delta t$; $b_S = \overline{b}$ holds if $\overline{b} < 1 + \theta + \Delta t$. These conditions lead to $\theta > \max\{1 - \underline{b} + \Delta t, \overline{b} - 1 - \Delta t\}$, which is equivalent to $\Delta t \in (\overline{b} - \theta - 1, \underline{b} + \theta - 1)$.

[9]This condition is equivalent to $\Delta t \in (\underline{b} + \theta - 1, \overline{b} - \theta - 1)$.

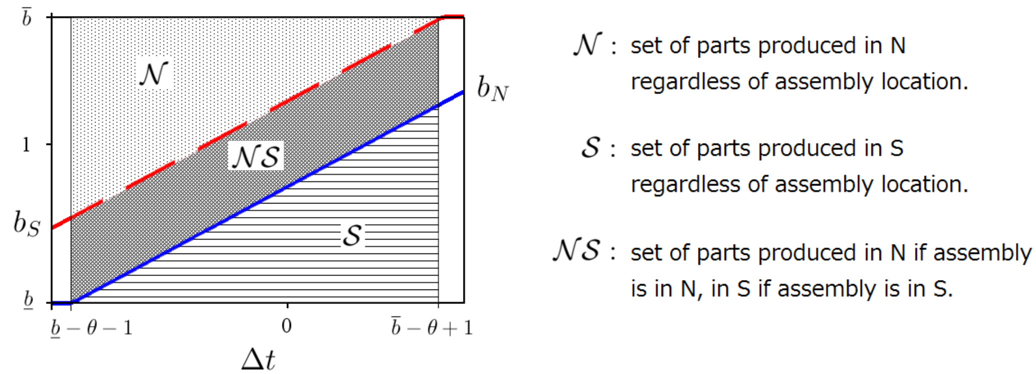

Figure 2.2: Sourcing pattern under low unbundling costs.

2.3.1 Assembly Location

Let C_i be the total costs of producing one unit of the final good, given assembly in $i \in \{N, S\}$. Noting $b_N = \underline{b}$, we have

$$\begin{aligned} C_N &= \underbrace{\int_{\underline{b}}^{b_N} (\widetilde{b}+\theta+t_S)d\widetilde{b}}_{\text{Parts from } S} + \underbrace{\int_{b_N}^{\bar{b}} (1+t_N)d\widetilde{b}}_{\text{Parts from } N} \\ &= (\bar{b}-\underline{b})(1+t_N). \end{aligned} \tag{3}$$

Similarly, noting $b_S = \bar{b}$, we have

$$\begin{aligned} C_S &= \tau + \underbrace{\int_{\underline{b}}^{b_S} (\widetilde{b}+t_S)d\widetilde{b}}_{\text{Parts from } S} + \underbrace{\int_{b_S}^{\bar{b}} (1+\theta+t_N)d\widetilde{b}}_{\text{Parts from } N} \\ &= \tau + (\bar{b}-\underline{b})\left(\frac{\underline{b}+\bar{b}}{2}+t_S\right), \end{aligned} \tag{4}$$

where trade costs τ enter since the good crosses the border. All parts are sourced locally and thus θ does not appear here.

The assembler chooses the location that yields the lower C_i. Assembly takes place in N if

$$\begin{aligned} &\Delta C \equiv C_N - C_S = -\tau + (\bar{b}-\underline{b})(\beta+\Delta t) \leq 0, \\ &\rightarrow \tau \geq \tau^* \equiv (\bar{b}-\underline{b})(\beta+\Delta t), \\ &\text{where} \quad \beta \equiv 1-(\underline{b}+\bar{b})/2. \end{aligned} \tag{5}$$

High trade costs ensure the assembler prefers the proximity to consumers. As seen from the switching point τ^*, below which assembly takes place in S, the assembler is more likely to locate in N as N's tax becomes lower (lower Δt) and/or N's parts are more costly (higher β). This tendency is magnified by the total number of parts: $\bar{b} - \underline{b}$.

2.3.2 Social Optimum

Environmental taxes potentially affect pollution arising from dirty parts production via two channels. First, as discussed in Section 2.2, a tax increase in one country makes its production cost of parts higher, inducing the assembler to change the sourcing pattern. The assembler sources more parts from the other country than before, where more pollution and environmental damage occur. Second, as discussed in Section 3.1, taxes affect the assembler's location choice through changes in the switching point, τ^*, and may lead to a discontinuous jump in pollution. If an increase in t_N makes τ^* higher than the exogenously given trade costs, τ, the assembler moves from S to N and brings N a discontinuous increase in pollution due to the colocation motive of parts and assembly.

Under high unbundling costs, however, the first channel, i.e., the assembler's sourcing decision, is ineffective. The colocation motive is so strong that the unbundling thresholds degenerate ($b_N = \underline{b}$; $b_S = \bar{b}$), implying that environmental taxes affect pollution only through the second channel, i.e., the assembler's location decision.

The social/global welfare W is the sum of each country's indirect utility V_i. Using (1) to (4), we have

$$W = \begin{cases} W|_{A=N} = \sum_{i=N,S} V_i|_{A=N} = u - (\bar{b} - \underline{b}) - (\gamma/2)(\bar{b} - \underline{b})^2 & \text{if } \ \tau \geq \tau^* \\ W|_{A=S} = \sum_{i=N,S} V_i|_{A=S} = u - \tau - (1/2)(\bar{b} - \underline{b})(\underline{b} + \bar{b}) - (\gamma/2)(\bar{b} - \underline{b})^2 & \text{if } \ \tau < \tau^* \end{cases},$$

where $u \equiv \widetilde{u} + 2(1 + \overline{\Lambda})$,

and where the subscript $A = i \in \{N, S\}$ indicates the assembler's location. Since all parts co-locate with assembly, the pollution level in i is $e_i = \bar{b} - \underline{b}$ if the assembler is in i and it is $e_i = 0$ otherwise. We do not examine each component of the social welfare here, but details about the final good's price and the environmental damage are in Appendix 2.A.1.

Surprisingly, taxes do not enter in W. Since the unbundling thresholds degenerate, the environmental damage does not depend on taxes: $D(e_i) = (\gamma/2)(\bar{b} - \underline{b})^2$. Higher taxes improve welfare by raising tax revenues, while they reduce welfare by raising the final good's price. These two counteracting effects offset each other.[10] Taxes thus affect parts location only through changes in

[10]For example, if assembly takes place in N, the sum of the consumer surplus and tax revenues in the world is

$$\begin{aligned}(\widetilde{u} - C_N) + t_N(\bar{b} - \underline{b}) &= \widetilde{u} - (\bar{b} - \underline{b})(1 + t_N) + t_N(\bar{b} - \underline{b}) \\ &= \widetilde{u} - (\bar{b} - \underline{b}),\end{aligned}$$

assembly location. The social planner cannot manipulate τ^* directly, but can do so indirectly by changing taxes.

Noting that τ^* depends on the tax difference, not individual levels, the planner chooses Δt to attain $\max\{W|_{A=N}, W|_{A=S}\}$ by (indirectly) manipulating the switching point τ^*. The optimal tax difference for any trade costs turns out to be $\Delta t = 0$, as Figure 2.3 illustrates.[11] That is, the planner should not intervene in the assembler's location choice. If the location of assembly were manipulated, comparative advantage would be distorted and thus the total cost would not be minimized. In addition, assembly location affects *local* environmental damage, but does not affect *global* environmental damage, since the assembler sources all parts locally. The planner is thus unable to reduce the global damage by changing assembly location. The planner fully respects the cost-minimization location choice of the assembler by setting the tax difference to zero. The socially optimal switching point then becomes $\widehat{\tau}^* \equiv \tau^*|_{\Delta t=0} = \beta(\bar{b} - \underline{b})$.

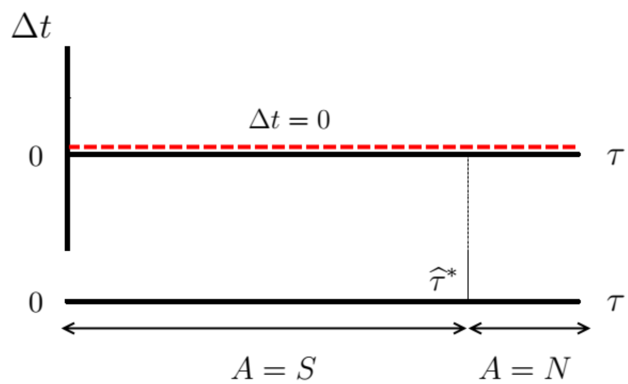

Figure 2.3: Socially optimal tax harmonization (dashed line) and assembly location under high unbundling costs.

Proposition 2.1 *Under high unbundling costs, environmental tax harmonization, i.e., $t_N = t_S$, always maximizes social welfare for any level of trade costs.*

which is independent of taxes. The same argument holds if assembly takes place in S. See Appendix 2.A.1 for the exact welfare expressions.

[11] All proofs of the propositions are in Appendix 2.A.2. Given τ, there may be other optimal tax differences than $\Delta t = 0$ (see Figure 2.A.2). But only $\Delta t = 0$ maximizes social welfare for any τ.

2.4 Low Unbundling Costs: Separation of Parts and Assembly

We turn to the case where unbundling costs are low: $\theta < \underline{\theta}$. Low unbundling costs allow parts and assembly to locate in different countries, capturing the second unbundling.

2.4.1 Assembly Location

As Figure 2.2 suggests, the two unbundling thresholds are within the interval of $[\underline{b}, \overline{b}]$. The total cost of the final good in each location is respectively

$$C_N = \underbrace{\left(\theta + t_S + \frac{\underline{b} + b_N}{2}\right)(b_N - \underline{b})}_{\text{Parts from } S} + \underbrace{(1 + t_N)(\overline{b} - b_N)}_{\text{Parts from } N}, \tag{6}$$

$$C_S = \tau + \underbrace{\left(t_S + \frac{\underline{b} + b_S}{2}\right)(b_S - \underline{b})}_{\text{Parts from } S} + \underbrace{(1 + \theta + t_N)(\overline{b} - b_S)}_{\text{Parts from } N}, \tag{7}$$

where $b_N = 1 - \theta + \Delta t$ and $b_S = 1 + \theta + \Delta t$. Assembly takes place in N if

$$\Delta C \equiv C_N - C_S = -\tau + 2\theta\left(1 - \frac{\underline{b} + \overline{b}}{2} + \Delta t\right) \leq 0,$$
$$\rightarrow \tau \geq \tau^{**} \equiv 2\theta\left(\beta + \Delta t\right).$$

Unlike τ^* defined in (5), τ^{**} depends on θ. Lower unbundling costs make the colocation of parts and assembly less important, whereas they make the proximity to the consumer in N more important. A lower θ decreases τ^{**}, making the assembler more likely to locate in N.

2.4.2 Social Optimum

In contrast to the case of high unbundling costs, environmental taxes affect pollution through both the assembler's sourcing and location decisions. A tax increase in one country leads to the offshoring of dirty parts production and may reduce pollution there without losing out the assembler. In the globalized world, taxes are more effective in reducing pollution than in the pre-globalized world. We thus expect that there is a need for more careful tax coordination than with just simple harmonization.

With low unbundling costs, we use (1), (2), (6), and (7) to express the social welfare as

$$
\begin{aligned}
W &= \begin{cases} W|_{A=S} = \sum_{i=N,S} V_i|_{A=S} & \text{if } \tau < \tau^{**} \\ W|_{A=N} = \sum_{i=N,S} V_i|_{A=N} & \text{if } \tau \geq \tau^{**} \end{cases}, \\
W|_{A=S} &= u - \left[\tau + \frac{1}{2}(\underline{b} + b_S)(b_S - \underline{b}) + (1+\theta)(\bar{b} - b_S)\right] - \frac{\gamma}{2}[(\bar{b} - b_S)^2 + (b_S - \underline{b})^2], \\
W|_{A=N} &= u - \left[\left(\theta + \frac{\underline{b} + b_N}{2}\right)(b_N - \underline{b}) + (\bar{b} - b_N)\right] - \frac{\gamma}{2}[(\bar{b} - b_N)^2 + (b_N - \underline{b})^2].
\end{aligned}
$$

Unlike the case of high unbundling costs, the tax difference Δt affects not just the switching point τ^{**} but the unbundling thresholds b_i. The planner chooses Δt to maximize W by (indirectly) manipulating b_i as well as τ^{**}. Although we do not look at each component of welfare here, one can find the details about the final good's price and the environmental damage in Appendix 2.A.1.

Formally, we can derive the socially optimal tax difference as follows and it is illustrated in Figure 2.4:[12]

$$
\Delta t = \begin{cases} \Delta t|_{A=S} \equiv -\dfrac{2\gamma(\beta+\theta)}{2\gamma+1} & \text{if } \tau < \tau^a \\ \widehat{\Delta t} + \varepsilon & \text{if } \tau^a \leq \tau < \widehat{\tau}^{**} \\ \widehat{\Delta t} \equiv \dfrac{\tau}{2\theta} - \beta & \text{if } \widehat{\tau}^{**} \leq \tau < \tau^b \\ \Delta t|_{A=N} \equiv \dfrac{2\gamma(\theta-\beta)}{2\gamma+1} & \text{if } \tau \geq \tau^b \end{cases},
$$
$$
\text{where } \tau^a \equiv \frac{2\theta(\beta - 2\gamma\theta)}{2\gamma+1}, \quad \widehat{\tau}^{**} \equiv \frac{2\beta\theta}{2\gamma+1}, \quad \tau^b \equiv \frac{2\theta(2\gamma\theta+\beta)}{2\gamma+1},
$$

and $\varepsilon > 0$ is a sufficiently small constant.[13] $\widehat{\tau}^{**}$ is the socially optimal switching point.

The socially optimal tax difference would be zero if there were no environmental damage $\gamma = 0$. The planner intervenes solely for reducing the global environmental damage. Since the global damage becomes more severe as pollution is more spatially concentrated, the planner aims to diversify the location of parts. The optimal tax difference is thus set to make the distribution of parts production more equal.[14]

As trade costs τ fall, more parts are shifted from N to S because (i) S's cost advantage begins to matter and (ii) the assembler moves from N to S. To avoid the concentration of pollution, N's tax compared with S's is set lower than before and thus the optimal tax difference decreases with lower τ. The simple harmonization is no longer desirable except for a special case at which the

[12] For τ^a to be positive, the sensitivity of environmental damage is assumed not to be too large: $\gamma < \bar{\gamma} \equiv \beta/(\bar{b} - \underline{b})$.

[13] In Figure 2.4, we ignore ε. $\Delta t|_{A=N}$ can be negative if θ is low enough.

[14] It can be checked that the socially optimal unbundling threshold b_i is closer to the middle point of the range $(\underline{b} + \bar{b})/2$ than the unbundling threshold under no taxes.

optimal tax difference coincides with zero.

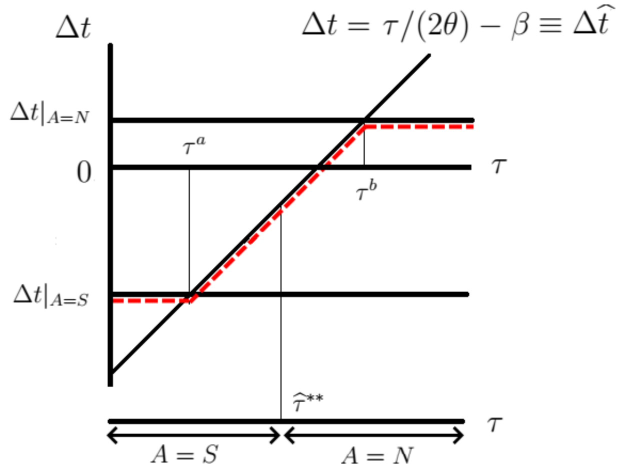

Figure 2.4: Socially optimal tax difference (dashed line) and assembly location under low unbundling costs.

Proposition 2.2 *Under low unbundling costs, environmental tax harmonization never maximizes social welfare except for a specific level of trade costs.*

2.5 Extensions

2.5.1 Environmental Damage Function

We assumed a convex form of the environmental damage function, i.e., $D(e_i) = \gamma e_i^2/2$, which is fairly common in the literature (e.g., Ulph, 1996; Copeland and Taylor, 2005b, Ch. 2). Our main results, Propositions 2.1 and 2.2, do not depend on the specific form of damage function, as we argue below.

Under high unbundling costs, where all parts production colocates with assembly, pollution occurs only in the country with assembly. The levels of pollution and environmental damage are then independent of taxes. Therefore, the social planner does not care about the function form of $D(\cdot)$. Regardless of whether it is convex or concave, the harmonized tax rates are also socially optimal ones.

Under low unbundling costs, the tax difference does affect which parts are produced in which country, even when it does not change assembly location. In this case, the harmonized tax rates can generally never be the socially optimal ones no matter what the function form of $D(\cdot)$ may be. For illustration, consider a situation where θ is close to zero and γ is so high that the planner cares solely about the environmental damage. The sum of the environmental damage in each country is given by $(\gamma/2)[D(e_N) + D(e_S)] = (\gamma/2)[D(\bar{b} - b) + D(b - \underline{b})]$, where $b \simeq 1 + \Delta t$ is the unbundling threshold below (above) which parts are produced in S (N). The planner attempts to minimize this by altering the unbundling threshold b through changes in the tax difference $\Delta t \equiv t_N - t_S$.

If $D(\cdot)$ is convex, as assumed in the main analysis, the global damage is minimized when b is at the middle point: $(\underline{b}+\bar{b})/2$.[15] The socially optimal tax difference must satisfy $b = 1+\Delta t = (\underline{b}+\bar{b})/2$, or $\Delta t = \beta \equiv 1 - (\underline{b} + \bar{b})/2 > 0$. The harmonized tax rates would lead to too much pollution in S.

If $D(\cdot)$ is concave, the global damage is minimized when b is at either of the endpoints: $\underline{b}$ or $\bar{b}$.[16] The socially optimal tax difference must be either $\Delta t = 1 - \underline{b} > 0$ or $\Delta t = 1 - \bar{b} < 0$ to induce all parts production to take place in one country. Tax harmonization that allows for the diversification of parts production is then poor policy.

2.5.2 Nash Equilibrium vs. Social Optimum

The focus of this chapter is on whether the harmonization policy maximizes social welfare. We could also ask whether decentralized policies chosen by noncooperative governments, i.e., Nash equilibrium policies, lead to the socially optimal outcome. Here, we intuitively argue that the Nash equilibrium tax difference is more likely to differ from the socially optimal one under low unbundling costs than under high unbundling costs. Our main finding carries over: globalization calls for more careful international coordination than a simple harmonization rule. The full characterization of Nash equilibria is relegated to Appendices 2.A.3 and 2.A.4.

High Unbundling Costs

We consider the governments' incentive to deviate from the harmonized tax rates: $t_N = t_S$, which maximizes social welfare (see Proposition 2.1). Since the unbundling thresholds degenerate under high unbundling costs, i.e., $b_N = \underline{b}$; $b_S = \bar{b}$, the levels of pollution and environmental damage are independent of taxes. The governments can then do little to reduce local pollution and thus do not tend to prefer specific tax rates.

If trade costs are sufficiently high such that $\tau \geq \hat{\tau}^*$, assembly takes place in N (see Section 3). In this case, government S does not wish to challenge government N over assembly by reducing t_S because attracting assembly by the reduced t_S would not bring with it much tax revenue. As there are neither assembly nor tax revenues in S, government S does not have any incentive to raise

[15] The FOC for the minimization problem is $-D'(\bar{b} - b) + D'(b - \underline{b}) = 0$, noting that the SOC is satisfied because of the convexity of $D(\cdot)$: $D''(\bar{b} - b) + D''(b - \underline{b}) > 0$. From the FOC, we have $D'(\bar{b} - b) = D'(b - \underline{b})$, or $b = (\underline{b} + \bar{b})/2$.

[16] This result comes from the fact that the SOC for the minimization problem is not satisfied: $D''(\bar{b}-b)+D''(b-\underline{b}) < 0$.

t_S, either. Government N is also unwilling to change t_N because t_N does not enter its objective function.[17] The harmonized tax rates are then indeed Nash-equilibrium ones.

If $\tau < \widehat{\tau}^*$, where assembly takes place in S, government S has an incentive to set t_S higher than t_N because by doing so S can increase tax revenues while not inducing assembly relocation. The Nash equilibrium tax difference can never be zero.

In sum, if $\tau \geq \widehat{\tau}^*$, the harmonized tax rates are the Nash equilibrium ones as well as the socially optimal ones.

Low Unbundling Costs

Under low unbundling costs, the unbundling thresholds do not degenerate, i.e., $b_N = 1 - \theta + \Delta t$; $b_S = 1 + \theta + \Delta t$. The country without assembly also suffers environmental damage from dirty input production, implying that both governments, regardless of hosting assembly, can affect the level of pollution through taxes. They want to choose a specific tax rate that maximizes their national welfare, which is in stark contrast to the case of high unbundling costs.

A tax increase by government $i \in \{N, S\}$ causes the relocation of parts and thus pollution to $j \neq i$. Government j then wishes to increase its tax rate as well to prevent environmental damage. That is, the two countries' tax rates are strategic complements: both governments wish to change their tax rates in the same direction.[18] Therefore, irrespective of the level of trade costs, the Nash equilibrium tax difference is in general different from the socially optimal one in such a way that the former is smaller than the latter.

2.6 Conclusion

Desirable environmental policies may drastically change before and after the current globalization characterized by the spatial unbundling of production processes. In the pre-globalized world, environmental tax harmonization avoids distorting efficient location choices and maximizes global welfare, despite heterogeneity between countries. In the globalized world, however, it leads to the excessive spatial concentration of pollution and (almost) never maximizes global welfare. The second unbundling may then call for careful international coordination beyond simple harmonization. These theoretical findings have implications for the experiences of earlier member states of the European Union (EU) prior to 2004, i.e., the EU 15, and the newer member states among the Central

[17] An increase in t_N has a positive effect on tax revenues and a negative effect on the consumer surplus, which cancel each other. Therefore, t_N does not matter for government N's welfare.

[18] The strategic complementarity leads to a race to the top, in which each country's tax rate at the Nash equilibrium is higher than their rate at the social optimum. The argument here assumes that the governments emphasize environmental damage, i.e., a high γ. If instead γ is low and thus the governments emphasize tax revenues, the complementarity results in a race to the bottom.

and Eastern European (CEE) countries since 2004.

We highlight two important issues that have not been addressed in the current chapter. First, it would be worthwhile investigating how we should coordinate environmental and trade polices such as import tariffs (Lai and Hu, 2008; Yomogida and Tarui, 2013; Keen and Kotsogiannis, 2014; Sanctuary, 2018; Ogawa et al., 2019). In the age of the second unbundling, the location of parts is sensitive to the international cost differences generated by both policy measures. Key questions would be as follows. Which measure is effective for the global environment? Are tariffs necessary as border tax adjustments given different emission taxes at home and abroad? Second, it would also be interesting to consider pollution emitted during the transportation of goods, considering its importance among all sources of pollution (Abe et al., 2014; Ishikawa and Tarui, 2018).[19] Transportation pollution is particularly relevant in *snake*-style production, in which parts move sequentially from upstream to downstream with value added at each stage. The snake-style production tends to generate more pollution than the spider-style production we consider in this chapter, because parts produced in one country can be shipped multiple times before they reach the final stage. Incorporating these aspects into our model would lead to greater externalities and thus larger deviations between harmonized and socially optimal taxes. We leave these issues for future research.

[19] For example, greenhouse gas (GHG) emissions from transportation account for 28.9 percent of total US GHG emissions in 2017, making it the largest contributor to US GHG emissions. Source: U.S. Environmental Protection Agency (`https://www.epa.gov/ghgemissions/sources-greenhouse-gas-emissions`, accessed on March 23, 2020).

2.A Appendix

2.A.1 Final Good's Price and Environmental Damage

High-unbundling-cost case. From the discussion in Section 3.1, we obtain the final good's price as

$$p = \min\{C_N, C_S\} = \begin{cases} C_N = (\bar{b} - \underline{b})(1 + t_N) & \text{if } \tau \geq \tau^* \\ C_S = \tau + (\bar{b} - \underline{b})\left[(\underline{b} + \bar{b})/2 + t_S\right] & \text{if } \tau < \tau^* \end{cases},$$

which is shown in Figure 2.A.1. We note that assembly takes place in $A = N$ ($A = S$) if $\tau \geq \tau^*$ ($\tau < \tau^*$).

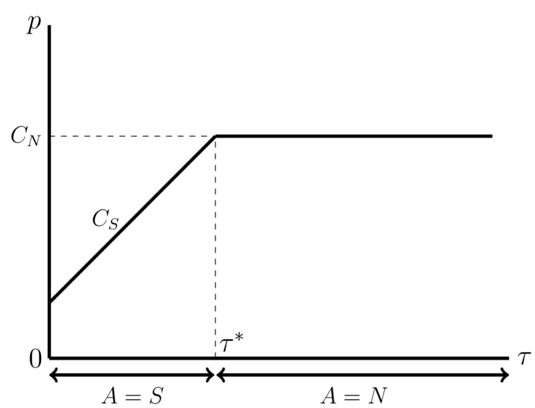

Figure 2.A.1: Final good's price under high unbundling costs.

The environmental damage in each country is

$$D(e_N) = \begin{cases} (\gamma/2)(\bar{b} - \underline{b})^2 & \text{if } \tau \geq \tau^* \\ 0 & \text{if } \tau < \tau^* \end{cases},$$

$$D(e_S) = \begin{cases} 0 & \text{if } \tau \geq \tau^* \\ (\gamma/2)(\bar{b} - \underline{b})^2 & \text{if } \tau < \tau^* \end{cases}.$$

The sum of the two equals

$$D(e_N) + D(e_S) = (\gamma/2)(\bar{b} - \underline{b})^2 \quad \text{for any } \tau.$$

These are illustrated in Figure 2.A.2.

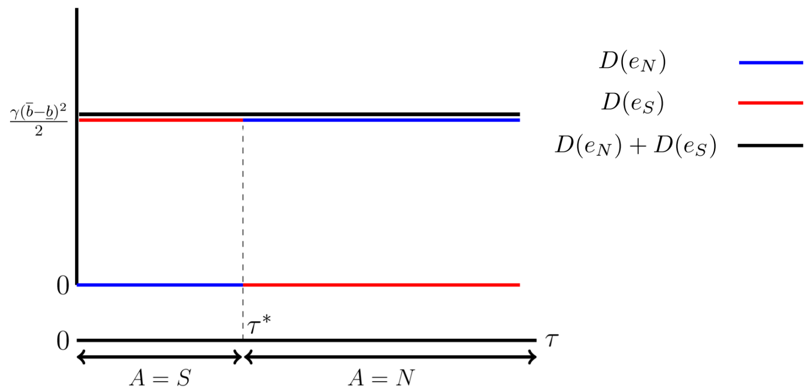

Figure 2.A.2: Environmental damage under high unbundling costs.

Low-unbundling-cost case. From the discussion in Section 4.1, we obtain the final good's price as

$$p=\min\{C_N,C_S\}=\begin{cases} C_N=\underbrace{\left(\theta+t_S+\dfrac{\underline{b}+b_N}{2}\right)(b_N-\underline{b})}_{\text{Parts from } S}+\underbrace{(1+t_N)(\bar{b}-b_N)}_{\text{Parts from } N} & \text{if} \quad \tau\geq\tau^{**} \\ C_S=\tau+\underbrace{\left(t_S+\dfrac{\underline{b}+b_S}{2}\right)(b_S-\underline{b})}_{\text{Parts from } S}+\underbrace{(1+\theta+t_N)(\bar{b}-b_S)}_{\text{Parts from } N} & \text{if} \quad \tau<\tau^{**} \end{cases},$$

which is shown in Figure 2.A.3. We note that assembly takes place in $A=N$ $(A=S)$ if $\tau\geq\tau^{**}$ $(\tau<\tau^{**})$.

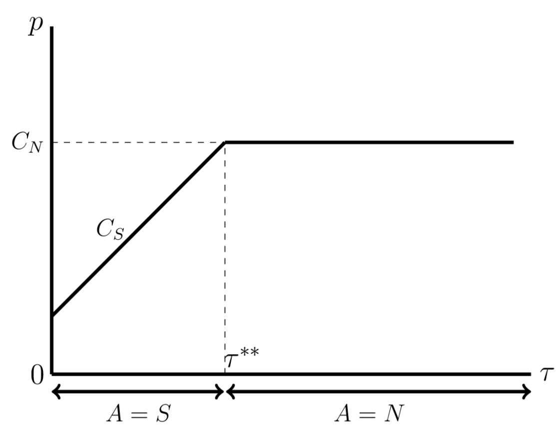

Figure 2.A.3: Final good's price under low unbundling costs.

The environmental damage in each country is

$$D(e_N) = \begin{cases} D(e_N)\big|_{A=N} = (\gamma/2)(\bar{b} - b_N)^2 & \text{if } \ \tau \geq \tau^{**} \\ D(e_N)\big|_{A=S} = (\gamma/2)(\bar{b} - b_S)^2 & \text{if } \ \tau < \tau^{**} \end{cases},$$

$$D(e_S) = \begin{cases} D(e_S)\big|_{A=N} = (\gamma/2)(b_N - \underline{b})^2 & \text{if } \ \tau \geq \tau^{**} \\ D(e_S)\big|_{A=S} = (\gamma/2)(b_S - \underline{b})^2 & \text{if } \ \tau < \tau^{**} \end{cases}.$$

The global damage is then

$$D(e_N) + D(e_S) = \begin{cases} [D(e_N) + D(e_S)]\big|_{A=N} = (\gamma/2)\left[(\bar{b} - b_N)^2 + (b_N - \underline{b})^2\right] & \text{if } \ \tau \geq \tau^{**} \\ [D(e_N) + D(e_S)]\big|_{A=S} = (\gamma/2)\left[(\bar{b} - b_S)^2 + (b_S - \underline{b})^2\right] & \text{if } \ \tau < \tau^{**} \end{cases}.$$

We note the following:

$$\begin{aligned}
&D(e_N)|_{A=N} > D(e_N)|_{A=S}, \\
&D(e_S)|_{A=N} < D(e_S)|_{A=S}, \\
&D(e_N)|_{A=S} - D(e_S)|_{A=S} = -\gamma(\bar{b} - \underline{b})(\beta + \Delta t + \theta) < 0, \\
&D(e_S)|_{A=N} - D(e_N)|_{A=S} = \gamma(b_N - \underline{b} + \bar{b} - b_S)(\beta + \Delta t) > 0, \\
&D(e_S)|_{A=S} - D(e_N)|_{A=N} = \gamma(b_S - \underline{b} + \bar{b} - b_N)(\beta + \Delta t) > 0, \\
&[D(e_N) + D(e_S)]\,\big|_{A=S} - [D(e_N) + D(e_S)]\,\big|_{A=N} = \gamma(b_S - b_N)(b_N + b_S - \bar{b} - \underline{b}) \\
&\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\quad = 4\gamma\theta(\beta + \Delta t) > 0.
\end{aligned}$$

Although the inequalities above unambiguously hold, we still need to check the relationship between the two countries' pollution levels when the assembly is in N:

$$D(e_N)|_{A=N} - D(e_S)|_{A=N} = -\gamma(\bar{b} - \underline{b})(\beta + \Delta t - \theta).$$

Country N's pollution level tends to be lower when country S's average cost advantage is larger (higher β); the tax difference is larger (high Δt); and the unbundling costs are lower (lower θ). Depending on the sign of $\beta + \Delta t - \theta$, the environmental damage is illustrated in Figs 2.A.4 and 2.A.5.

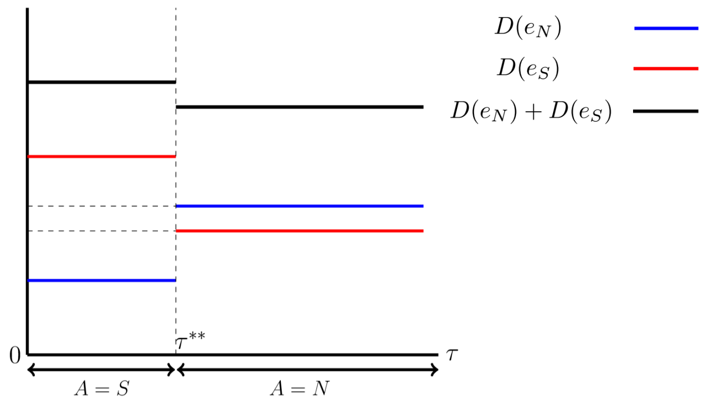

Figure 2.A.4: Environmental damage under low unbundling costs if $\beta + \Delta t - \theta < 0$.

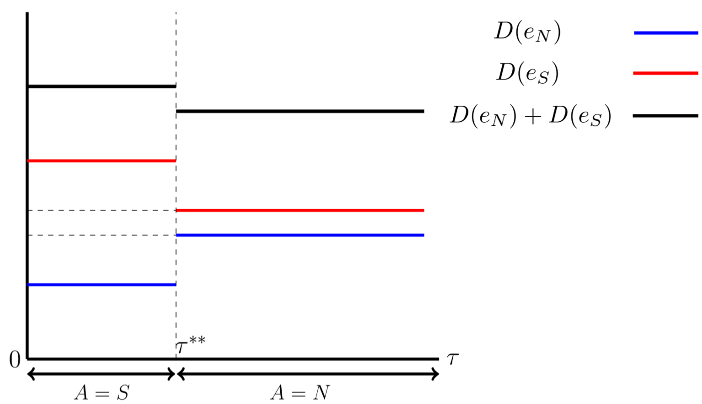

Figure 2.A.5: Environmental damage under low unbundling costs if $\beta + \Delta t - \theta > 0$.

2.A.2 Proofs of Propositions

Proof of Proposition 2.1

From (1), (2), (3), and (4), the indirect utility of the representative agent in each country is given by

$$V_N = \begin{cases} V_N|_{A=S} = \widetilde{u} - C_S + 1 + \overline{\Lambda} & \text{if} \ \ \tau < \tau^* \\ V_N|_{A=N} = \widetilde{u} - C_N + t_N(\bar{b} - \underline{b}) - (\gamma/2)(\bar{b} - \underline{b})^2 + 1 + \overline{\Lambda} & \text{if} \ \ \tau \geq \tau^* \end{cases},$$

$$V_S = \begin{cases} V_S|_{A=S} = t_S(\bar{b} - \underline{b}) - (\gamma/2)(\bar{b} - \underline{b})^2 + 1 + \overline{\Lambda} & \text{if} \ \ \tau < \tau^* \\ V_S|_{A=N} = 1 + \overline{\Lambda} & \text{if} \ \ \tau \geq \tau^* \end{cases},$$

where $C_S = \tau + (\bar{b} - \underline{b})/[(\bar{b} + \underline{b})/2 + t_S]$; $C_N = (\bar{b} - \underline{b})(1 + t_N)$; $\tau^* \equiv (\bar{b} - \underline{b})(\beta + \Delta t)$; $\beta \equiv 1 - (\underline{b} + \bar{b})/2$. The social welfare is defined by the sum of each country's indirect utility:

$$W = \begin{cases} W|_{A=S} = V_N|_{A=S} + V_S|_{A=S} = u - \tau - (1/2)(\bar{b} - \underline{b})(\underline{b} + \bar{b}) - (\gamma/2)(\bar{b} - \underline{b})^2 & \text{if } \tau < \tau^* \\ W|_{A=N} = V_N|_{A=N} + V_S|_{A=N} = u - (\bar{b} - \underline{b}) - (\gamma/2)(\bar{b} - \underline{b})^2 & \text{if } \tau \geq \tau^* \end{cases},$$

where $u \equiv \widetilde{u} + 2(1 + \overline{\Lambda})$, as given in the main text.

Taxes do not enter the expressions of social welfare and only affect the location decision of the assembler. The social planner thus chooses the assembly location through taxes that gives the higher social welfare. A simple comparison of welfare between the two locations reveals

$$\max\{W|_{A=N}, W|_{A=S}\} = \begin{cases} W|_{A=S} = u - \tau - (\bar{b} - \underline{b})(\underline{b} + \bar{b})/2 - (\gamma/2)(\bar{b} - \underline{b})^2 & \text{if } \tau < \widehat{\tau}^* \\ W|_{A=N} = u - (\bar{b} - \underline{b}) - (\gamma/2)(\bar{b} - \underline{b})^2 & \text{if } \tau \geq \widehat{\tau}^* \end{cases},$$

where $W|_{A=N} = W|_{A=S}$ holds at $\widehat{\tau}^* \equiv \beta(\bar{b} - \underline{b})$.

To see the results intuitively, it is helpful to illustrate the assembly location pattern in the (τ, Δ) plane, as Figure 2.A.6 shows. The upward-sloping line is the cost-indifference one: $\tau = \tau^*$, or equivalently, $\Delta t = \tau/(\bar{b} - \underline{b}) - \beta$, which represents N's maximum tax rate that keeps assembly there. The social planner should set taxes so that the assembly locates in N if $\tau \geq \widehat{\tau}^*$ and it locates in S otherwise. The optimal tax difference is thus

$$\Delta t \begin{cases} > \tau/(\bar{b} - \underline{b}) - \beta & \text{if } \tau < \widehat{\tau}^* \\ \leq \tau/(\bar{b} - \underline{b}) - \beta & \text{if } \tau \geq \widehat{\tau}^* \end{cases},$$

which is represented by the shaded area in Figure 2.A.7. As is clear from Figure 2.A.7, only the tax harmonization $\Delta t = 0$ (dashed line) maximizes the social welfare for any level of trade costs.

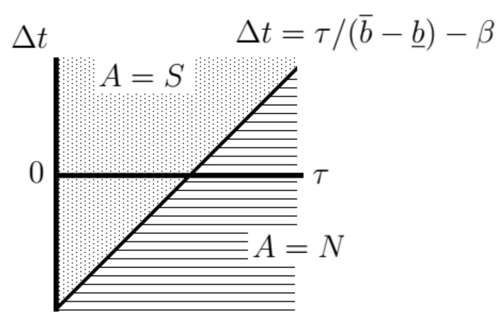

Figure 2.A.6: Location of assembly under high unbundling costs.

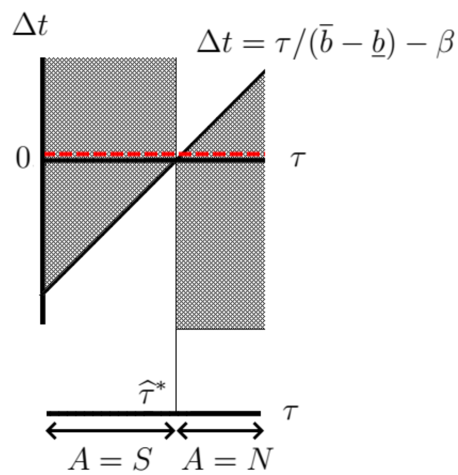

Figure 2.A.7: Socially optimal tax difference (shaded areas) and assembly location under high unbundling costs.

Proof of Proposition 2.2

We first derive the unconstrained socially optimal taxes given the location of assembly. With low unbundling costs, the indirect utility of the representative agent in each country is given by

$$V_N = \begin{cases} V_N|_{A=S} = \widetilde{u} - C_S + t_N(\bar{b} - b_S) - (\gamma/2)(\bar{b} - b_S)^2 + 1 + \overline{\Lambda} & \text{if } \tau < \tau^{**} \\ V_N|_{A=N} = \widetilde{u} - C_N + t_N(\bar{b} - b_N) - (\gamma/2)(\bar{b} - b_N)^2 + 1 + \overline{\Lambda} & \text{if } \tau \geq \tau^{**} \end{cases},$$

$$V_S = \begin{cases} V_S|_{A=S} = t_S(b_S - \underline{b}) - (\gamma/2)(b_S - \underline{b})^2 + 1 + \overline{\Lambda} & \text{if } \tau < \tau^{**} \\ V_S|_{A=N} = t_S(b_N - \underline{b}) - (\gamma/2)(b_N - \underline{b})^2 + 1 + \overline{\Lambda} & \text{if } \tau \geq \tau^{**} \end{cases},$$

where C_i is defined in (6) and (7); and $\tau^{**} \equiv 2\theta(\beta + \Delta t)$; $b_N = 1 - \theta + \Delta t$; $b_S = 1 + \theta + \Delta t$. The social welfare is defined by the sum of the two country's indirect utility:

$$W = \begin{cases} W|_{A=S} = \sum_{i=N,S} V_i|_{A=S} & \text{if } \tau < \tau^{**} \\ W|_{A=N} = \sum_{i=N,S} V_i|_{A=N} & \text{if } \tau \geq \tau^{**} \end{cases},$$

$$W|_{A=S} = u - \left[\tau + \frac{1}{2}(\underline{b} + b_S)(b_S - \underline{b}) + (1 + \theta)(\bar{b} - b_S)\right] - (\gamma/2)[(\bar{b} - b_S)^2 + (b_S - \underline{b})^2],$$

$$W|_{A=N} = u - \left[\left(\theta + \frac{\underline{b} + b_N}{2}\right)(b_N - \underline{b}) + (\bar{b} - b_N)\right] - (\gamma/2)[(\bar{b} - b_N)^2 + (b_N - \underline{b})^2],$$

as given in the text.

For the social welfare level at each assembly location, the first-order conditions give

$$\begin{aligned}
&\frac{dW|_{A=S}}{dt_N} = -\frac{dW|_{A=S}}{dt_S} = 0,\\
&\rightarrow (t_N - t_S)|_{A=S} = -\frac{2\gamma}{2\gamma+1}(\theta+\beta) \equiv \Delta t|_{A=S},\\
&\frac{dW|_{A=N}}{dt_N} = -\frac{dW|_{A=N}}{dt_S} = 0,\\
&\rightarrow (t_N - t_S)|_{A=N} = \frac{2\gamma}{2\gamma+1}(\theta-\beta) \equiv \Delta t|_{A=N}.
\end{aligned}$$

Since $dW|_{A=i}/dt_N$ and $(-dW|_{A=i}/dt_S)$ are collinear, what matters for the social welfare maximization is the tax difference and not the absolute levels of taxes.

We then allow for endogenous assembly location and see how it affects the optimal taxes. As in Appendix 2.A.2.1, it is helpful to consider in the $(\tau, \Delta t)$ plane. The upward-sloping line in Figure 2.A.8 is the cost-indifference line: $\tau = \tau^{**}$, or equivalently, $\Delta t = \tau/(2\theta) - \beta \equiv \Delta\widehat{t}$. Putting the unconstrained maximizers derived before into the plane, we can obtain Figure 2.A.9 and identify that there are three cases to be considered. Letting τ^a (or τ^b) be the intersection of the cost-indifference line and $\Delta t|_{A=S}$ (or $\Delta t|_{A=N}$), the three cases are characterized as follows.

Case (i) $\tau < \tau^a$. The social optimum will be either the constrained maximum with assembly in N, $W|_{A=N,\ \Delta t=\Delta\widehat{t}}$, or the unconstrained maximum with assembly in S, $W|_{A=S,\ \Delta t=\Delta t|_{A=S}}$.

Case (ii) $\tau^a \leq \tau < \tau^b$. The social optimum will be either the constrained maximum with assembly in N, $W|_{A=N,\ \Delta t=\Delta\widehat{t}}$, or the constrained maximum with assembly in S, $W|_{A=S,\ \Delta t=\Delta\widehat{t}+\varepsilon}$.

Case (iii) $\tau \geq \tau^b$. The social optimum will be either the unconstrained maximum with assembly in N, $W|_{A=N,\ \Delta t=\Delta t|_{A=N}}$, or the constrained maximum with assembly in S, $W|_{A=S,\ \Delta t=\Delta\widehat{t}+\varepsilon}$.

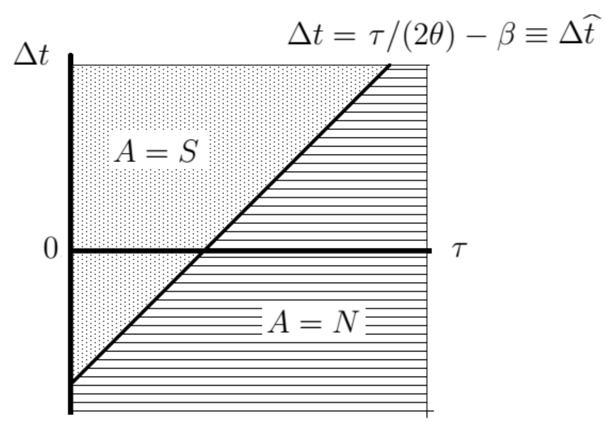

Figure 2.A.8: Location of assembly under low unbundling costs.

For the latter reference, it is informative here to compare the constrained maxima between the

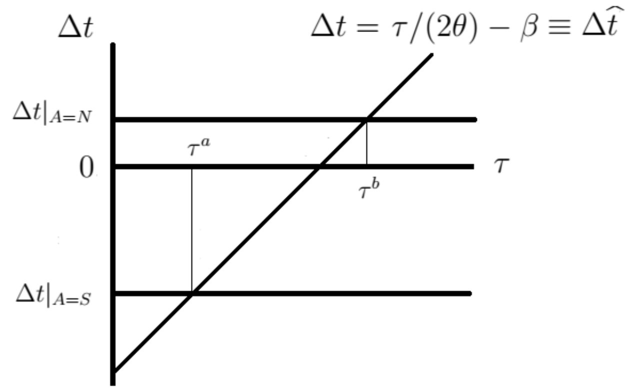

Figure 2.A.9: Unconstrained optimal tax differences under low unbundling costs.

two locations.

$$\begin{aligned} W|_{A=N,\ \Delta t=\Delta\widehat{t}} - W|_{A=S,\ \Delta t=\Delta\widehat{t}+\varepsilon} &= \tau + \beta(b_N - b_S) + 2[\theta + \gamma(b_N - b_S)][1 - (b_N + b_S)/2 - \beta] \\ &= \tau(2\gamma + 1) - 2\beta\theta, \end{aligned}$$

noting that ε is sufficiently small. On $\Delta t = \Delta\widehat{t}$, it holds that $b_N - b_S = -2\theta$ and $b_N + b_S = 2(1+\Delta\widehat{t})$. We thus have $W|_{A=N,\ \Delta t=\Delta\widehat{t}} \geq W|_{A=S,\ \Delta t=\Delta\widehat{t}+\varepsilon}$ if $\tau \geq \widehat{\tau}^{**} \equiv 2\beta\theta/(2\gamma+1)$ and $W|_{A=N,\ \Delta t=\Delta\widehat{t}} < W|_{A=S,\ \Delta t=\Delta\widehat{t}+\varepsilon}$ otherwise. It can be also checked that $\tau^a < \widehat{\tau}^{**} < \tau^b$.

With these in hand, we will derive the socially optimal taxes in each case.

Case (i) $\tau < \tau^a$. In this case, we have

$$W|_{A=S,\ \Delta t=\Delta t|_{A=S}} > W|_{A=S,\ \Delta t=\Delta\widehat{t}} > W|_{A=N,\ \Delta t=\Delta\widehat{t}}.$$

The socially optimal outcome is the unconstrained maximum with assembly in S.

Case (ii) $\tau^a \leq \tau < \tau^b$. As $\widehat{\tau}^{**}$ is in between τ^a and τ^b, this case is further divided into two subcases.

Case (ii-a) $\tau^a \leq \tau < \widehat{\tau}^{**}$. We have

$$W|_{A=S,\ \Delta t=\Delta\widehat{t}+\varepsilon} > W|_{A=N,\ \Delta t=\Delta\widehat{t}}.$$

The socially optimal outcome is that assembly takes place in S and the tax difference is set at $\Delta t = \Delta\widehat{t} + \varepsilon$.

Case (ii-b) $\widehat{\tau}^{**} \leq \tau < \tau^b$. We have

$$W|_{A=N,\ \Delta t=\Delta\widetilde{t}} \geq W|_{A=S,\ \Delta t=\Delta\widehat{t}+\varepsilon}.$$

The socially optimal outcome is that assembly takes place in N and the tax difference is set at $\Delta t = \Delta\widehat{t}$.

Case (iii) $\tau \geq \tau^b$. In this case, we have

$$W|_{A=N,\ \Delta t=\Delta t|_{A=N}} > W|_{A=N,\ \Delta t=\Delta\widehat{t}} > W|_{A=S,\ \Delta t=\Delta\widehat{t}+\varepsilon}.$$

The socially optimal outcome is the unconstrained maximum with assembly in N.

In sum, the socially optimal tax difference is

$$\Delta t = \begin{cases} \Delta t|_{A=S} = -\dfrac{2\gamma(\beta+\theta)}{2\gamma+1} & \text{if } \tau < \tau^a \\ \Delta\widehat{t}+\varepsilon & \text{if } \tau^a \leq \tau < \widehat{\tau}^{**} \\ \Delta\widehat{t} = \dfrac{\tau}{2\theta} - \beta & \text{if } \widehat{\tau}^{**} \leq \tau < \tau^b \\ \Delta t|_{A=N} = \dfrac{2\gamma(\theta-\beta)}{1+2\gamma} & \text{if } \tau \geq \tau^b \end{cases},$$

$$\text{where } \tau^a \equiv \frac{2\theta(\beta-2\gamma\theta)}{2\gamma+1}, \quad \widehat{\tau}^{**} \equiv \frac{2\beta\theta}{2\gamma+1}, \quad \tau^b \equiv \frac{2\theta(2\gamma\theta+\beta)}{2\gamma+1},$$

as given in the main text.

2.A.3 Nash Equilibrium Outcome Under High Unbundling Costs

As noted in Appendix 2.A.2.1, under high unbundling costs, the indirect utility of the representative agent in each country is given by

$$V_N = \begin{cases} V_N|_{A=S} = \widetilde{u} - C_S + 1 + \overline{\Lambda} & \text{if } \tau < \tau^* \\ V_N|_{A=N} = \widetilde{u} - C_N + t_N(\bar{b}-\underline{b}) - (\gamma/2)(\bar{b}-\underline{b})^2 + 1 + \overline{\Lambda} & \text{if } \tau \geq \tau^* \end{cases},$$

$$V_S = \begin{cases} V_S|_{A=S} = t_S(\bar{b}-\underline{b}) - (\gamma/2)(\bar{b}-\underline{b})^2 + 1 + \overline{\Lambda} & \text{if } \tau < \tau^* \\ V_S|_{A=N} = 1 + \overline{\Lambda} & \text{if } \tau \geq \tau^* \end{cases},$$

where $C_N = (\bar{b}-\underline{b})(1+t_N)$; $C_S = \tau + (\bar{b}-\underline{b})[(\underline{b}+\bar{b})/2 + t_S]$; $\tau^* \equiv (\bar{b}-\underline{b})(\beta+\Delta t)$. The unbundling thresholds degenrate: $b_N = \underline{b}$; $b_S = \bar{b}$.

(i) First, we investigate S's best responses given N's pollution tax. Evaluating the switching point τ^* at taxes making the locations indifferent to S (i.e., $V_S|_{A=S} = V_S|_{A=N}$), we get the threshold tax rate: $\widehat{t}_N = \tau/(\bar{b} - \underline{b}) - \beta + (\gamma/2)(\bar{b} - \underline{b})$.

If $t_N \in [0, \widehat{t}_N]$, S imposes a pollution tax satisfying $t_S \geq t_N - \tau/(\bar{b} - \underline{b}) + \beta$ so as to induce $A = N$ and $V_S|_{A=N} = 0$. Or else, S's welfare is negative ($A = S$, $V_S|_{A=S} < 0$).

If $t_N \in (\widehat{t}_N, \infty)$, S imposes a pollution tax satisfying $t_S < t_N - \tau/(\bar{b} - \underline{b}) + \beta - \varepsilon$ so as to induce $A = S$ and positive welfare where ε is a sufficiently small constant.

(ii) Second, we investigate N's best responses given S's pollution tax. Similarly, evaluating the switching point τ^* at taxes making the locations indifferent to N (i.e., $V_N|_{A=S} = V_N|_{A=N}$), we get the threshold tax rate: $\widehat{t}_S = -\tau/(\bar{b} - \underline{b}) + \beta + (\gamma/2)(\bar{b} - \underline{b})$.

If $t_S \in [0, \widehat{t}_S)$, then $V_N|_{A=S} > V_N|_{A=N}$ holds. N imposes $t_N > t_S + \tau/(\bar{b} - \underline{b}) - \beta$ and chooses $A = S$.

If $t_S \in [\widehat{t}_S, \infty)$, then $V_N|_{A=S} < V_N|_{A=N}$ holds. N imposes $t_N < t_S + \tau/(\bar{b} - \underline{b}) - \beta$ and chooses $A = N$.

(iii) Third, we combine (i) and (ii) together to get the Nash equilibria as follows.

If $\tau/(\bar{b} - \underline{b}) - \beta < 0$, or $\tau < \widehat{\tau}^*$, both locations can be the Nash equilibria, i.e., $A^{NE} \in \{N, S\}$. The Nash equilibrium tax differences at $A^{NE} = N$ are $\Delta t^{NE} < 2[\tau/(\bar{b} - \underline{b}) - \beta]$, and those at $A^{NE} = S$ are $\Delta t^{NE} = \tau/(\bar{b} - \underline{b}) - \beta$.

If $\tau/(\bar{b} - \underline{b}) - \beta = 0$, or $\tau = \widehat{\tau}^*$, the tax differences and the assembly location at the Nash equilibria are respectively $\Delta t^{NE} \leq 0$ and $A^{NE} = N$.

If $\tau/(\bar{b} - \underline{b}) - \beta > 0$, or $\tau > \widehat{\tau}^*$, the tax differences and the assembly location at the Nash equilibria are respectively $\Delta t^{NE} < \tau/(\bar{b} - \underline{b}) - \beta$ and $A^{NE} = N$.

From Appendix 2.A.2, we can see that the Nash equilibria coincide with the socially optimal outcomes for $\tau \geq \widehat{\tau}^*$, which are shown in Figure 2.A.10. Nash equilibrium tax difference is described by the shaded area and $\Delta t = \tau/(\bar{b} - \underline{b}) - \beta$.

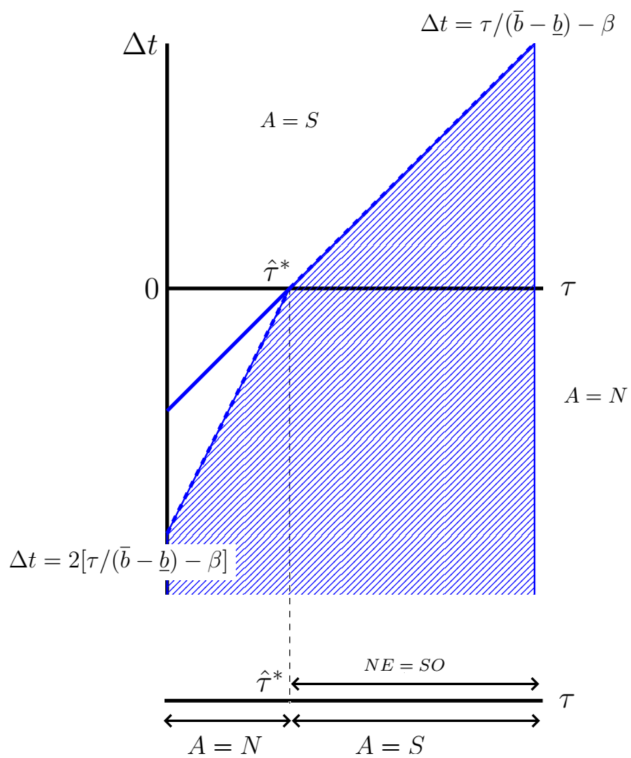

Figure 2.A.10: Nash equilibrium tax difference and assembly location under high unbundling costs.

2.A.4 Nash Equilibrium Outcome Under Low Unbundling Costs

As noted in Appendix 2.A.2, the indirect utility of the representative agent in each country is given by

$$V_N = \begin{cases} V_N|_{A=S} = \widetilde{u} - C_S + t_N(\bar{b} - b_S) - (\gamma/2)(\bar{b} - b_S)^2 + 1 + \overline{\Lambda} & \text{if } \tau < \tau^{**} \\ V_N|_{A=N} = \widetilde{u} - C_N + t_N(\bar{b} - b_N) - (\gamma/2)(\bar{b} - b_N)^2 + 1 + \overline{\Lambda} & \text{if } \tau \geq \tau^{**} \end{cases},$$

$$V_S = \begin{cases} V_S|_{A=S} = t_S(b_S - \underline{b}) - (\gamma/2)(b_S - \underline{b})^2 + 1 + \overline{\Lambda} & \text{if } \tau < \tau^{**} \\ V_S|_{A=N} = t_S(b_N - \underline{b}) - (\gamma/2)(b_N - \underline{b})^2 + 1 + \overline{\Lambda} & \text{if } \tau \geq \tau^{**} \end{cases},$$

where C_i is defined in (6) and (7); and $\tau^{**} \equiv 2\theta(\beta + \Delta t)$; $b_N = 1 - \theta + \Delta t$; $b_S = 1 + \theta + \Delta t$.

(i) First, we derive the best responses of each country with exogenous assembly location.

N's best response given t_S and $A = N$ is

$$\tilde{t}_N^{BR}(t_S)|_{A=N} \equiv t_N = \frac{\gamma}{1+\gamma} t_S + \frac{\gamma}{1+\gamma}(\bar{b} - 1 + \theta).$$

N's best response given t_S and $A = S$ is

$$\tilde{t}_N^{BR}(t_S)|_{A=S} \equiv t_N = \frac{\gamma}{1+\gamma}t_S + \frac{\gamma}{1+\gamma}(\bar{b} - 1 - \theta).$$

S's best response given t_N and $A = N$ is

$$\tilde{t}_S^{BR}(t_N)|_{A=N} \equiv t_S = \frac{1+\gamma}{2+\gamma}t_N + \frac{1+\gamma}{2+\gamma}(1 - \theta - \underline{b}).$$

S's best response given t_N and $A = S$ is

$$\tilde{t}_S^{BR}(t_N)|_{A=S} \equiv t_S = \frac{1+\gamma}{2+\gamma}t_N + \frac{1+\gamma}{2+\gamma}(1 + \theta - \underline{b}).$$

(ii) Second, we allow for endogenous location and derive S's best response with endogenous assembly given t_N.

$$t_S^{BR}(t_N) = \begin{cases} \tilde{t}_S^{BR}(t_N)|_{A=N} & \text{if } \; t_N < \widehat{t}_N^* \\ t_S|_{A=S} = t_N - \tau/(2\theta) + \beta & \text{if } \; \widehat{t}_N^* \leq t_N \leq t_N^1 \\ \tilde{t}_S^{BR}(t_N)|_{A=S} & \text{if } \; t_N > t_N^1 \end{cases},$$

where $\widehat{t}_N^* = \tau(2+\gamma)/(2\theta) + (3+\gamma)\theta + (\gamma/2)(\bar{b} - \underline{b}) + (\bar{b} - 1) - \sqrt{2(2+\gamma)\tau + 2\theta(2+\gamma)(\bar{b} - \underline{b} + 2\theta)}$ is the switching point of assembly location at which S is indifferent to where assembly takes place; $t_N^1 = (2+\gamma)[\tau/(2\theta) - \gamma] + (1+\gamma)(1 + \theta - \underline{b})$.[20] It is illustrated in Figure 2.A.11.

[20]We need to assume that $\theta < (\bar{b} - \underline{b})/2(1+\gamma)$ to avoid the case where the switching point falls between the two exogenous best response lines. The assumption is reasonable since we restrict our attention to the case of low unbundling costs.

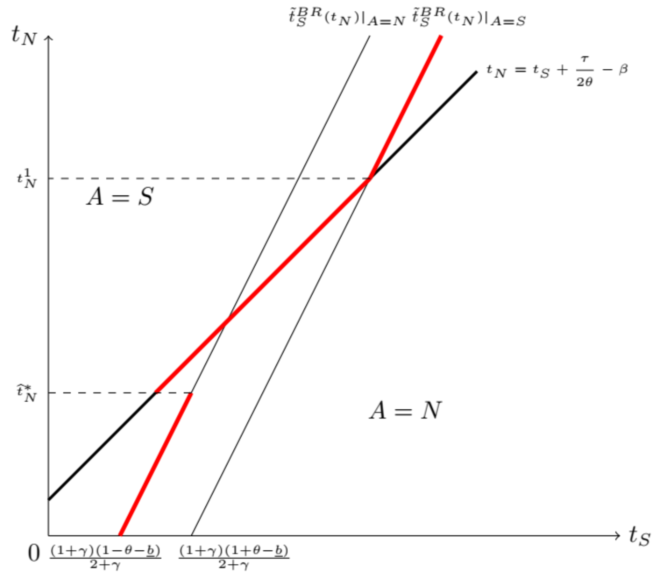

Figure 2.A.11: S's best response with endogenous assembly location (red curve).

(iii) Third, we allow for endogenous location and derive N's best response given t_S.

$$t_N^{BR}(t_S) = \begin{cases} \tilde{t}_N^{BR}(t_S)|_{A=S} & \text{if } \ t_S < t_S^1 \\ t_N|_{A=S} \equiv t_S + \tau/(2\theta) - \beta & \text{if } \ t_S^1 \leq t_S \leq \widehat{t}_S^* \\ t_N|_{A=N} \equiv t_S + \tau/(2\theta) - \beta & \text{if } \ \widehat{t}_S^* < t_S \leq t_S^2 \\ \tilde{t}_N^{BR}(t_N)|_{A=N} & \text{if } \ t_S > t_S^2 \end{cases},$$

where $\widehat{t}_S^* \equiv \gamma(\overline{b}-1) - (1+\gamma)[\tau/(2\theta) - \beta]$ is the switching point of assembly location at which N is indifferent to where assembly takes place; $t_S^1 \equiv \gamma(\overline{b}-1-\theta) - (1+\gamma)[\tau/(2\theta) - \beta]$; $t_S^2 \equiv \gamma(\overline{b}-1+\theta) - (1+\gamma)[\tau/(2\theta) - \beta]$. Note that $\widehat{t}_S^* = (t_S^1 + t_S^2)/2$. N's best response is illustrated in Figure 2.A.12.

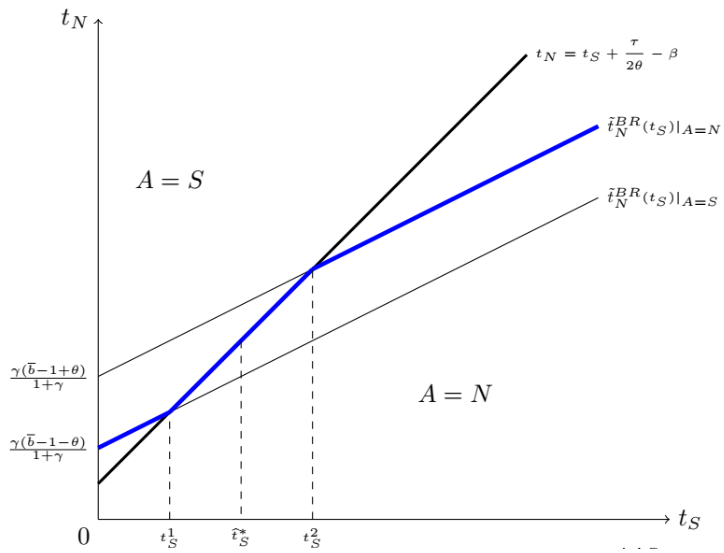

Figure 2.A.12: S's best response with endogenous assembly location (blue curve).

(iv) Fourth, we derive Nash equilibria with endogenous assembly location. We only need to combine the best responses of the two countries together and then to see whether there exist intersections or overlapping lines. Figure 2.A.13 draws the cost-indifference line at $\tau = 0$, i.e., $\tau^{**} \equiv 2\theta(\beta + \Delta t) = 0$, or $t_N = t_S - \beta$. Note that the cost-indifference line locates above the intersection of $\tilde{t}_N^{BR}(t_S)|_{A=S}$ and $\tilde{t}_S^{BR}(t_N)|_{A=S}$. Therefore, there are two types of Nash equilibria depending on τ: one characterized by the cost-indifference line; the other by the intersection of $\tilde{t}_N^{BR}(t_S)|_{A=N}$ and $\tilde{t}_S^{BR}(t_N)|_{A=N}$, i.e., point B.

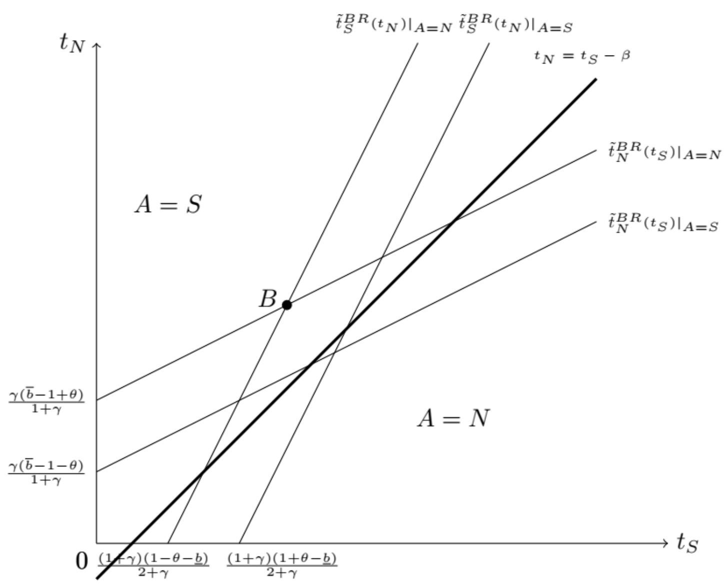

Figure 2.A.13: Cost-indifference line at $\tau = 0$.

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We have seen that N is indifferent to where assembly takes place if $t_N = t_N^*$, so is S at $t_S = \widehat{t}_S^*$, or equivalently $t_N = \widehat{t}_N^{**} \equiv \widehat{t}_S^* + \tau/(2\theta) - \beta$. Noting that the two countries' switching points are $\widehat{t}_N^*$ and $\widehat{t}_N^{**}$, the two switching points are equalized at[21]

$$\tau_1 \equiv \frac{\theta\left[\sqrt{\theta(2+\gamma)\{2\gamma^2(\theta+\bar{b}-\underline{b})+\gamma(2+2\bar{b}-4\underline{b}+\theta)\}+2(1-\underline{b})}-(\gamma^2+3\gamma+1)\theta-(\bar{b}-1)(1+\gamma)\right]}{(1+\gamma)^2}.$$

Then, for $\tau < \tau_1$, the Nash equilibria occur on the cost-indifference line where $\Delta t|_{A=S}^{NE} = \tau/(2\theta) - \beta$ (see Figure 2.A.15). At point B, N's and S's pollution taxes are

$$t_N^B = \frac{\gamma(2+\gamma)}{2(1+\gamma)}(\bar{b}-1+\theta) + \frac{\gamma}{2}(1-\theta-\underline{b}),$$

$$t_S^B = \frac{\gamma}{2}(\bar{b}-1+\theta) + \frac{1+\gamma}{2}(1-\theta-\underline{b}).$$

Equalizing t_N^B and $\widehat{t}_N^*$ gives

$$\tau_2 \equiv \frac{\theta\left[2\sqrt{2\theta(1+\gamma)\left[\gamma^2(\bar{b}-\underline{b})+\gamma(\theta+1+2\bar{b}-3\underline{b})\right]+2(1-\underline{b})}-\theta(2\gamma^2+3\gamma+2)-(\bar{b}-1)(2+\gamma)\right]}{(1+\gamma)(2+\gamma)}$$

Then, for $\tau > \tau_2$ the Nash equilibrium occurs at point B where $\Delta t|_{A=N}^{NE} = \gamma(\bar{b}-1+\theta)/[2(\gamma+1)] - (1-\theta-\underline{b})/2$ (see Figure 2.A.18).

For $\tau_1 \leq \tau \leq \tau_2$, there are two possible cases: (a) both countries still impose pollution taxes along the cost-indifference line, but they choose different assembly locations (see Figure 2.A.16); (b) their best-response curves have neither intersections nor overlapping parts (see Figure 2.A.17). In both cases, there is no Nash equilibrium.

To conclude, we have

$$\Delta t^{NE} = \begin{cases} \Delta t|_{A=S}^{NE} \equiv \tau/(2\theta) - \beta & \text{if } \ \tau < \tau_1 \\ \text{No Nash equilibrium} & \text{if } \ \tau_1 \leq \tau \leq \tau_2 \\ \Delta t|_{A=N}^{NE} \equiv \gamma(\bar{b}-1+\theta)/[2(\gamma+1)] - (1-\theta-\underline{b})/2 & \text{if } \ \tau > \tau_2 \end{cases},$$

which is shown in Figure 2.A.14. The Nash equilibria coincide with the socially optimal outcomes only for $\tau \in (\tau^a, \widehat{\tau}^{**})$, which is narrower than $\tau \geq \widehat{\tau}^*$. We can thus conclude that the decentralized

[21] It can checked that $\partial \widehat{t}_N^*/\partial\tau > 0$; $\partial \widehat{t}_N^{**}/\partial\tau < 0$; and $\widehat{t}_N^* < \widehat{t}_N^{**}$ holds at $\tau = 0$.

policy outcomes are more likely to deviate from the socially optimal ones in the age of the second unbundling.

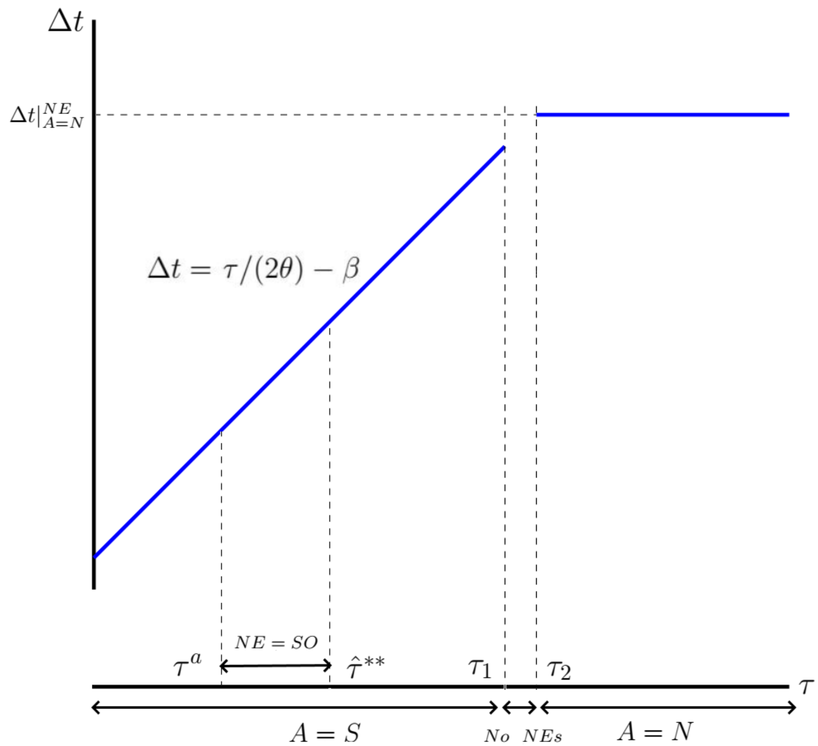

Figure 2.A.14: Nash equilibrium tax difference (blue line) and assebly location under low unbundling costs.

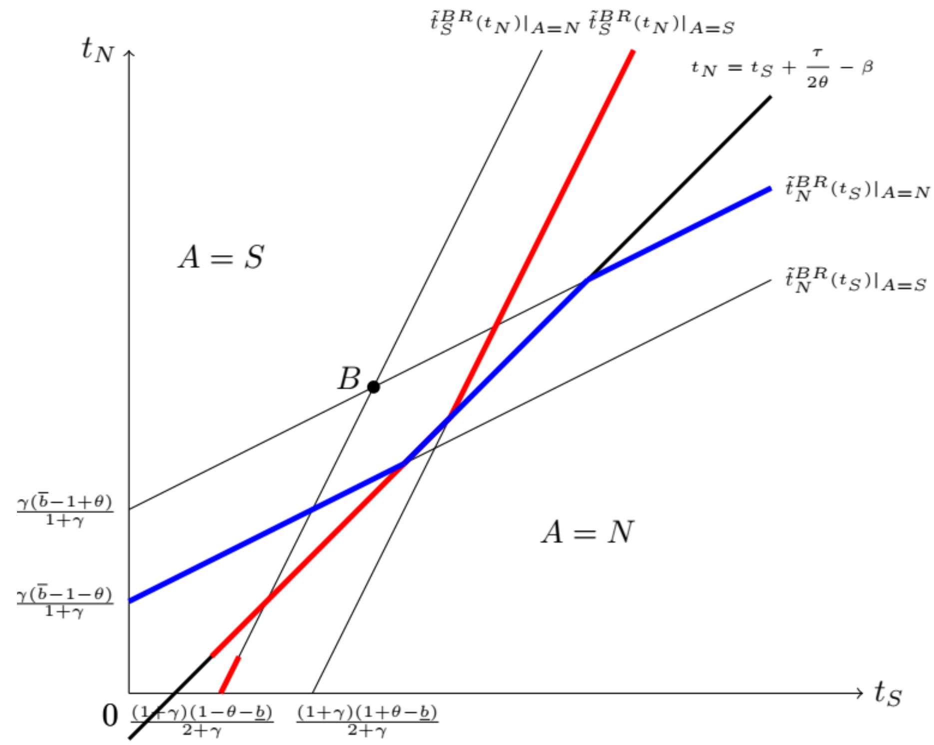

Figure 2.A.15: Nash equilibrium for $\tau < \tau_1$.

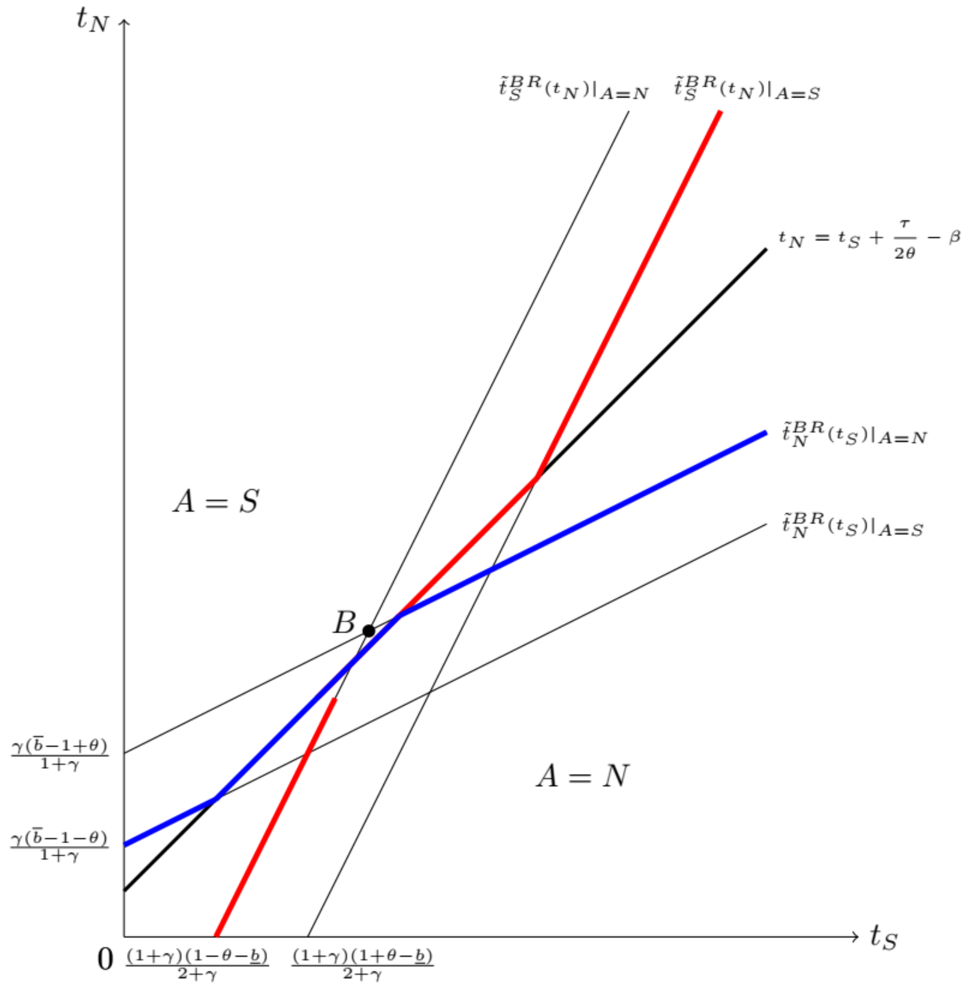

Figure 2.A.16: Case (a) for $\tau_1 \leq \tau \leq \tau_2$: overlapping line with different assembly location.

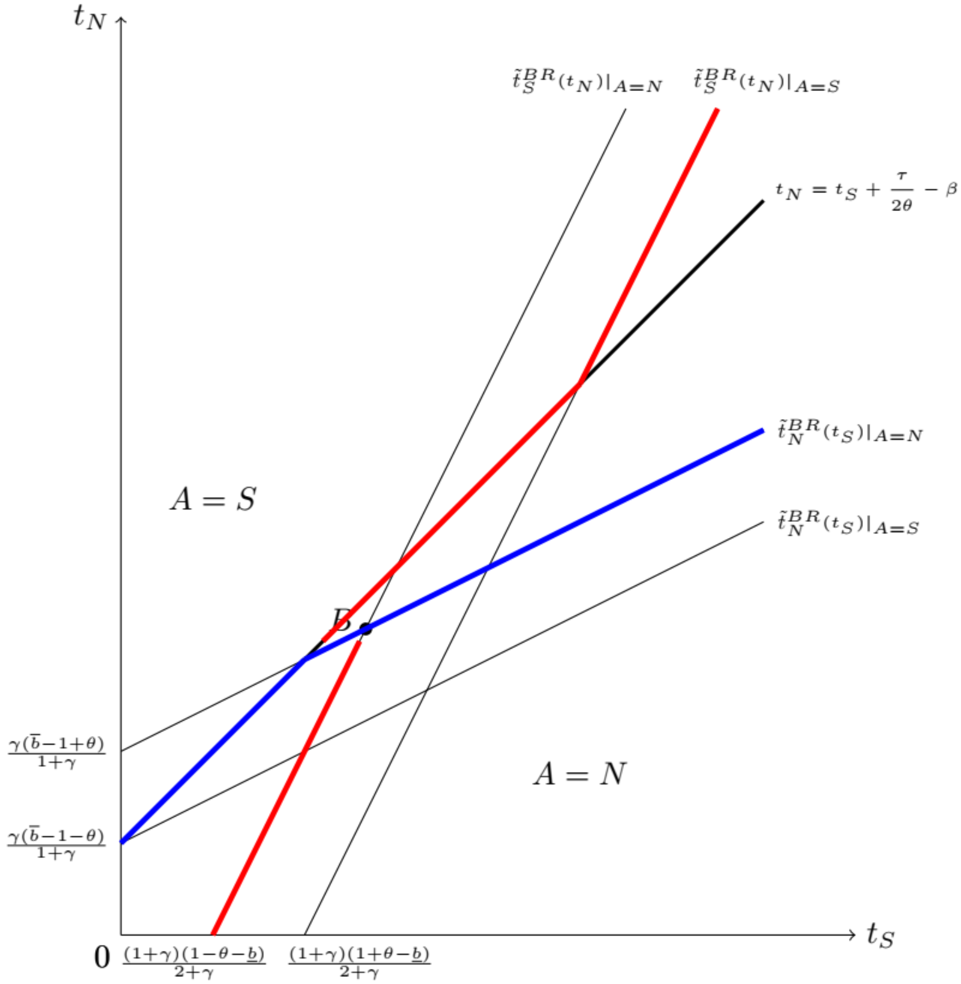

Figure 2.A.17: Case (b) for $\tau_1 \leq \tau \leq \tau_2$: no intersections.

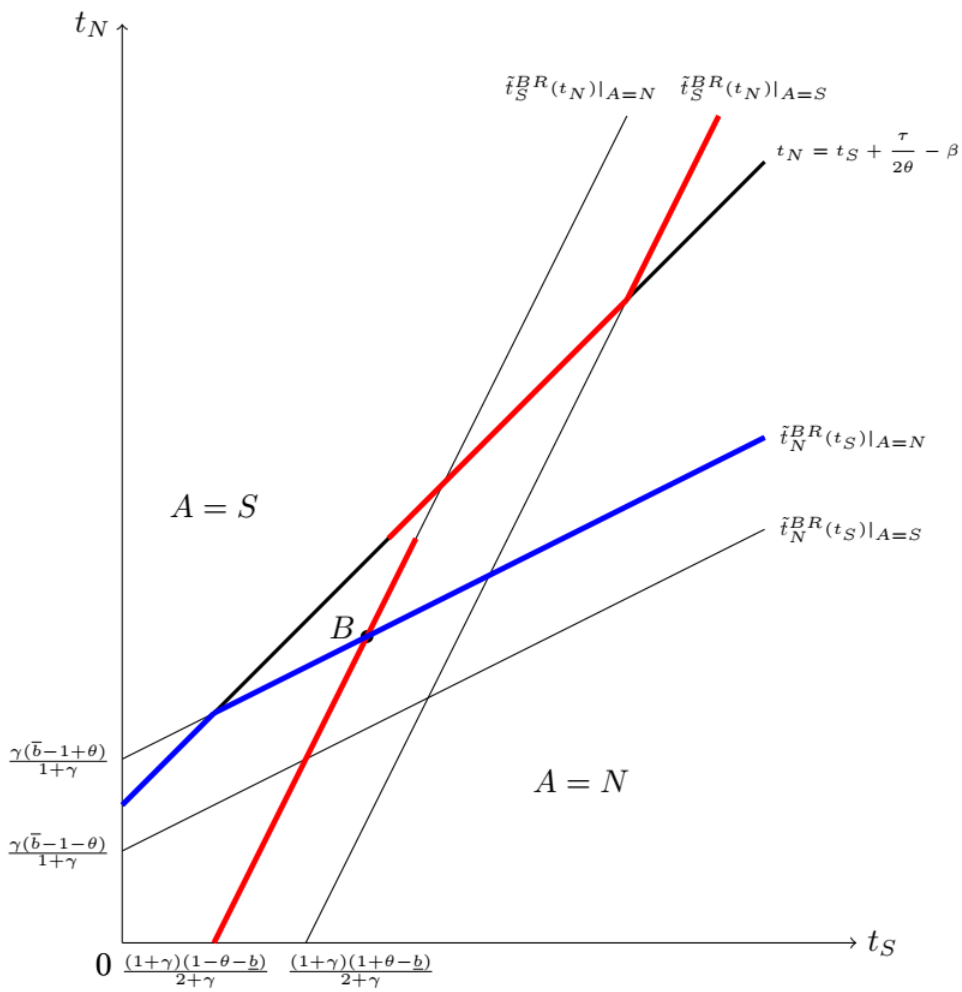

Figure 2.A.18: Nash equilibrium for $\tau > \tau_2$.

2.A.5 Discussion: Global Pollution

Due to the perfectly inelastic demand assumption about the final good, our model is not suitable to analyze global pollution, i.e., $e_N + e_S = \overline{b} - \underline{b}$ is always constant before and after the second unbundling. A potential way to consider global pollution is to assume asymmetric pollution intensities across countries. For instance, we can assume that the pollution per unit of production is 1 in North and $\delta > 1$ in South. The higher the level of δ is, the more likely it is that the assembly would be located in North. When unbundling costs are high, environmental tax harmonization may not be socially desirable for some trade costs; however, we can find that $t_N - \delta t_S = -\frac{\gamma}{2}(\overline{b} + \underline{b})(\delta^2 - 1)$ is always socially desirable as shown in Figure 2.A.19 where $\hat{\tau} = (\overline{b} - \underline{b})\beta - \frac{\gamma}{2}(\overline{b} - \underline{b})^2(\delta^2 - 1)$. When unbundling costs are low, environmental taxes affect not only the assembly location but also the offshoring patterns; it is intuitive that a simple environmental tax set cannot always be socially desirable. Therefore, the essence of this chapter would not change. That is, under high unbundling costs, a simple environmental tax set can always be socially desirable, the social planner does not need to adjust the tax rates as trade costs decline; under low unbundling costs, more international coordination is needed.

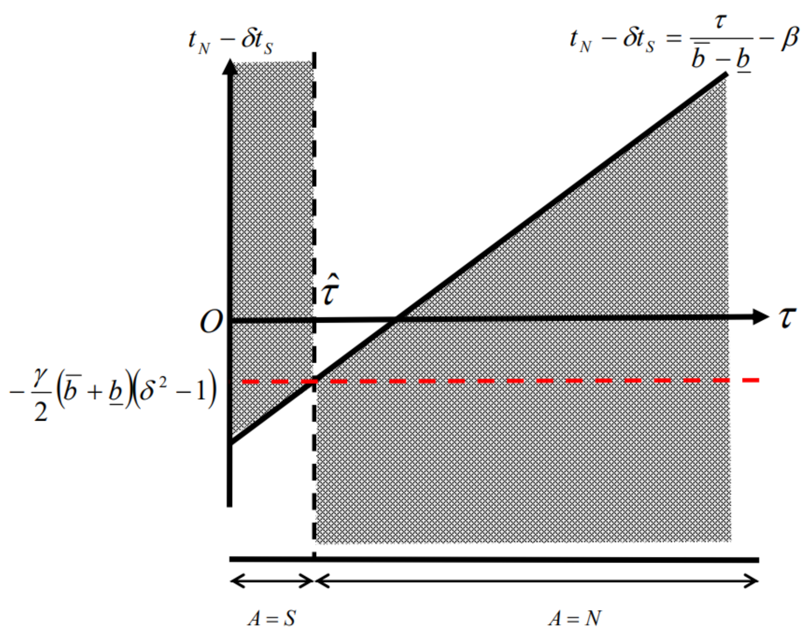

Figure 2.A.19: Socially optimal tax difference (shaded areas) and assembly location under high unbundling costs and asymmetric pollution intensities.

Chapter 3

Trade, Consumption Pollution and Tax

3.1 Introduction

Previous research on trade and the environment strongly focuses on emissions from the production side; however, less attention is paid to the consumption side.[1] Consumption is an important source of GHG emissions, such as fossil fuel combustion for cooking, heating and transportation needs and leaks from refrigerants in businesses and homes. According to the US Environmental Protection Agency, direct GHG emissions from residents and businesses (excluding agricultural and industrial activities) accounted for approximately 11.6 percent of total US GHG emissions in 2017. Besides, the Japanese Ministry of the Environment announced that the commercial and residential sectors generated about 33.4 percent of Japanese CO_2 emissions in 2016.

GHG emissions from the production and consumption sides should be distinguished. Production emissions occur where the dirty goods are produced, while consumption emissions appear where they are consumed. Due to this difference, the behaviors of consumers, firms and countries can also be different in the presence of environmental regulations. For instance, if a country becomes a periphery with no firm, its domestic environmental regulation does not affect production emissions any more because there is no production there. But it still affects consumption emissions as long as the residents consume imported goods.

We intend to investigate environmental issues of consumption in this paper. Specifically, we investigate how trade liberalization and environmental taxes affect GHG emissions and examine

[1] Examples of papers dealing with production pollution are Markusen et al. (1993, 1995) and Copeland and Taylor (1994, 1995b) among others. Compared to the little attention to consumption emissions in the theoretical literature, the empirical literature has already investigated a lot, e.g., Druckman et al. (2008), Wiedmann (2009) and Davis and Caldeira (2010).

how heterogeneous countries choose their tax levels cooperatively and non-cooperatively. To do so, we employ the footloose capital model in Martin and Rogers (1995) which is feasible to emphasize diversity of goods and endogenous firm locations which are key features of today's trade liberalization. To do policy analysis, we assume an ad valorem consumption tax on consumers as the (indirect) environmental instrument. Changing the consumption tax into an emission tax has no impact on our main conclusions; however, we will lose the tractability and feasibility of the analysis in the current model. An example of a consumption tax functioning as environmental regulation is the tax on the consumption of fossil fuel. Several governments, such as Norway and the UK, impose a fuel tax as an ecotax to control CO_2 emissions from vehicles. We consider heterogeneous countries to capture the fact that not only developed countries but also developing countries are obliged to control GHG emissions under the Paris Agreement.

To analyze how trade liberalization and consumption taxes affect GHG emissions, we decompose the total effect into a firm-relocation effect and a demand effect. The firm-relocation effect describes the changes in GHG emissions due to the relocation of firms. It differs from the composition effect discussed in previous research in that the composition effect measures the reallocation of production factors across relatively clean and dirty goods. The net firm-relocation effect is always neutral in the model. The demand effect captures the changes in GHG emissions due to the changes in the consumption of dirty goods. It plays an essential role in the following analyses. Given a consumption tax, as trade costs decline, the demand effect tends to initially decrease global emissions and then increase them. We can understand the intuition behind the non-monotonicity as follows. The consumption level of dirty goods in free trade is equal to that in autarky because there are no trade costs in either case. However, under trade with costs, consumers have to pay the extra trade costs, which decreases the consumption scale around the world. Hence, GHG emissions are lower than the two extreme cases.

The literature has not achieved a consensus on how trade affects the environment. Previous theoretical analyses with neo-classical settings show that free trade can increase world pollution (e.g., Copeland and Taylor, 1994, 1995b). On the other hand, Antweiler et al. (2001) empirically find that openness to international goods market appears to be good for the environment and they explain it because trade increases the income level and induces the development of cleaner production technology. Our finding suggests an alternative answer to the question through the substitution between variety and quantity. Trade may reduce the world consumption and pollution by increasing the varieties of consumption goods.

Given trade costs, as the consumption tax increases in either country, local emissions decrease in that country and increase in the other country; global emissions always decline because the demand effect is always negative. There exist many studies examining carbon leakage under production emissions, claiming that a more stringent environmental regulation in a country increases other countries' emissions (e.g., Markusen et al., 1993, 1995). Our finding indicates that carbon leakage still exists under consumption pollution. Intuitively, an increase in the consumption tax in a country decreases its consumption scale and thus its emissions from consumption. However, it is not straightforward why consumption emissions in the other country increase.

In the welfare analysis, we first focus on the global optimum to see what countries should do cooperatively. The analysis shows how supranational regimes (e.g., EU) should design an environmental tax to control GHG emissions. We find that if firms initially disperse across countries under no environmental regulation, identical consumption taxes are globally desirable regardless of market sizes. The finding is related to the literature on environmental tax harmonization, which seeks to construct a simple policy to deal with complicated environmental problems especially in the presence of heterogeneous countries (e.g., Vlassis, 2013; Cremer and Gahvari, 2004; Cheng et al., 2020) Among others, Cheng et al. (2020) examine whether environmental tax harmonization is globally desirable in global value chains given that countries differ in their average cost advantages of input production. They find that environmental tax harmonization is socially optimal when unbundling costs are high, but not when unbundling costs are low. Compared to theirs, our finding does not depend on the levels of trade costs; besides, the model settings about production process, market structure, environmental issues and country heterogeneity are different. In consumption tax competition, we investigate how countries choose their taxes in the presence of endogenous firm locations and how market sizes affect the decisions of them. We show that there may exist a Nash equilibrium where firms disperse across countries and the consumption tax is always higher in the larger country. The analysis is related to the literature on environmental tax competition in the presence of imperfect competition and endogenous firm locations (e.g., Markusen et al., 1995; Rauscher, 1995; Hoel, 1997; Dong et al., 2012). Markusen et al. (1995) and Hoel (1997) claim that optimal environmental taxes at the Nash equilibrium depend on the marginal environmental damage, which is also revealed in our results. Dong et al. (2012) show that countries' choices are relevant to their market sizes which are assumed to be identical. Different from their analyses, we emphasize the asymmetry of market sizes.

3.1.1 Related Literature

This paper follows the literature on new economic geography and the environment. Examples are Zeng and Zhao (2009), Ishikawa and Okubo (2011, 2016, 2017). The basic setup in this paper is very close to Ishikawa and Okubo (2011).[2] However, they only analyze unilateral environmental

[2]The other three papers cited here all focus on production pollution. Zeng and Zhao (2009) investigate the effect of production pollution on agricultural productivity, while Ishikawa and Okubo (2016, 2017) investigate the effect of

product standards and do not look further through a welfare analysis. By contrast, we investigate bilateral consumption taxes in both countries and derive the global and national optima, which is the main contribution here to the previous literature. The examination of how consumption taxes affect firm behaviors and GHG emissions is quite similar to the analysis of full border tax adjustments (BTAs) in Ishikawa and Okubo (2017) in that environmental regulation appears in the consumption country. However, they focus on a comparison of unilateral emission quotas and emission taxes in the presence of GHG emissions from production, and derive a neutral effect of BTAs on firm locations which is different from the finding in this paper.

Ishikawa and Okubo (2016) also find a non-monotonic effect of trade liberalization on the GHG emissions in a model where the emissions originate from production. Our mechanism is different from theirs. First, in their model, trade liberalization affects the global emissions only when the emission tax is strictly positive; if the tax rate is zero, the global emissions are independent of trade costs. However, our result holds even without the environmental tax. Second, if our model is modified so that the emissions originate from production instead of consumption, trade liberalization actually has no effect on the global emissions. Therefore, the distinction of the consumption emissions and the production emissions is important.

Although few, some papers do exist examining trade and consumption pollution (e.g., Krutilla, 1991; Copeland and Taylor, 1995a; Ishikawa and Kuroda, 2007; Ishikawa and Okubo, 2010, 2011; Hu and McKitrick, 2016). Krutilla (1991) derives a series of second-best consumption taxes with the existence of production and consumption pollution and concludes that environmental production and consumption taxes affect the world price and trade balance in the opposite direction. Ishikawa and Kuroda (2007) and Ishikawa and Okubo (2010) examine and compare the effectiveness of various taxes in reducing emissions from production and (or) consumption. They find that emission taxes may not be very effective to decrease consumption emissions compared to other taxes such as production taxes and tariffs. Hu and McKitrick (2016) compare production and consumption pollution with a model similar to Antweiler et al. (2001) and find that trade liberalization affects the two kinds of pollution differently through trade-induced composition effects. Copeland and Taylor (1995a) employ a traditional Heckscher-Ohlin model and verify that the dirty industry migration hypothesis is still valid in the presence of local consumption pollution. Compared to their findings, we demonstrate that whether firms migrate to countries with laxer environmental regulations also depends on market size. Except Ishikawa and Okubo (2011), the papers mentioned in this strand consider neither endogenous firm locations nor the monopolistic competition.

This paper can also be treated as a complement to the literature on the conventional trade policy competition and coordination (e.g., Ludema and Wooton, 2000; Baldwin and Krugman,

production pollution on residents.

2004; Haufler and Wooton, 2010; Haufler and Pflüger, 2004). The basic setup of this paper is similar to the tax regime based on destination principle in Haufler and Pflüger (2004). However, they do not consider asymmetric market sizes, full agglomeration of firms and environmental issues. With consumption externality, governments take into account not only consumer surplus and tax revenue but also environmental damage. If environmental damage is large, governments are likely to impose stringent environmental regulation (or lower consumption subsidies), although it hurts consumer surplus.

The remainder of this chapter is organized as follows. Section 3.2 introduces the basic setup of the model. Section 3.3 derives the equilibrium in trade with footloose capital and investigates how trade liberalization and consumption taxes affect firm locations and GHG emissions. Sections 3.4 studies the global optimum. Section 3.5 discusses the consumption tax competition respectively. Section 3.6 concludes the chapter.

3.2 The Basic Model

The basic model extends the footloose capital model in Martin and Rogers (1995) by including the GHG emissions from consumption and consumption taxes. Consider a world with two countries called Home and Foreign and two factors named capital and labor. Individuals in each country consume two types of goods: a dirty manufacturing good with different varieties and a clean agricultural good. Each firm produces a variety of dirty goods at a fixed cost of one unit of capital; besides, one unit of dirty goods requires one unit of labor.[3] Dirty goods are traded with symmetric trade costs τ of the "iceberg" form such that τ units of dirty goods are traded for one unit that is eventually consumed. The clean good is the numéraire. It is homogeneous and freely tradeable. The production of clean goods is subject to constant returns to scale, and each unit of them is produced by one unit of labor. The wage rates across countries are equalized due to the existence of the numéraire, and they are normalized to 1 for simplicity. Denote labor and capital stock in Home as L and K, and those in Foreign as L^* and K^*.[4] The two production factors are distributed proportionately across countries, and capital is distributed uniformly across residents within each country. Denote s as the share of the world's labor and capital belonging to Home, i.e., $L/(L+L^*) = K/(K+K^*) = s$. Without loss of generality, the total levels of capital and labor are both normalized to unity; assume that Home owns a larger market size ($s > 1/2$). Labor is immobile across countries but can freely move across sectors and firms. Capital is mobile across countries and capital rents are paid to the local owners. GHG emissions are generated during the consumption of dirty goods, with one unit of dirty goods emitting one unit of GHG. Governments impose ad valorem consumption taxes on

[3] Note that the term of "firm" only refers to the producers of dirty goods throughout this chapter.

[4] Variables in Foreign are denoted with asterisks throughout this chapter.

consumers to control GHG emissions under the requirements of environmental agreements such as the Paris Agreement.

The utility of a representative individual in Home is described as a quasi-linear function:

$$U = \mu \ln M + A - D(E^G) \tag{3.1}$$

where

$$M \equiv \left(n x^{HH^{1-\frac{1}{\sigma}}} + n^* x^{FH^{1-\frac{1}{\sigma}}} \right)^{\frac{\sigma}{\sigma-1}} \tag{3.2}$$

is the CES composite consumption of the dirty manufacturing varieties and A is the consumption of the numéraire. $D(\cdot)$ is the damage function of GHG emissions. E^G represents the global level of GHG emissions. n is the number (or the *ratio*) of differentiated varieties in Home, and n^* is that in Foreign. x^{HH} denotes the quantity of Home consumption of each variety produced in Home, x^{FH} is the counterpart produced in Foreign. Note that the first capital letter in the superscript represents the location of production and the second represents the location of consumption. $\sigma > 1$ is the constant elasticity of substitution between different varieties, as is usually observed in the CES function. μ is the intensity of preference toward good M. The larger the value of μ is, the more the individual spends on dirty goods.

The budget constraint of the representative individual in Home is

$$np(1+t)x^{HH} + n^* \tau p^* (1+t) x^{FH} + A = I/L. \tag{3.3}$$

$I = L + rK + TR$ denotes the total income where r is the capital rents in Home and $TR = Lt\left(npx^{HH} + n^* \tau p^* x^{FH}\right)$ is the total tax revenue, with t representing the Home ad valorem consumption tax. The term x^{FH} but not x^{HF} enters into the total tax revenue because the consumption tax is imposed on consumers but not producers. p and p^* are the pre-trade prices of dirty goods in each country, τp^* is the import price of Foreign dirty goods in Home adjusted by trade costs. Similarly, the utility function and corresponding variables for Foreign can be derived. For simplicity, μ and σ are assumed to be the same across countries.

The aggregate price index facing the individual in Home is

$$P = (1+t)\left[np^{1-\sigma} + n^*(\tau p^*)^{1-\sigma}\right]^{\frac{1}{1-\sigma}}. \tag{3.4}$$

Unlike a tax on producers, a country's consumption tax cannot affect the aggregate price in the other country directly. However, the indirect channel still exists through the effect of the consumption tax on firm locations. On the other hand, trade liberalization can affect the aggregate prices in the two countries both directly and indirectly.

The consumption of each Home- and Foreign-produced variety in Home and Foreign is

$$x^{HH} = \mu P^{\sigma-1}\left[p(1+t)\right]^{-\sigma}; \quad x^{FH} = \mu P^{\sigma-1}\left[\tau p^*(1+t)\right]^{-\sigma}; \tag{3.5}$$

$$x^{FF} = \mu P^{*\sigma-1}\left[p^*(1+t^*)\right]^{-\sigma}; \quad x^{HF} = \mu P^{*\sigma-1}\left[\tau p(1+t^*)\right]^{-\sigma}. \tag{3.6}$$

For a representative firm in Home and Foreign, if any, its capital rents are

$$r = (p-1)Y; \quad r^* = (p^*-1)Y^*; \tag{3.7}$$

where

$$Y = sx^{HH} + (1-s)\tau x^{HF}; \quad Y^* = s\tau x^{FH} + (1-s)x^{FF} \tag{3.8}$$

are the total production of each variety. The markup pricing rule of the Dixit-Stiglitz monopolistic competition model in Dixit and Stiglitz (1977) still holds here, and the identical pre-tax prices across varieties are derived as

$$p = p^* = \sigma/(\sigma-1). \tag{3.9}$$

3.3 Trade Equilibrium

In the section, we will derive the trade equilibrium and examine how the location patterns of firms affect consumption and the resulting GHG emissions when they are endogenously determined by trade costs and the consumption tax. At trade equilibrium, there are two possible cases. In the first case, firms disperse across countries; in the second case, full agglomeration of firms occurs in one country.

If the difference between consumption taxes is moderate, firms disperse across countries, i.e., $s\tau^{1-\sigma}/(1-s) < (1+t)/(1+t^*) < s\tau^{\sigma-1}/(1-s)$. The difference between capital rents in the two countries is

$$\begin{aligned}\Delta r = r - r^* &= (p-1)Y - (p^*-1)Y^* = (Y-Y^*)/(\sigma-1)\\ &= \mu(\tau^\sigma - \tau)\left[\frac{s}{(1+t)(n\tau^\sigma + n^*\tau)} - \frac{1-s}{(1+t^*)(n\tau + n^*\tau^\sigma)}\right].\end{aligned} \tag{3.10}$$

Because capital is footloose across countries, no arbitrage exists. capital rents are the same ($r = r^*$), which in turn equalizes the total production of each variety ($Y = Y^*$).

Along with the condition that $n + n^* = K + K^* = 1$, the number of firms (or varieties) in Home and Foreign are derived as

$$n = \frac{1}{\tau^{\sigma-1}-1}\frac{s(1+t^*)\tau^{\sigma-1}-(1-s)(1+t)}{s(1+t^*)+(1-s)(1+t)}; \quad n^* = 1-n. \tag{3.11}$$

Lemma 3.1. *When firms disperse across countries,*
(i) *an increase in a country's consumption tax induces firms to relocate to the other country, i.e.,* $\mathrm{d}n/\mathrm{d}t < 0$, $\mathrm{d}n^*/\mathrm{d}t^* < 0$.
(ii) *how trade liberalization affects firm locations depends on the strengths between the market sizes and consumption taxes, i.e.,*

$$\frac{\mathrm{d}n}{\mathrm{d}\tau} = \frac{(\sigma-1)\tau^{\sigma-2}(1+t)(1+t^*)}{(\tau^{\sigma-1}-1)^2\left[s(1+t^*)+(1-s)(1+t)\right]}\left(\frac{1-s}{1+t^*}-\frac{s}{1+t}\right). \tag{3.12}$$

To understand the intuitions behind the findings, we first investigate how the number of firms and consumption tax affect the capital rents difference in equation (3.10). First, as more firms locate in Home, Home market becomes more competitive, lowering the capital rents of each firm ($\partial\Delta r/\partial n < 0$). Second, as the consumption tax in Home increases, residents consume fewer of each variety of dirty goods, capital rents in both Home and Foreign decreases; however, firms suffer more in Home because residents in Home consume more of each Home variety, which makes Foreign more attractive ($\partial\Delta r/\partial t < 0$). At the trade equilibrium, $\Delta r = 0$. In Lemma 3.1-(i), as t increases, capital rents in Foreign becomes relatively higher, firms relocate from Home to Foreign until the capital rents are equalized again. In Lemma 3.1-(ii), suppose there are no consumption taxes, then our model collapses into the traditional footloose model; firms locate in the larger country more than proportionately and trade liberalization strengthens up the tendency until firms fully agglomerate in the larger country, i.e., $\partial\Delta r/\partial\tau|_{t=t^*=0} < 0$, $\partial\Delta r/\partial n|_{t=t^*=0} < 0$, $\mathrm{d}n/\mathrm{d}\tau|_{t=t^*=0} < 0$. However, the relationship between trade liberalization and capital rents difference is ambiguous in the presence of consumption taxes because consumption taxes play a role in shrinking the market. Therefore, how trade liberalization affects firm locations depends on to what extent the consumption tax shrinks the market. Suppose $t > t^*$. If t is sufficiently high so that $(1-s)/(1+t^*) > s/(1+t)$, firms relocate to Foreign under trade liberalization because the *effective* market size is higher in Foreign. If t is not so high that $(1-s)/(1+t^*) < s/(1+t)$, trade liberalization induces firms to relocate to the country with a higher consumption tax. If t fully offsets Home's market size advantage, i.e., $(1-s)/(1+t^*) = s/(1+t)$, trade liberalization has no effect on firm locations, which is the same as the case of symmetric market sizes in the footloose capital model.

The specific levels of each type of consumption are

$$x^{HH} = \frac{\mu(\sigma-1)}{\sigma}\frac{\tau^\sigma}{\tau^\sigma+\tau}\left(\frac{1}{1+t}+\frac{1-s}{s}\frac{1}{1+t^*}\right); \quad x^{FH} = \frac{x^{HH}}{\tau^\sigma}; \tag{3.13}$$

$$x^{FF} = \frac{\mu(\sigma-1)}{\sigma}\frac{\tau^\sigma}{\tau^\sigma+\tau}\left(\frac{1}{1+t^*}+\frac{s}{1-s}\frac{1}{1+t}\right); \quad x^{HF} = \frac{x^{HF}}{\tau^\sigma}. \tag{3.14}$$

Lemma 3.2. *When firms disperse across countries,*
(i) $x^{HH} > x^{FH}$, $x^{FF} > x^{HF}$*;*
(ii) $\frac{\mathrm{d}x^{HH}}{\mathrm{d}\tau} > 0$, $\frac{\mathrm{d}x^{FH}}{\mathrm{d}\tau} < 0$, $\frac{\mathrm{d}x^{FF}}{\mathrm{d}\tau} > 0$, $\frac{\mathrm{d}x^{HF}}{\mathrm{d}\tau} < 0$*;*
(iii) $\frac{\mathrm{d}x^{ij}}{\mathrm{d}t} < 0$, $\frac{\mathrm{d}x^{ij}}{\mathrm{d}t^*} < 0$ *where* $i, j = H, F$*.*

The consumption of domestic dirty goods is always larger than that of imported goods due to trade costs. Trade liberalization raises the consumption of each imported variety and decreases that of each domestic variety because the imported varieties become relatively cheaper as trade costs decline. In addition, an increase in the consumption tax of either country always reduces the consumption of each variety of dirty goods. Suppose that t increases, then the after-tax price of each variety of dirty goods increases in Home. Therefore, x^{HH} and x^{FH} decreases. On the other hand, an increase in t lowers P^*, which in turn decreases the consumption of each variety, as shown in equation (3.6).

Each country's GHG emissions are the sum of emissions from domestic and imported consumption and global GHG emissions are the sum of emissions from the two countries.

$$E = nsx^{HH} + n^*sx^{FH}; \quad E^* = n(1-s)x^{HF} + n^*(1-s)x^{FF}; \quad E^G = E + E^*. \tag{3.15}$$

In the following part, we show how trade liberalization affects global GHG emissions. Equations above show that GHG emissions depend strongly on trade costs, and the model illustrates a special phenomenon in which trade liberalization itself may increase global GHG emissions.

Proposition 3.1 *The effect of trade liberalization on global GHG emissions is not monotonic. As trade costs decline, global GHG emissions decrease at first and then rise.*

The impact of trade liberalization on GHG emissions can be decomposed into the firm-relocation effect and the demand effect.

$$
\begin{aligned}
\frac{\mathrm{d}E^G}{\mathrm{d}\tau} &= \frac{\mathrm{d}E}{\mathrm{d}\tau} + \frac{\mathrm{d}E^*}{\mathrm{d}\tau} \\
&= \underbrace{sx^{HH}\frac{\mathrm{d}n}{\mathrm{d}\tau} + sx^{FH}\frac{\mathrm{d}n^*}{\mathrm{d}\tau} + (1-s)x^{HF}\frac{\mathrm{d}n}{\mathrm{d}\tau} + (1-s)x^{FF}\frac{\mathrm{d}n^*}{\mathrm{d}\tau}}_{0} + \\
&\quad \underbrace{n\frac{\mathrm{d}sx^{HH}}{\mathrm{d}\tau} + n^*\frac{\mathrm{d}(1-s)x^{FF}}{\mathrm{d}\tau}}_{+} + \underbrace{n^*\frac{\mathrm{d}sx^{FH}}{\mathrm{d}\tau} + n\frac{\mathrm{d}(1-s)x^{HF}}{\mathrm{d}\tau}}_{-} \\
&= \frac{\mu(\sigma-1)}{\sigma}\left(\frac{s}{1+t} + \frac{1-s}{1+t^*}\right)\frac{(\sigma-1)\tau^\sigma - \sigma\tau^{\sigma-1} - 1}{(\tau^\sigma+\tau)^2}.
\end{aligned}
\tag{3.16}
$$

The firm-relocation effect measures the impact of firm relocation, and the demand effect captures the impact of changes in consumption. The firm-relocation effect in each country can be positive, negative or neutral depending on the relationship between consumption taxes and market size. However, the net firm-relocation effect of trade liberalization is always neutral because the consumption scales of each domestic variety and imported variety are the same separately across countries.[5] A change in GHG emissions in one country caused by firm relocation is accurately offset by the change in emissions in the other country. Thus, how trade liberalization affects global GHG emissions is determined by the demand effect of dirty goods. As trade costs decline, the consumption of each imported variety increases and that of each domestic variety decreases. At the beginning of trade liberalization, trade costs are still high. The increase in GHG emissions from more consumption of imported goods is dominated by the decrease of them from less consumption of domestic goods; the total emissions tend to decrease. However, as trade liberalization proceeds, GHG emissions from imported goods increase more than GHG emissions from domestic goods decrease; then, the total emissions begin to increase. We can understand the non-monotonicity in another way. The consumption level of dirty goods in free trade is equal to that in autarky because there are no trade costs in either case. However, under trade with costs, consumers have to pay the extra trade costs, which decreases the consumption scale around the world. Hence, GHG emissions are lower than the two extreme cases.

we now turn to examine how a consumption tax affects GHG emissions. In this part, the consumption tax is still exogenous. The endogenous case follows in sections 4 and 5.

Proposition 3.2 *An increase in the consumption tax in one country reduces the emissions in that country and raises the emissions in the other country. Global GHG emissions always decrease.*

[5] Note that $sx^{HH} = (1-s)x^{FF}$ and $sx^{FH} = (1-s)x^{HF}$.

Note that

$$\frac{\mathrm{d}E}{\mathrm{d}t} = \underbrace{sx^{HH}\frac{\mathrm{d}n}{\mathrm{d}t} + sx^{FH}\frac{\mathrm{d}n^*}{\mathrm{d}t}}_{-} + \underbrace{n\frac{\mathrm{d}sx^{HH}}{\mathrm{d}t} + n^*\frac{\mathrm{d}sx^{FH}}{\mathrm{d}t}}_{-} < 0; \tag{3.17}$$

$$\frac{\mathrm{d}E^*}{\mathrm{d}t} = \underbrace{(1-s)x^{HF}\frac{\mathrm{d}n}{\mathrm{d}t} + (1-s)x^{FF}\frac{\mathrm{d}n^*}{\mathrm{d}t}}_{+} + \underbrace{n\frac{\mathrm{d}(1-s)x^{HF}}{\mathrm{d}t} + n^*\frac{\mathrm{d}(1-s)x^{FF}}{\mathrm{d}t}}_{-} > 0; \tag{3.18}$$

$$\frac{\mathrm{d}E^G}{\mathrm{d}t} = \frac{\mathrm{d}E}{\mathrm{d}t} + \frac{\mathrm{d}E^*}{\mathrm{d}t} < 0. \tag{3.19}$$

The impact of the consumption tax on GHG emissions can also be decomposed into the firm-relocation effect and the demand effect. The demand effect is always negative because an increase in the consumption tax decreases the demand for both domestic and imported dirty goods. The firm-relocation effect is negative in one country and positive in the other country due to the relatively larger scale of consumption of domestic goods compared to imported goods. The net firm-relocation effect of a consumption tax is also neutral because the scale of total consumption of dirty goods is the same in the two countries. Thus, the total effect of a consumption tax on global GHG emissions is always negative because of the decreasing demand for dirty goods. In addition, the total effect of a consumption tax on GHG emissions is negative for Home and positive for Foreign, which verifies the existence of carbon leakage under consumption pollution. The intuition behind the finding is that an increase in Home consumption tax increases the aggregate price index in Home and decreases that in Foreign; therefore, the consumption of dirty goods decreases in Home and increases in Foreign, i.e., $s\mu/P$ decreases and $(1-s)\mu/P^*$ increases.

If the consumption tax in Home is sufficiently smaller than that in Foreign, then firms fully agglomerate in Home for larger market and lax environmental regulation, and vice versa. For $(1+t)/(1+t^*) \leq s\tau^{1-\sigma}/(1-s)$, all firms agglomerate in Home, Foreign specializes in the production of the clean good, and Foreign imports the dirty goods from Home. For $(1+t)/(1+t^*) \geq s\tau^{\sigma-1}/(1-s)$, all firms agglomerate in Foreign, Home specializes in the production of the clean good, and Home imports the dirty goods from Foreign.[6]

3.4 Global Optimum

This section studies how the social planner maximizes global welfare by deciding on the consumption taxes in each country. Following the literature (e.g., Copeland and Taylor, 1994), we assume that environmental damage is increasing and convex with respect to global emissions, i.e., $D'(E^G) > 0$ and $D''(E^G) > 0$. For simplicity, we only consider a case where the firms disperse across countries

[6]See Appendix 3.A.1 for the specific levels of consumption and emissions under full agglomeration.

when there is no consumption tax, i.e., $s/(1-s) < \tau^{\sigma-1}$.[7]

Define global welfare as the sum of individual utility around the world:

$$W^G = sU + (1-s)U^*. \tag{3.20}$$

Suppose the social planner has no incentive to induce full agglomeration of firms in a country. The first order conditions of global welfare concerning t and t^* are derived as

$$\frac{\mathrm{d}W^G}{\mathrm{d}t} = \mu\zeta\left(-1 + \phi\zeta - \frac{1}{\sigma-1}\frac{\zeta^*}{\zeta+\zeta^*} + \frac{1}{\sigma-1}\frac{1-s}{s}\frac{\zeta}{\zeta+\zeta^*}\right) = 0, \tag{3.21}$$

$$\frac{\mathrm{d}W^G}{\mathrm{d}t^*} = \mu\zeta^*\left(-1 + \phi^*\zeta - \frac{1}{\sigma-1}\frac{\zeta}{\zeta+\zeta^*} + \frac{1}{\sigma-1}\frac{s}{1-s}\frac{\zeta^*}{\zeta+\zeta^*}\right) = 0, \tag{3.22}$$

where

$$\zeta = \frac{s}{1+t}, \quad \zeta^* = \frac{1-s}{1+t^*}, \tag{3.23}$$

$$\phi = \frac{1}{s}\frac{\sigma-1}{\sigma} + \frac{1}{s}\frac{\sigma-1}{\sigma}\frac{\tau^\sigma+1}{\tau^\sigma+\tau}D', \tag{3.24}$$

$$\phi^* = \frac{1}{1-s}\frac{\sigma-1}{\sigma} + \frac{1}{1-s}\frac{\sigma-1}{\sigma}\frac{\tau^\sigma+1}{\tau^\sigma+\tau}D'. \tag{3.25}$$

Note that $\phi^* = \frac{s}{1-s}\phi$. Rearranging the first order conditions gives

$$\left(\frac{\zeta}{s} - \frac{\zeta^*}{1-s}\right)\left(\frac{1}{\sigma-1} + \phi s(\zeta+\zeta^*)\right) = 0, \tag{3.26}$$

which implies identical consumption taxes

$$t_{GO} = t^*_{GO}. \tag{3.27}$$

Bringing the equation back into $\frac{\mathrm{d}W^G}{\mathrm{d}t} = 0$ shows

$$\underbrace{1 + t_{GO}}_{LHS} = \underbrace{\frac{\sigma-1}{\sigma} + \frac{\sigma-1}{\sigma}\frac{\tau^\sigma+1}{\tau^\sigma+\tau}D'}_{RHS}. \tag{3.28}$$

According to the conditions that $D'' > 0$ and $\frac{\mathrm{d}E^G}{\mathrm{d}t} < 0$, $\frac{\mathrm{d}D'}{\mathrm{d}t} = \frac{\mathrm{d}D'}{\mathrm{d}E^G}\frac{\mathrm{d}E^G}{\mathrm{d}t} = D''\frac{\mathrm{d}E^G}{\mathrm{d}t} < 0$ holds. Thus, the optimal tax rates are determined by the intersection in Figure 3.1.

[7] The case where $s/(1-s) \geq \tau^{\sigma-1}$ is studied in Appendix 3.A.3.

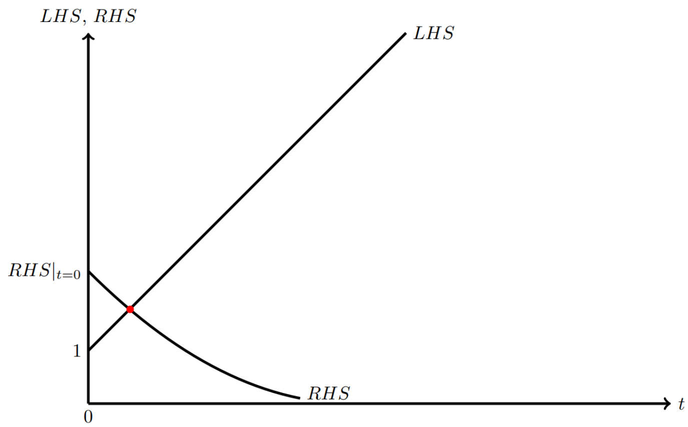

Figure 3.1: Optimal consumption tax when $RHS|_{t=0} > 1$.

The optimal consumption taxes are identical, regardless of asymmetric market sizes. The finding is based on the fact that the net firm-relocation effect is neutral in our model. The social planner imposes identical taxes in both countries to control emissions through the demand effect and will not trouble to adjust the firm locations. Besides, the tax rates can be negative ($t_{GO} = t^*_{GO} < 0$), which implies consumption subsidies.[8] If σ is sufficiently small, the varieties are very differentiated. Firms have strong market powers and tend to produce less. The social planner imposes consumption subsidies to correct the monopolistic distortion. If σ is sufficiently large, the varieties are close substitutes. Firms' market powers are weakened and they produce relatively more, which leads to more consumption emissions. In this case, the social planner imposes consumption taxes to control the demand for dirty goods.

As shown in the new economic geography literature, without environmental issues, global welfare becomes higher as more firms are located in the larger country. In the current settings with consumption emissions, we also examine whether the social planner has an incentive to induce full agglomeration in Home. Since the firm-relocation effect is neutral and emission targets can be realized by the demand effect, full agglomeration cannot be motivated by emission issues. In other words, even if full agglomeration occurs in Home, global emissions will not change. Since the emissions per unit of consumption is 1, total consumption of dirty goods is the same. Therefore, capital rents and total tax revenue are also the same in the two cases. Inducing full agglomeration in Home only reallocates tax revenue and consumption emissions across countries but has no effect on the total levels of them. Denote the variables in the case of full agglomeration with "H" in the subscripts. We can get the following lemma.[9]

[8]This case occurs when $RHS|_{t=0} < 1$.

[9]See Appendix 3.A.3 for the proofs of Lemma 3.3 and Proposition 3.3.

Lemma 3.3. *In the two cases where firms disperse across countries and firms full agglomerate in Home, (i)* $E^G_{GO} = E^G_{GO,H}$*; (ii)* $r_{GO} = r_{GO,H}$*; (iii)* $TR_{GO} + TR^*_{GO} = TR_{GO,H} + TR^*_{GO,H}$.

Whether the social planner has an incentive to induce full agglomeration depends only on the consumer surplus given the consumption level of dirty goods. In other words, the question is how the social planner maximizes the total consumer surplus by distributing the firms (and thus the dirty goods) in the presence of asymmetric market sizes. Note that the mass of firms affects consumer surplus through changes in the aggregate price indices (P and P^*). When trade costs are high, i.e., $s/(1-s) < \tau^{\sigma-1}$, P^* would become too high and the consumer surplus in Foreign would become too low if firms fully agglomerate in Home. Therefore, the social planner always keeps the dispersion of firms.

Proposition 3.3. *Suppose firms disperse across countries under no environmental regulation, i.e.,* $s/(1-s) < \tau^{\sigma-1}$*. Identical consumption taxes (or subsidies) are socially optimal regardless of market sizes.*

3.5 Discussion: Consumption Tax Competition

This section discusses how to derive the Nash equilibrium in a two-stage game. At the first stage, the countries simultaneously decide on the levels of consumption taxes. At the second stage, firms determine their location and production patterns in response to environmental regulations. In the main part of this paper, we have already investigated firm behaviors under the consumption tax. Here, we concentrate on the first stage of the game. For simplicity, we assume that $D(E^W) = \delta E^W$.[10]

Figure 3.2 describes the relationship between firm locations and environmental regulations where $\zeta = s/(1+t)$ and $\zeta^* = (1-s)/(1+t^*)$ are defined as market-size-adjusted inverse consumption taxes in Home and Foreign. The coordinate system consists of three areas; in area (i), full agglomeration occurs in Home, in area (iii), full agglomeration occurs in Foreign, and in area (ii), firms disperse across countries.

Denote Home welfare in each area as $W_{(i)}$, $W_{(ii)}$ and $W_{(iii)}$, respectively. Foreign welfare is still with asterisks. With endogenous location patterns, Home can not always choose the consumption taxes according to the first order conditions because location patterns may change among the three areas in which case Home has to behave at the threshold values of taxes. Then, Home compares the welfare levels in the three areas to decide on the optimal consumption tax with endogenous firm

[10]Linear environmental damage function is often used in the analysis with endogenous firm locations, e.g., Markusen et al. (1993, 1995); Dong et al. (2012).

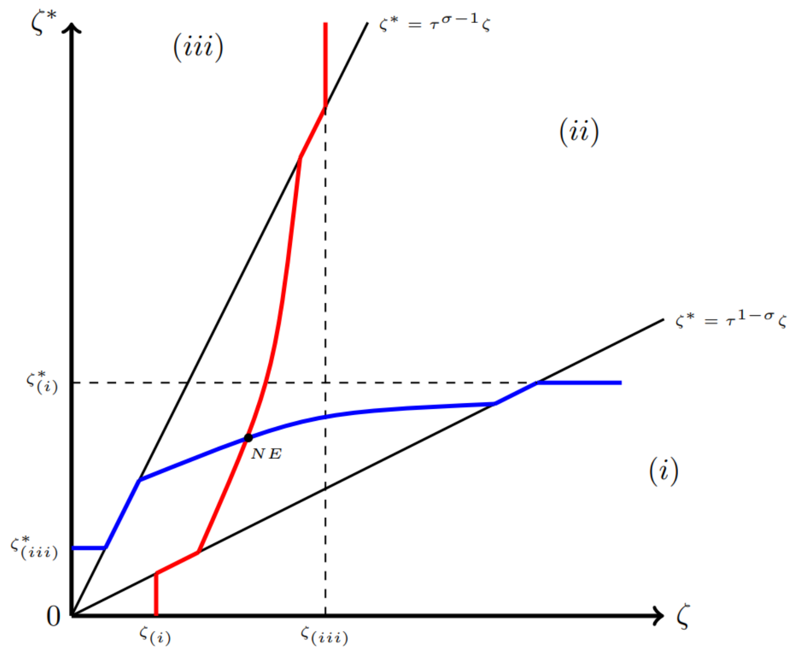

Figure 3.2: Nash equilibrium when σ and τ are sufficiently large.

locations.

$$\zeta_{BR} = \begin{cases} \zeta_{(i)} = \dfrac{1}{\frac{1}{s} - \frac{1}{\sigma} + \frac{\sigma-1}{\sigma}\delta} & \text{if } \ 0 < \zeta^* < \zeta_1^* \\ \tau^{1-\sigma}\zeta^* & \text{if } \ \zeta_1^* \leq \zeta^* < \zeta_2^* \\ \frac{-(\beta\zeta^*-1)+\sqrt{(\beta\zeta^*-1)^2+4\beta\frac{\sigma}{\sigma-1}\zeta^*}}{2\beta} & \text{if } \ \zeta_2^* \leq \zeta^* < \zeta_3^* \ , \\ \tau^{\sigma-1}\zeta^* & \text{if } \ \zeta_3^* \leq \zeta^* < \zeta_4^* \\ \zeta_{(iii)} = \dfrac{1}{\frac{1}{s} - \frac{1}{\sigma} + \frac{\sigma-1}{\sigma}\frac{\delta}{\tau}} & \text{if } \ \zeta^* \geq \zeta_4^* \end{cases} \tag{3.29}$$

$$\text{where } \ \zeta_1^* = \tau^{1-\sigma}\zeta_{(i)} = \frac{\tau^{1-\sigma}}{\frac{1}{s} - \frac{1}{\sigma} + \frac{\sigma-1}{\sigma}\delta}, \quad \zeta_2^* = \frac{1 + \frac{\sigma}{\sigma-1}\tau^{1-\sigma}}{\beta(1+\tau^{\sigma-1})},$$

$$\zeta_3^* = \frac{1 + \frac{\sigma}{\sigma-1}\tau^{\sigma-1}}{\beta(1+\tau^{1-\sigma})}, \quad \zeta_4^* = \tau^{\sigma-1}\zeta_{(iii)} = \frac{\tau^{\sigma-1}}{\frac{1}{s} - \frac{1}{\sigma} + \frac{\sigma-1}{\sigma}\frac{\delta}{\tau}},$$

$$\beta = \frac{1}{s} - \frac{1}{\sigma} + \frac{\sigma-1}{\sigma}\frac{\tau^\sigma+1}{\tau^\sigma+\tau}\delta.$$

How Home responds to Foreign consumption taxes depends on the relative strengths between consumer surplus, capital rents, tax revenue and environmental damage. Consumer surplus decreases in Home consumption tax because the aggregate price of dirty goods in Home increases in its tax rates. Capital rents, derived as $r = Y/(\sigma-1) = \frac{\mu}{\sigma}\left(\frac{s}{1+t} + \frac{1-s}{1+t^*}\right)$, also decrease in t. However, tax revenue, $TR = \mu t/(1+t)$, always increases in t. Besides, as shown above, an increase in consumption tax decreases environmental damage.

When Foreign consumption tax is high ($0 < \zeta^* < \zeta_2^*$), Home imposes consumption taxes so that firms fully agglomerate there. By doing so, Home benefits from high consumer surplus and high capital rents, which dominate low tax revenue and high environmental damage. As Foreign tax decreases ($\zeta_2^* \le \zeta^* < \zeta_3^*$), Home also decreases its tax to increase its consumer surplus. During this process, capital rents and environmental damage continue to increase, while tax revenue keeps decreasing. When Foreign tax becomes lower ($\zeta^* \ge \zeta_3^*$), Home induces all firms to relocate to Foreign, or else its tax revenue and environmental quality would be too low. For $\zeta_2^* \le \zeta^* < \zeta_3^*$, Home responses are strategic complements to Foreign consumption taxes. An increase in Foreign consumption taxes derives Home's marginal loss below marginal benefit, i.e., $\frac{\mathrm{d}^2[(CS+r+TR)-D]}{\mathrm{d}\zeta \mathrm{d}\zeta^*} = \frac{\mu}{(\sigma-1)(\zeta+\zeta^*)^2} > 0$; therefore, Home has an incentive to further decrease its emissions by increasing the consumption tax.

Analogously, Foreign best responses are

$$\zeta_{BR}^* = \begin{cases} \zeta_{(iii)}^* = \dfrac{1}{\frac{1}{1-s} - \frac{1}{\sigma} + \frac{\sigma-1}{\sigma}\delta} & \text{if } \ 0 < \zeta < \zeta_1 \\ \tau^{\sigma-1}\zeta & \text{if } \ \zeta_1 \le \zeta < \zeta_2 \\ \frac{-(\beta^*\zeta-1)+\sqrt{(\beta^*\zeta-1)^2+4\beta^*\frac{\sigma}{\sigma-1}\zeta}}{2\beta^*} & \text{if } \ \zeta_2 \le \zeta < \zeta_3 \, , \\ \tau^{1-\sigma}\zeta & \text{if } \ \zeta_3 \le \zeta < \zeta_4 \\ \zeta_{(i)}^* = \dfrac{1}{\frac{1}{1-s} - \frac{1}{\sigma} + \frac{\sigma-1}{\sigma}\frac{\delta}{\tau}} & \text{if } \ \zeta \ge \zeta_4 \end{cases} \tag{3.30}$$

$$\text{where } \ \zeta_1 = \tau^{1-\sigma}\zeta_{(iii)}^* = \frac{\tau^{1-\sigma}}{\frac{1}{1-s} - \frac{1}{\sigma} + \frac{\sigma-1}{\sigma}\delta}, \quad \zeta_2 = \frac{1 + \frac{\sigma}{\sigma-1}\tau^{1-\sigma}}{\beta^*(1+\tau^{\sigma-1})},$$

$$\zeta_3 = \frac{1 + \frac{\sigma}{\sigma-1}\tau^{\sigma-1}}{\beta^*(1+\tau^{1-\sigma})}, \quad \zeta_4 = \tau^{\sigma-1}\zeta_{(i)}^* = \frac{\tau^{\sigma-1}}{\frac{1}{1-s} - \frac{1}{\sigma} + \frac{\sigma-1}{\sigma}\frac{\delta}{\tau}},$$

$$\beta^* = \frac{1}{1-s} - \frac{1}{\sigma} + \frac{\sigma-1}{\sigma}\frac{\tau^\sigma+1}{\tau^\sigma+\tau}\delta.$$

The intuition behind Foreign best responses is the same as Home. Generally, as Home consumption taxes increase, Foreign also increases its consumption taxes due to the relative strengths between consumer surplus, capital rents, tax revenue and environmental damage. Correspondingly, location patterns shift from full agglomeration in Home to dispersion across countries and eventually to full agglomeration in Foreign. Figure 3.2 describes the reaction curves of Home (denoted by red curves) and Foreign (denoted by blue curves). As long as σ and τ are sufficiently high, there always exists a unique Nash equilibrium where firms disperse across countries.[11]

[11] σ and τ are sufficiently large so that $T_3^* < T_4^*$ and $T_3 < T_4$ hold. Or else the reaction curves of Home and Foreign when firms disperse will expand outward in which case the model becomes intractable.

The consumption taxes at equilibrium are derived as

$$t_{NE} = \frac{2(\beta\beta^* - \beta^2)s}{\beta^* - \frac{3\sigma-1}{\sigma-1}\beta + \sqrt{(\beta^* - \beta)^2 + \frac{4\sigma^2}{(\sigma-1)^2}\beta\beta^*}} - 1; \tag{3.31}$$

$$t^*_{NE} = \frac{2(\beta^{*2} - \beta\beta^*)(1-s)}{\frac{3\sigma-1}{\sigma-1}\beta^* - \beta - \sqrt{(\beta^* - \beta)^2 + \frac{4\sigma^2}{(\sigma-1)^2}\beta\beta^*}} - 1 \tag{3.32}$$

which are strongly dependent on the market size in each country. If market sizes are identical, then $\beta = \beta^*$ holds, leading to the equalization of consumption taxes across countries.[12] However, if market sizes are asymmetric, Home always imposes a higher consumption tax than Foreign ($t_{NE} > t^*_{NE}$).[13] The advantage of larger market size encourages Home to decrease its consumption subsidy (or increase its consumption tax). As a response, Foreign makes decisions in the same direction because consumption subsidies (or taxes) are complementary.

3.6 Conclusion

In this chapter, we extended the footloose capital model to answer several old questions in the literature on trade and the environment under consumption pollution. Specifically, we explored how trade liberalization and consumption taxes affect firm locations and GHG emissions and how countries decide on their consumption taxes cooperatively and non-cooperatively in the presence of monopolistic competition, endogenous firm locations and asymmetric market sizes. We found that when firms disperse across countries, an increase in a country's consumption tax drives firms to move to the other country. However, how trade liberalization affects firm location patterns is ambiguous and depends on the tensions between consumption tax and market size. If the market size is large enough, firms may relocate to the country with more stringent consumption taxes. Trade liberalization decreases GHG emissions initially and then increases them. An increase in a country's consumption tax always decreases its own and global emissions, while increasing the other country's emissions. In the global optimum, the social planner imposes identical consumption taxes across countries if trade costs are high and may induce full agglomeration in the larger country if trade costs are low. In the consumption tax competition, if the elasticity of substitution among different varieties and trade costs are sufficiently high, there exists a Nash equilibrium where firms disperse across countries and the consumption tax is higher in the larger country.

Lastly, we emphasize two potential extensions of this chapter. As an essential source of consumption pollution, gasoline is always at the center of this issue. Gasoline is crucial not only because

[12] In this case, $t_{NE} = t^*_{NE} = \frac{2\beta s(\sigma-1)}{2\sigma-1} - 1$.

[13] See Appendix 3.A.4.

its consumption is massive but also because changes in its price have been demonstrated to be an important channel of carbon leakage (e.g., Kiyono and Ishikawa, 2013). Further analysis should be performed to study how policy-makers design their policies to control GHG emissions with the existence of carbon leakage stemming from the price changes of natural resources. The other issue is the endogenous choices of firms between abatement investment and FDI. If environmental regulation is not stringent compared to abatement costs, firms may prefer to pay for their emissions. However, if environmental regulation is strict but not as strict as the costs of FDI, firms may abate their emissions by investing in expensive equipment and machines. If environmental regulation is sufficiently stringent, firms may choose to do FDI instead of investing in abatement. Such endogenous choices are important especially when firms are heterogeneous in their productivity, mobility and emission intensities.

3.A Appendix

3.A.1 Consumption and Emissions under Full Agglomeration.

For $\frac{1+t}{1+t^*} \leq \frac{s}{1-s}\tau^{1-\sigma}$, all firms agglomerate in Home, Foreign specializes in the production of the clean good, and Foreign imports the dirty goods from Home. In this case, $n = 1$, $n^* = 0$; $x^{HH} = \frac{\mu(\sigma-1)}{\sigma}\frac{1}{1+t}$, $x^{HF} = \frac{\mu(\sigma-1)}{\sigma}\frac{1}{\tau(1+t^*)}$, $x^{FH} = x^{FF} = 0$; $E = \frac{\mu(\sigma-1)}{\sigma}\frac{s}{1+t}$, $E^* = \frac{\mu(\sigma-1)}{\sigma}\frac{1-s}{\tau(1+t^*)}$ and $E^G = \frac{\mu(\sigma-1)}{\sigma}\left[\frac{s}{1+t} + \frac{1-s}{\tau(1+t^*)}\right]$. For $\frac{1+t}{1+t^*} \geq \frac{s}{1-s}\tau^{\sigma-1}$, all firms agglomerate in Foreign, Home specializes in the production of the clean good, and Home imports the dirty goods from Foreign. In this case, $n = 0$, $n^* = 1$; $x^{FF} = \frac{\mu(\sigma-1)}{\sigma}\frac{1}{1+t^*}$, $x^{FH} = \frac{\mu(\sigma-1)}{\sigma}\frac{1}{\tau(1+t)}$, $x^{HH} = x^{HF} = 0$; $E^* = \frac{\mu(\sigma-1)}{\sigma}\frac{1-s}{1+t^*}$, $E = \frac{\mu(\sigma-1)}{\sigma}\frac{s}{\tau(1+t)}$ and $E^G = \frac{\mu(\sigma-1)}{\sigma}\left[\frac{1-s}{1+t^*} + \frac{s}{\tau(1+t)}\right]$.

3.A.2 Proof of Proposition 3.1.

Differentiating global GHG emissions in trade with footloose capital with respect to τ gives

$$\frac{\mathrm{d}E^G}{\mathrm{d}\tau} = \frac{\mu(\sigma-1)}{\sigma}\left(\frac{s}{1+t} + \frac{1-s}{1+t^*}\right)\frac{(\sigma-1)\tau^\sigma - \sigma\tau^{\sigma-1} - 1}{(\tau^\sigma + \tau)^2}.$$

Note that $\frac{\mathrm{d}(\sigma-1)\tau^\sigma - \sigma\tau^{\sigma-1} - 1}{\mathrm{d}\tau} = \sigma(\sigma-1)\tau^{\sigma-2}(\tau-1) > 0$ always holds, so $(\sigma-1)\tau^\sigma - \sigma\tau^{\sigma-1} - 1$ is an increasing function of τ for $\tau > 1$. When $\tau = 1$, the polynomial is -2; when $\tau = \frac{\sigma+1}{\sigma-1}$, the polynomial is equal to $\tau^{\sigma-1} - 1 > 0$. Thus, $\frac{\mathrm{d}E^G}{\mathrm{d}\tau} = 0$ exists for $1 < \tau < \frac{\sigma+1}{\sigma-1}$. Denote the certain point as τ_0, then E^G decreases for $1 < \tau < \tau_0$ and increases for $\tau > \tau_0$. In other words, as trade costs decline from infinity to unity, global GHG emissions initially decrease and then increase.

3.A.3 Global Optimum

Global Optimum: Firms Disperse

Define global welfare as the sum of individual welfare around the world:

$$W^G = sU + (1-s)U^*$$

where

$$\begin{aligned}U &= \mu \ln M + I/s - \mu - D(E^G) \\ &= \mu \ln \mu - \mu \ln P + 1 + r + TR/s - \mu - D(E^G) \\ &= \mu \ln \mu - \left\{ \mu \ln(\frac{\sigma}{\sigma - 1}) - \frac{\mu}{\sigma - 1} \ln(1 + \tau^{1-\sigma}) + \mu \ln(1 + t) + \frac{\mu}{\sigma - 1} \ln \left(1 + \frac{1 - s}{s} \frac{1 + t}{1 + t^*} \right) \right\} + 1 \\ &\quad + \frac{\mu}{\sigma} \left(\frac{s}{1 + t} + \frac{1 - s}{1 + t^*} \right) + \mu \frac{t}{1 + t} - \mu - D(E^G).\end{aligned}$$

and

$$\begin{aligned}U^* &= \mu \ln \mu - \mu \ln(\frac{\sigma}{\sigma - 1}) + \frac{\mu}{\sigma - 1} \ln(1 + \tau^{1-\sigma}) - \mu \ln(1 + t^*) - \frac{\mu}{\sigma - 1} \ln \left(1 + \frac{s}{1 - s} \frac{1 + t^*}{1 + t} \right) + 1 \\ &\quad + \frac{\mu}{\sigma} \left(\frac{1 - s}{1 + t^*} + \frac{s}{1 + t} \right) + \mu \frac{t^*}{1 + t^*} - \mu - D(E^G).\end{aligned}$$

Remind that for $s/(1-s) < \tau^{\sigma-1}$,

$$1 + t_{GO} = \frac{\sigma - 1}{\sigma} + \frac{\sigma - 1}{\sigma} \frac{\tau^\sigma + 1}{\tau^\sigma + \tau} D'(E^G),$$

global emissions at the social optimum are determined by

$$E^G_{GO} = \frac{\mu(1 + \tau^\sigma)}{\tau^\sigma + \tau + (1 + \tau^\sigma) D'(E^G_{GO})}.$$

Global Optimum: Full Agglomeration in Home

If the social planner induces full agglomeration in Home, global welfare becomes

$$\begin{aligned}W^G_H &= W_{H,H} + W_{H,F} = \mu \ln \mu - \mu \ln(\frac{\sigma}{\sigma - 1}) - \mu(1 - s) \ln \tau + 1 - \mu s \ln(1 + t) - \mu(1 - s) \ln(1 + t^*) \\ &\quad - \frac{\mu(\sigma - 1)}{\sigma} \left(\frac{s}{1 + t} + \frac{1 - s}{1 + t^*} \right) - D(E^G_H)\end{aligned}$$

where $W_{H,H}$ and $W_{H,F}$ denote Home and Foreign welfare which are as follows.

$$W_{H,H} = \mu \ln \mu - \mu \ln(\frac{\sigma}{\sigma - 1}) - \mu \ln(1 + t) + 1 + \frac{\mu}{\sigma} \left(\frac{s}{1 + t} + \frac{1 - s}{1 + t^*} \right) + \mu \frac{t}{1 + t} - \mu - D(E^G_H);$$

$$W_{H,F} = \mu \ln \mu - \mu \ln(\frac{\sigma}{\sigma - 1}) - \mu \ln(1 + t^*) - \mu \ln \tau + 1 + \frac{\mu}{\sigma} \left(\frac{s}{1 + t} + \frac{1 - s}{1 + t^*} \right) + \mu \frac{t^*}{1 + t^*} - \mu - D(E^G_H).$$

Solving the first order conditions with respect to t and t^* gives

$$t = \frac{(\sigma-1)(1+D')}{\sigma} - 1; \quad t^* = \frac{\sigma-1}{\sigma}\left(1+\frac{D'}{\tau}\right) - 1.$$

Note that

$$\frac{1+t}{1+t^*} = \frac{\tau(1+D')}{\tau+D'} > 1 > \frac{s}{1-s}\tau^{(1-\sigma)}.$$

The taxes are not available because full agglomeration in Home never happens if the consumption taxes are imposed. So the social planner acts at the threshold value where $\frac{1+t}{1+t^*} = \frac{s}{1-s}\tau^{(1-\sigma)}$.

Proof of Lemma 3.3

Taking $\frac{1+t}{1+t^*} = \frac{s}{1-s}\tau^{(1-\sigma)}$ into W_H^G and solving the welfare maximization problem give

$$1 + t_{GO,H} = \frac{s(\sigma-1)}{\sigma}\left(1+\tau^{1-\sigma}+\frac{1+\tau^{\sigma}}{\tau^{\sigma}}D'(E_H^G)\right)$$

Hence, the global emissions at the global optimum when full agglomeration occurs in Home are

$$E_{GO,H}^G = \frac{\mu(1+\tau^{\sigma})}{\tau^{\sigma}+\tau+(1+\tau^{\sigma})D'(E_{GO,H}^G)},$$

which takes the same form as E_{GO}^W. For both E_{GO}^G and $E_{GO,H}^G$, their left hand sides increase in global emissions and their right hand sides decrease in global emissions (i.e., $D'' > 0$). There exists only one solution for the equation, which implies that $E_{GO}^G = E_{GO,H}^G$.

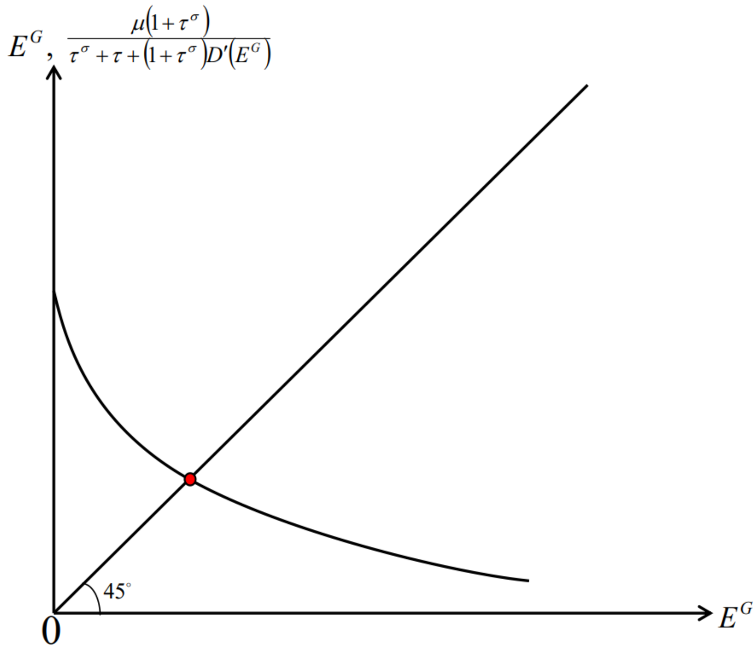

Figure A.1: $E^G_{GO} = E^G_{GO,H}$ must hold.

With $\frac{1+t}{1+t^*} = \frac{s}{1-s}\tau^{(1-\sigma)}$ and $E^G_{GO} = E^G_{GO,H}$, we can get the optimal consumption taxes when firms fully agglomeration in Home.

$$t_{GO,H} = s(1+\tau^{1-\sigma})(1+t_{GO}) - 1; \quad t^*_{GO,H} = (1-s)(1+\tau^{\sigma-1})(1+t_{GO}) - 1.$$

Note that

$$\frac{s}{1+t_{GO}} + \frac{1-s}{1+t^*_{GO}} = \frac{s}{1+t_{GO,H}} + \frac{1-s}{1+t^*_{GO,H}}. \tag{3.33}$$

Therefore, capital rents, i.e., $r = \frac{\mu}{\sigma}\left(\frac{s}{1+t} + \frac{1-s}{1+t^*}\right)$, and total tax revenue, i.e., $TR+TR^* = \frac{\mu t}{1+t} + \frac{\mu t^*}{1+t^*}$, are the same in the two cases.

Proof of Proposition 3.3

For $s/(1-s) < \tau^{\sigma-1}$, the difference between the global welfare levels in the two cases is

$$W^G_{GO} - W^G_{GO,H} = \frac{\mu\sigma}{\sigma-1}\left[s\ln s + (1-s)\ln(1-s) + \ln(1+\tau^{1-\sigma}) + (1-s)(\sigma-1)\ln\tau\right].$$

$$\frac{\mathrm{d}\left(W^G_{GO} - W^G_{GO,H}\right)}{\mathrm{d}\tau} = 0 \Longrightarrow \tau^{\sigma-1} = \frac{s}{1-s}.$$

$$W_{GO}^G - W_{GO,H}^G > \left(W_{GO}^G - W_{GO,H}^G\right)\big|_{\tau^{\sigma-1}=\frac{s}{1-s}} = 0.$$

Therefore, the social planner never has an incentive to induce full agglomeration in the larger country.

In the case where $s/(1-s) \geq \tau^{\sigma-1}$ holds, firms fully agglomerate in Home when there is no environmental regulation. The social planner has no incentive to make firms disperse across countries because identical consumption taxes cannot be achieved. This case happens because trade costs are low. Consequently, P^* will not be so high under full agglomeration in Home. The increase in Home consumer surplus due to a lower P can be higher than the decrease in Foreign consumer surplus due to a higher P^*. Hence, the social planner maintains full agglomeration in Home and sets a higher consumption tax in Home than in Foreign. The social planner has no incentive to change firm locations in the two cases.

3.A.4 Consumption Tax Competition

Comparison of Consumption Taxes at the Nash Equilibrium

Compare t_{NE} and t_{NE}^* as follows.

$$\frac{1+t_{NE}}{1+t_{NE}^*} = \frac{\beta s}{\beta^*(1-s)} \frac{\frac{3\sigma-1}{\sigma-1}\beta^* - \beta - \sqrt{(\beta^*-\beta)^2 + \frac{4\sigma^2}{(\sigma-1)^2}\beta\beta^*}}{\beta^* - \frac{3\sigma-1}{\sigma-1}\beta + \sqrt{(\beta^*-\beta)^2 + \frac{4\sigma^2}{(\sigma-1)^2}\beta\beta^*}}$$

where $\beta^* = \dfrac{2s-1}{s(1-s)} + \beta$. Because σ and τ are sufficiently large, then $\beta > \dfrac{1}{s}$ holds. Therefore,

$$\frac{\beta s}{\beta^*(1-s)} = \frac{\beta s}{\frac{2s-1}{s} + \beta(1-s)} = \frac{1}{\frac{2s-1}{\beta s^2} + \frac{1-s}{s}} > 1.$$

On the other hand,

$$\frac{3\sigma-1}{\sigma-1}\beta^* - \beta - \sqrt{(\beta^*-\beta)^2 + \frac{4\sigma^2}{(\sigma-1)^2}\beta\beta^*} - \left\{\beta^* - \frac{3\sigma-1}{\sigma-1}\beta + \sqrt{(\beta^*-\beta)^2 + \frac{4\sigma^2}{(\sigma-1)^2}\beta\beta^*}\right\}$$
$$= \frac{2\sigma}{\sigma-1}\beta^* + \frac{2\sigma}{\sigma-1}\beta - 2\sqrt{(\beta^*-\beta)^2 + \frac{4\sigma^2}{(\sigma-1)^2}\beta\beta^*};$$

besides,

$$\left(\frac{2\sigma}{\sigma-1}\beta^* + \frac{2\sigma}{\sigma-1}\beta\right)^2 - \left(2\sqrt{(\beta^*-\beta)^2 + \frac{4\sigma^2}{(\sigma-1)^2}\beta\beta^*}\right)^2 = \frac{4(2\sigma-1)}{(\sigma-1)^2}(\beta^*-\beta)^2 > 0.$$

Therefore,

$$\frac{\frac{3\sigma-1}{\sigma-1}\beta^* - \beta - \sqrt{(\beta^* - \beta)^2 + \frac{4\sigma^2}{(\sigma-1)^2}\beta\beta^*}}{\beta^* - \frac{3\sigma-1}{\sigma-1}\beta + \sqrt{(\beta^* - \beta)^2 + \frac{4\sigma^2}{(\sigma-1)^2}\beta\beta^*}} > 1.$$

Hence, $\dfrac{1+t_{NE}}{1+t^*_{NE}} > 1$ stands, implying that $t_{NE} > t^*_{NE}$.

Chapter 4

Emission Tax and Border Tax Adjustments with Technology and Location Choices

This chapter is based on a joint work with Professor Jota Ishikawa.

4.1 Introduction

A country's attempt to cope with climate change may be undermined by international carbon leakage. That is, greenhouse-gas (GHG) emission regulations in one country decrease emissions there but may increase those in other countries. In the Kyoto Protocol, developed countries, called the Annex I Parties, committed to decrease their GHG emissions. However, developing countries had no obligation to the reduction. Thus, carbon leakage was expected between developed and developing countries. In the Paris Agreement, both developed and developing countries submitted their GHG reduction targets. However, those targets are diverse because of the lack of coordination among countries. This would also mean a risk of international carbon leakage.

When a country introduces carbon pricing, domestic firms lose their competitiveness in markets and decrease their market shares. Although GHG emissions from domestic firms decrease, those from foreign rivals are likely to increase. This is a typical channel of international carbon leakage.[1] In particular, it is possible that the latter dominates the former and global emissions increase. However, facing carbon pricing, firms try to mitigate losses from it. Typically, there are two strategies employed by firms. One is to abate GHG emissions. Firms may adopt or invest in alternative technologies which reduce emissions but are more costly. This may mitigate international carbon

[1] See Copeland and Taylor (2005a), Ishikawa and Kiyono (2006), and Ishikawa et al. (2012, 2020), for example.

leakage. The other is to locate production plants abroad to avoid the cost of carbon pricing. This is identified as another channel of international carbon leakage,[2] which has been studied extensively.[3]

Under these circumstances, policy makers are inclined toward carbon border adjustments (CBAs) when adopting carbon pricing within the jurisdiction. They consider that CBAs can internalize the environmental costs of production and hence can be more effective than carbon pricing alone to deal with global warming. However, various CBAs have been proposed. Some proposals include regulations on only imports. For instance, the American Clean Energy and Security Act of 2009 proposes a cap-and-trade system requiring importers to purchase emission permits as domestic producers are required.[4] The European Green Deal includes a CBA mechanism aiming to "counteract carbon leakage by putting a carbon price on imports of certain goods from outside the EU".[5] The EU has announced the introduction of carbon-content tariffs by 2023 at the latest. On the other hand, other CBAs also allow exports to be exempted from carbon pricing to eliminate the cost disadvantage in foreign markets. Elliott et al. (2010) call an emission tax involving a tax rebate for exports as well as a tax on imports a "full" CBA. Examples include the SB 775 California Global Warming Solutions Act of 2006. Facing different CBA schemes, a legitimate question is how different their effects are. This question has not been fully addressed in the existing literature.

Against this background, the purpose of this study is to explore the effects of carbon pricing and CBAs on firm behaviors and GHG emissions. To this end, we examine a unilateral tax on GHG emissions and border tax adjustments (BTAs) in a simple international duopoly model. Specifically, we compare the following three policy regimes: i) emission taxes alone (Regime α); ii) emission taxes accompanied by carbon-content tariffs (Regime β); and iii) emission taxes coupled with emission-tax refunds for exports and carbon-content tariffs (Regime γ). Regime α is the case without any BTAs, Regime γ is the case with full BTAs, and Regime β is the case in between (i.e., partial BTAs).

Our oligopolistic setup captures the feature of those firms which emit lots of GHGs such as blast furnace steelmakers and chemical manufacturers. In our analysis, we explicitly take into account emission abatement activities and production locations. We assume that firms can abate emissions by adopting a clean technology. Regarding firm locations, we consider two cases: fixed and endogenous locations. Thus, our setup is simple but rich enough to analyze firms' reactions against carbon pricing and BTAs which may cause unexpected distortions in addition to cross-border carbon

[2] Changes in the price of fossil fuels can also lead to international carbon leakage (Bohm, 1993; Felder and Rutherford, 1993; Kiyono and Ishikawa, 2004, 2013; Hoel, 2005; Eichner and Pethig, 2015b). A decrease in fossil fuel demand caused by GHG emission regulations in one country lowers the global price of fossil fuels, boosting fossil fuel demand and, hence, GHG emissions in other countries.

[3] See Markusen et al. (1993, 1995); Hoel (1997); Kayalica and Lahiri (2005); Zeng and Zhao (2009); Dijkstra et al. (2011); Ishikawa and Okubo (2011, 2016, 2017), among others. See also Erdogan (2014) for a survey on FDI and environmental regulations.

[4] https://www.congress.gov/bill/111th-congress/house-bill/2454

[5] https://ec.europa.eu/info/law/better-regulation/have-your-say/initiatives/12228-Carbon-Border-Adjustment-Mechanism

leakage.

With fixed firm locations, two firms are assumed to be located in different countries. In this case, cross-border carbon leakage is just leakage between the two firms. With endogenous firm locations, however, cross-border carbon leakage is not necessarily leakage between the two firms, because both firms may choose the non-taxing country as a result of the emission tax. In our model, BTAs mitigate cross-border carbon leakage if the firm locations are fixed. In particular, cross-border carbon leakage is completely eliminated with full BTAs. However, complete elimination of carbon leakage does not necessarily result in less global GHG emissions. For a given emission tax rate, global GHG emissions are less with partial BTAs (i.e., Regime β) than without any BTAs (i.e., Regime α) while they can be more with full BTAs (i.e., Regime γ) than with partial BTAs. If the firm locations are endogenous, the pollution haven effect can also cause cross-border carbon leakage. Thus, even if full BTAs are employed, carbon leakage can occur.

In what follows, Section 4.2 describes the relationship between our analysis and previous CBA literature. Section 4.3 develops the basic model. Section 4.4 explores the effects of an emission tax on emissions with and without BTAs when firm locations are fixed. Section 4.5 extends the analysis to the case with endogenous location choices. Section 4.6 briefly discusses the welfare effects of the emission tax. Section 4.7 concludes the chapter.

4.2 Relation to Previous Literature

The rationale of CBAs can be traced back to the discussion about the optimal mix of environmental and trade policies in dealing with pollution. Markusen (1975b) argued that two taxes among production, consumption and trade taxes are sufficient to have the first-best. Since then, CBAs have been shown to be more effective to avoid or mitigate carbon leakage compared to some other environmental instruments (Veenendaal et al., 2008; Elliott et al., 2010; Böhringer et al., 2012; Fischer and Fox, 2012; Yomogida and Tarui, 2013; Ma and Yomogida, 2019), though CBAs' practicality and compatibility with the WTO rules are still under debate (Ismer and Neuhoff, 2007; Lockwood and Whalley, 2010; Kortum and Weisbach, 2017; Cosbey et al., 2019).

We contribute to the CBA literature by examining and comparing policy distortions under different policy regimes. The previous papers primarily focus on questions how carbon leakage occurs without CBAs and how (full) CBAs are effective to reduce global emissions. For example, Yomogida and Tarui (2013) employ an international oligopoly model and investigate the optimal emission tax with and without BTAs. They show that an emission tax is more effective with BTAs than that without BTAs, because it achieves higher national welfare for the taxing country and better environmental quality. In particular, carbon leakage disappears under identical emission intensities across countries. By contrast, we investigate and compare not only emissions but also firms' decisions on locations and abatement investments among the three different policy regimes.

According to the weak version of the Porter hypothesis in Jaffe and Palmer (1997), stricter environmental regulations would induce firms to engage in abatement activities. Interestingly, we show that the relationship between the emission tax rate and emission abatement activities may not be straightforward; more concretely, a sufficiently high tax rate does not necessarily induce abatement investment. We also show that even if the Porter hypothesis holds, abatement investment can make an emission tax backfire. That is, firm's abatement can increase global emissions and an increase in the emission tax can increase global emissions with firm's abatement.

Copeland (1996) points out that a pollution-content tariff is part of the optimal policies in the presence of variable abatement technologies in the foreign country. We find that if firm locations are fixed, the carbon-content tariff is more effective in reducing global emissions than an emission tax alone but the tax refund may weaken this effect. On the other hand, if firm locations are endogenous, firms tend to produce in the non-taxing country to avoid the losses from emission taxes. BTAs basically discourage firms from locating themselves in the non-taxing country. This effect is stronger with the tax refunds than without them.

With endogenous location choices, our analysis is related to the pollution haven effect. Although the hypothesis has extensively been studied, there are only a few studies that investigate it with CBAs. Ishikawa and Okubo (2017) use the footloose capital model to show that an emission tax with BTAs has no impact on firm locations while decreasing the production of each firm in the non-taxing country. Therefore, no carbon leakage occurs under BTAs. Ma and Yomogida (2019) develop a North-South duopoly model and examine how North's unilateral emission tax affects North firm's location and technology choice. They demonstrate that BTAs could encourage the firm to conduct FDI with a clean technology, leading to a decrease in global emissions (called "negative" carbon leakage in their paper); and North may have an incentive to induce such clean FDI for its welfare maximization.

Ma and Yomogida (2019) is most closely related to our study, because they take into account North firm's decisions on both production location and technology adoption. However, their focus is rather on indicating negative carbon leakage mentioned above and deriving the optimal emission tax. More importantly, asymmetric features regarding both countries and firms are crucial to their results. By contrast, we maintain symmetries of countries and firms except that one of the countries unilaterally introduces an emission tax. In particular, we show that even if both firms choose the non-taxing country as their production base without emission abatement at some tax rate, a higher tax rate can lead one of the firms not only to adopt the clean technology but also to produce in the taxing country. We also obtain negative carbon leakage under certain conditions with endogenous locations.

The qualitative features of emission taxes coupled with full BTAs are similar to those of consumption-based policies such as consumption taxes. Studies examining the efficiency of such policies in mitigating carbon leakage include Jakob et al. (2013), Eichner and Pethig (2015a,b), and Böhringer et al. (2017).[6] Their focus is basically on constructing more practical policies which can achieve the same effectiveness of CBAs in mitigating carbon leakage concerning that the administration costs of CBAs would be too high to be compensated by the benefit from them. However, our concern is about the question how an emission tax with different BTAs affects firm behaviors and consequential emissions.

4.3 The Basic Model

There are two symmetric countries, country h (Home) and country f (Foreign), and two symmetric firms, firms 1 and 2. The firms produce a homogeneous good with the same fixed costs (FCs) and constant marginal costs (MCs). Both FCs and MCs are normalized to zero. The home and foreign markets are segmented and the firms engage in Cournot competition in each market. To trade the good between the two countries, transportation costs which are τ per unit of the traded good are required. We assume that both firms have a positive supply in each market.

The goods demand is identical between the two markets. Specifically, the inverse demand function is given by[7]

$$p_i(X_i) = a - \frac{X_i^{1-\varepsilon}}{1-\varepsilon};\ i = h, f, \tag{4.1}$$

where h and f, respectively, stand for Home and Foreign; X_i and p_i are, respectively, the demand and consumer price in country i; and a and ε are parameters. Note that ε is the elasticity of the slope of the inverse demand function which is assumed to be constant:

$$\varepsilon = -\frac{X_i p''(X_i)}{p'(X_i)}. \tag{4.2}$$

The (inverse) demand curve is concave if $\varepsilon \leq 0$ and convex if $\varepsilon \geq 0$. If $\varepsilon = 0$, then (4.1) becomes the linear demand function:

$$p_i = a - X_i;\ i = h, f. \tag{4.3}$$

In the following analysis, we impose the following assumption which implies that the outputs are

[6] Consumption-based policies are often investigated when pollution is caused by consumption. In the context of international trade, see Ishikawa and Okubo (2010, 2011) and Tsakiris et al. (2019), for example.

[7] This demand function is often used in the literature of monopoly and oligopoly. It is well known that the elasticity of the slope of the inverse demand function, ε, plays a crucial role in various analyses of monopoly and oligopoly. See Mrázová and Neary (2017).

always strategic substitutes, that is, $p' + p'' x_j < 0$, where x_j is the supply of firm j ($j = 1, 2$), always holds.[8]

Assumption 4.1 $\varepsilon < 1$.

The goods production is dirty in the sense that one unit of production emits one unit of GHGs. The firms can adopt a clean technology by incurring a fixed cost, $F(> 0)$. We call the adoption of a clean technology the abatement investment. The clean technology does not affect production costs but the emissions per unit of production reduce to k ($0 < k < 1$) units. The clean technology is unique and k is exogenously given and fixed. A smaller k means a more efficient abatement. To control the emissions, the home government unilaterally sets a specific emission tax, the rate of which is t, on domestic production. The home government may introduce BTAs.

In the following, we specifically examine three policy regimes. In the first regime (Regime α), the home government imposes an emission tax on domestic production; in the second regime (Regime β), the home government also imposes a specific carbon-content tariff on the imports of the good; and in the third regime (Regime γ), in addition to the emission tax and the carbon-content tariff, the home government refunds the emission tax on exports. The rates of the emission tax, tariff and refund are the same. There is no BAT in Regime α. Two different BTAs, partial and full BTAs, are considered in Regimes β and γ, respectively. Basically, in the presence of an emission tax in Home, production in Home is protected by a tariff in Regime β and is further benefited by an export subsidy in Regime γ.

The profits of firm j ($j = 1, 2$) depend on its technology and location choices and policy regimes. If it does not engage in abatement, the profits producing in Home and Foreign are, respectively, given by

$$\pi_j^{HN} = (p_h - t)x_{jhh} + (p_f - t - \tau + \gamma t)x_{jhf}, \tag{4.4}$$

$$\pi_j^{FN} = (p_h - \tau - \beta t)x_{jfh} + p_f x_{jff}, \tag{4.5}$$

where the first term and the second term are, respectively, the profits from the home market and those from the foreign market. The superscripts of π indicate firm location (H for Home and F for Foreign) and abatement status (N for no abatement and A for abatement). The subscripts indicate the firm, the production location, and the consumption location. For example, "jhf" stands for firm j's output produced in Home and consumed in Foreign. We have $\beta = \gamma = 0$ in Regime α; $\beta = 1$ and $\gamma = 0$ in Regime β; and $\beta = \gamma = 1$ in Regime γ. The profits of firm j with abatement

[8] For details, see Furusawa et al. (2003) and Mrázová and Neary (2017), for example.

are given by

$$\pi_j^{HA} = (p_h - kt)x_{jhh} + (p_f - kt - \tau + \gamma kt)x_{jhf} - F, \tag{4.6}$$
$$\pi_j^{FA} = (p_h - \tau - \beta kt)x_{jfh} + p_f x_{jff} - F, \tag{4.7}$$

If firm j incurs the fixed costs of the abatement investment F, its emission tax per unit of output becomes kt.

We next state two lemmas which are useful for our analysis.[9] In Regime α, for example, an increase in the emission tax rate increases only firm 1's effective MCs. Then the following lemma tells us the effects of an increase in the effective MCs on outputs and profits.

Lemma 4.1 *An increase in the effective MCs of firm j ($j = 1, 2$) to serve a market decreases its supply and profits in the market and increases the supply and profits of the other firm. Total supply in the market decreases.*

In Regimes β and γ, an increase in the emission tax rate increases the effective MCs of both firms to serve Home. Without emission abatement, an increase in the effective MCs to serve Home caused by an increase in the tax rate, Δt, are the same between firms 1 and 2 and equal to Δt. With only firm 1's emission abatement, an increase in firm 1's effective MCs becomes Δkt, which is less than an increase in firm 2's effective MCs Δt.[10] Then the following lemma tells us how a simultaneous increase in the effective MCs affect outputs and profits in Home. The condition in the lemma depends on the share of firm j in Home, σ_{jh}.[11]

Lemma 4.2 *Suppose that the effective MCs of firm 1 to serve Home increase by Δkt and those of firm 2 increase by Δt. Then, firm 1's (firm 2's) supply in Home decreases if and only if $(1-\varepsilon\sigma_{1h}) - k(2 - \varepsilon\sigma_{2h}) < 0$ ($(2 - \varepsilon\sigma_{1h}) - k(1 - \varepsilon\sigma_{2h}) > 0$). Firm 1's (Firm 2's) profits in Home decrease if and only if $(\varepsilon(\sigma_{1h} + 2\sigma_{2h}) - 4)k + (2 - \varepsilon\sigma_{1h}) < 0$ ($(2 - \varepsilon\sigma_{2h})k + (2\varepsilon\sigma_{1h} + \varepsilon\sigma_{2h} - 4) < 0$).*

Note that the condition for the supply decrease becomes $(1 - \varepsilon\sigma_{1h}) - (2 - \varepsilon\sigma_{2h}) < 0$ ($(2 - \varepsilon\sigma_{1h}) - (1 - \varepsilon\sigma_{2h}) > 0$) if neither firm adopts the clean technology or if both firms adopt the clean technology. Also note that an increase in t may increase the supply of one of the two firms. For example, with linear demands (i.e., $\varepsilon = 0$), $(1 - \varepsilon\sigma_{1h}) - k(2 - \varepsilon\sigma_{2h}) > 0$ holds if and only if $k < \frac{1}{2}$.

[9] The proofs are given in the appendix.

[10] If both firms engage in abatement, an increase in the effective MC equals Δkt. The effects an increase in t on supplies and profits in this case are qualitatively the same with those without any abatement.

[11] Ishikawa and Komoriya (2007, 2009) derive similar conditions.

With $k = 1$, $(1 - \varepsilon\sigma_{1h}) - k(2 - \varepsilon\sigma_{2h}) > 0$ holds if and only if $\varepsilon(1 - 2\sigma_{1h}) > 1$.[12] The economic intuition is as follows. The direct effect of an increase in the effective MCs is less output. However, there is an indirect effect; a decrease in the output increases the output of the other firm because of strategic substitutability. The output increase caused by the indirect effect can dominate the output decrease by the direct effect. This is the case only if the effective MCs are different between the two firms.

4.4 Fixed Location

In this section, we investigate the case where firm locations are fixed. We assume that firm 1 is in Home while firm 2 is in Foreign. There are two stages of decision. In the first stage, taking home environmental policies as given, the firms decide whether to adopt a clean technology (i.e., to invest in emission abatement). In the second stage, the firms compete in both home and foreign markets.

If the environmental regulation is not very stringent, the firms have no incentive to abate emissions. However, if the emission tax is high, the firms may engage in emission abatement to reduce their tax payments. We are particularly interested in how the three policy regimes affect firms' decisions and the consequent emissions.

4.4.1 Emission Tax without Any BTAs (Regime α)

In this regime, the home government sets only an emission tax on domestic production. When there is no BTA, firm 2 has no incentive to adopt the clean technology because its abatement does not affect its effective MCs for exports. The profits of each firm without emission abatement are, respectively, given by

$$\pi_1^{HFNN\alpha} = (p_h^{NN\alpha} - t)x_{1hh}^{NN\alpha} + (p_f^{NN\alpha} - t - \tau)x_{1hf}^{NN\alpha} = -p_h'(x_{1hh}^{NN\alpha})^2 - p_f'(x_{1hf}^{NN\alpha})^2, \quad (4.8)$$

$$\pi_2^{HFNN\alpha} = (p_h^{NN\alpha} - \tau)x_{2fh}^{NN\alpha} + p_f^{NN\alpha}x_{2ff}^{NN\alpha}. \quad (4.9)$$

The superscripts of π_j $(j = 1, 2)$ indicate firm 1's location, firm 2's location, firm 1's abatement status, firm 2's abatement status, and the regime. For example, "$HFNN\alpha$" stands for the profits when firm 1 is in Home, firm 2 is in Foreign, and neither firm is engaged in abatement in Regime α. The superscripts of x and p_i $(i = h, f)$ indicate firm 1's abatement status, firm 2's abatement

[12] $\varepsilon(1 - 2\sigma_{1h}) > 1$ holds only if both $\varepsilon < 0$ (i.e., the demands are concave) and $\sigma_{1h} > 1/2$ hold.

status, and the regime. The profits of each firm with firm 1's abatement are, respectively, given by

$$\pi_1^{HFAN\alpha} = (p_h^{AN\alpha} - kt)x_{1hh}^{AN\alpha} + (p_f^{AN\alpha} - kt - \tau)x_{1hf}^{AN\alpha} - F, \tag{4.10}$$

$$\pi_2^{HFAN\alpha} = (p_h^{AN\alpha} - \tau)x_{2fh}^{AN\alpha} + p_f^{AN\alpha}x_{2ff}^{AN\alpha}. \tag{4.11}$$

With $t = 0$, $\pi_1^{HFNN\alpha} - \pi_1^{HFAN\alpha} = F$, implying firm 1 has no incentive for emission abatement. Although both $\pi_1^{HFNN\alpha}$ and $\pi_1^{HFAN\alpha}$ are decreasing in t, $\pi_1^{HFNN\alpha} < \pi_1^{HFAN\alpha}$ can hold for some $t(> 0)$. With $\pi_1^{HFNN\alpha} < \pi_1^{HFAN\alpha}$, firm 1 would engage in emission abatement.

It should be pointed out that $\pi_1^{HFNN\alpha} = \pi_1^{HFAN\alpha}$ can hold multiple times. To illustrate this possibility, we consider the linear demands (4.3).[13] To ensure both $x_{1hi} > 0$ and $x_{2fi} > 0$ in the following analysis, we assume $a - 2(t + \tau) > 0$, i.e., $t < \frac{a-2\tau}{2} \equiv \bar{t}$ in the case of linear demands. We obtain

$$g^\alpha(t) \equiv (\pi_1^{HFAN\alpha} + F) - \pi_1^{HFNN\alpha} = \frac{4t}{9}(1-k)(2a - 2t - \tau - 2kt), \tag{4.12}$$

which is an inverted parabola with the vertex $\left(\frac{2a-\tau}{4(k+1)}, \frac{(1-k)(2a-\tau)^2}{18(1+k)}\right)$, implying that $\pi_1^{HFNN\alpha} = \pi_1^{HFAN\alpha}$ holds twice if $F < \frac{(1-k)(2a-\tau)^2}{18(1+k)}$. We let $t_1^{\alpha S}$ and $t_1^{\alpha L}$ ($t_1^{\alpha S} < t_1^{\alpha L}$) denote the tax rates at which $\pi_1^{HFNN\alpha} = \pi_1^{HFAN\alpha}$ holds. Noting $\bar{t}$, therefore, firm 1 with $F < \frac{(1-k)(2a-\tau)^2}{18(1+k)}$ would abate its emissions if $t_1^{\alpha S} < t < \min\{t_1^{\alpha L}, \bar{t}\}$ holds.[14]

It is intuitive that firm 1 would not engage in emission abatement if F is too high. Interestingly, however, firm 1 also loses an incentive for emission abatement if $t_1^{\alpha L} < t < \bar{t}$ holds. Although both $\pi_1^{HFNN\alpha}$ and $\pi_1^{HFAN\alpha}$ are decreasing in t, the incentive depends on the gap between $\pi_1^{HFNN\alpha}$ and $\pi_1^{HFAN\alpha}$ (i.e., $g^\alpha(t)$). Thus, the relationship between the emission tax rate and emission abatement is not very straightforward.

To explore this, let us consider

$$\frac{dg^\alpha(t)}{dt} = \frac{4}{3}[(x_{1hh}^{NN\alpha} + x_{1hf}^{NN\alpha}) - k(x_{1hh}^{AN\alpha} + x_{1hf}^{AN\alpha})]. \tag{4.13}$$

$\left.\frac{dg^\alpha(t)}{dt}\right|_{t=0} > 0$ because both $x_{1hh}^{NN\alpha} = x_{1hh}^{AN\alpha}$ and $x_{1hf}^{NN\alpha} = x_{1hf}^{AN\alpha}$ hold at $t = 0$. Thus, the marginal benefit from emission abatement is positive when t is sufficiently small. Note that $(x_{1hh}^{AN\alpha} + x_{1hf}^{AN\alpha}) > (x_{1hh}^{NN\alpha} + x_{1hf}^{NN\alpha})$ holds if $t > 0$. When t is large, $k(x_{1hh}^{AN\alpha} + x_{1hf}^{AN\alpha}) > (x_{1hf}^{NN\alpha} + x_{1hf}^{NN\alpha})$ holds. $\frac{dg^\alpha(t)}{dt} < 0$ implies that firm 1 may lose an incentive for abatement. The above argument can be rephrased in terms of intuition as follows. Emission abatement makes the tax per output lower but the tax base larger. The former is a positive effect of emission abatement while the latter is a negative effect. The positive effect dominates the negative effect if t is small, and vice versa if t is large. Thus, firm

[13] The following argument is valid with general demands.
[14] The following is a necessary condition for $t_1^{\alpha L} < \bar{t}$: $\frac{2a-\tau}{4(k+1)} < \bar{t}$ (i.e., $k < \frac{3\tau}{2(a-2\tau)}$).

1 may not have an incentive for emission abatement if t is large.

Figure 4.1 illustrates the above result. When $F = F_a$, firm 1 would not adopt the clean technology. When $F = F_b$, firm 1 would adopt the clean technology if the tax rate is in the middle range (i.e., $t_1^{\alpha S} < t < t_1^{\alpha L}$). When $F = F_c$, firm 1 would adopt the clean technology if the tax rate is high (i.e., $t_1^{\alpha S} < t < \bar{t}$).

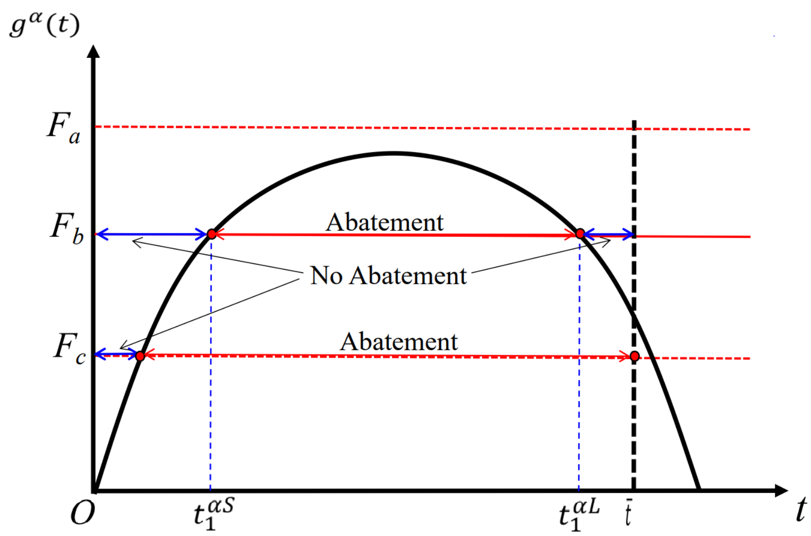

Figure 4.1: Abatement decisions in Regime α.

Another interesting point is that an emission tax may backfire. Without emission abatement, an increase in the emission tax decreases firm 1's emissions but increases firm 2's emissions (see Lemma 4.1). Thus, cross-border carbon leakage occurs but global emissions decrease. However, if firm 1 adopts the clean technology at the lowest tax rate which leads to $\pi_1^{HFNN\alpha} = \pi_1^{HFAN\alpha}$, firm 2's emissions necessarily decrease while firm 1's emissions can increase. The reason is as follows. Since firm 1's abatement investment raises its total output, its total emissions can increase even though emissions per unit of firm 1's output decrease.[15] If the increase in firm 1' emissions dominates the decrease in firm 2's emissions, global emissions increase as a result of the abatement investment.

[15]If $k = 0$, firm 1's emissions necessarily decrease. Thus, from the continuity argument, firm 1's emissions decrease as long as k is close to zero.

This can be confirmed with liner demands (4.3). For a given t, we have

$$\begin{aligned} E_1^{HFNN\alpha} - E_1^{HFAN\alpha} &= \frac{1}{3}(a - 2t + \tau) + (a - 2(t + \tau))) \\ &\quad -\frac{k}{3}((a - 2kt + \tau) + (a - 2(kt + \tau)))) \\ &= \frac{1}{3}(1 - k)(2a - 4t - \tau - 4kt) < 0 \\ &\Leftrightarrow (2a - 4t - \tau - 4kt) < 0. \qquad (4.14) \\ E^{HFNN\alpha} - E^{HFAN\alpha} &= \frac{1}{3}(2(2a - t - \tau)) - \frac{1}{3}((-4t)k^2 + (2a + 2t - \tau)k + (2a - \tau)) \\ &= \frac{1}{3}(1 - k)(2a - 2t - \tau - 4kt) < 0 \\ &\Leftrightarrow (2a - 2t - \tau - 4kt) < 0. \qquad (4.15) \end{aligned}$$

We can easily find parameter values (a, τ, and k) and $t(< \bar{t})$ with which $E^{HFNN\alpha} < E^{HFAN\alpha}$and/or $E_1^{HFNN\alpha} < E_1^{HFAN\alpha}$ hold.

It is also noteworthy that $E_1^{HFNN\alpha}$, $E_1^{HFAN\alpha}$ and $E^{HFNN\alpha}$ are decreasing in t, while $E^{HFAN\alpha}$ can be increasing in t. At first glance, it seems counter intuitive that an increase in t increases global emissions regardless of the presence of the abatement investment. The economic intuition behind this result is as follows. An increase in t decreases firm 1's output and increases firm 2's output. When $k(> 0)$ is small, the decrease in firm 1's emissions caused by an increase in the emission tax is small because it is equal to k times the decrease in firm 1's output. Thus, it is dominated by the increase in firm 2's emissions caused by an increase in the emission tax, which is simply equal to the increase in firm 2's output. In the case of linear demands, $E^{HFAN\alpha}$ is decreasing in t if and only if $k > \frac{1}{2}$.

Thus, the following proposition is established.

Proposition 4.1 *An emission tax can induce firm 1 to invest in emission abatement if the investment cost is not too high. Even if firm 1 has an incentive for emission abatement for some emission tax rates, it may lose the incentive for higher tax rates. For a given t, firm 1's emission abatement decreases firm 2's emissions but may increase global emissions as well as firm 1's emissions. If firm 1's emission abatement is highly efficient (i.e., k is small), an increase in t increases global emissions in the presence of firm 1's abatement.*

4.4.2 Emission Tax with Carbon-content Tariff (Regime β)

In this regime, an emission tax is accompanied by the carbon-content tariff whose tax rate is the same with the emission tax rate. The carbon-content tariff affects only firm 2's effective MCs for exports. Without emission abatement, the introduction of the tariff for a given t increases firm 1's output for the home market and decreases firm 2's output for the home market (recall Lemma 4.1). Since the decrease dominates the increase, the total output for the home market falls. Thus, for a given t, a carbon-content tariff raises firm 1's emissions and reduces both firm 2's emissions and global emissions, i.e., $E_1^{HFNN\beta} > E_1^{HFNN\alpha}$, $E_2^{HFNN\beta} < E_2^{HFNN\alpha}$, and $E^{HFNN\beta} < E^{HFNN\alpha}$. Note that compared with Regime α, cross-border carbon leakage is weakened because emissions from firm 2's output for the home market become lower.

Next we consider emission abatement. The profits of each firm with only firm 1's abatement investment are, respectively, given by

$$\pi_1^{HFAN\beta} = (p_h^{AN\beta} - kt)x_{1hh}^{AN\beta} + (p_f^{AN\beta} - kt - \tau)x_{1hf}^{AN\beta} - F, \tag{4.16}$$

$$\pi_2^{HFAN\beta} = (p_h^{AN\beta} - \tau - t)x_{2fh}^{AN\beta} + p_f^{AN\beta}x_{2ff}^{AN\beta}. \tag{4.17}$$

The profits of each firm with only firm 2's abatement investment are analogous:

$$\pi_1^{HFNA\beta} = (p_h^{NA\beta} - t)x_{1hh}^{NA\beta} + (p_f^{NA\beta} - t - \tau)x_{1hf}^{NA\beta}, \tag{4.18}$$

$$\pi_2^{HFNA\beta} = (p_h^{NA\beta} - \tau - kt)x_{2fh}^{NA\beta} + p_f^{NA\beta}x_{2ff}^{NA\beta} - F. \tag{4.19}$$

The profits with abatement investment by both firms are, respectively, given by

$$\pi_1^{HFAA\beta} = (p_h^{AA\beta} - kt)x_{1hh}^{AA\beta} + (p_f^{AA\beta} - kt - \tau)x_{1hf}^{AA\beta} - F, \tag{4.20}$$

$$\pi_2^{HFAA\beta} = (p_h^{AA\beta} - \tau - kt)x_{2fh}^{AA\beta} + p_f^{AA\beta}x_{2ff}^{AA\beta} - F. \tag{4.21}$$

The carbon-content tariff affects firm 2's effective MCs, implying that firm 2 may also have an incentive for the abatement investment if t is sufficiently high. Whereas firm 1's abatement makes its effective MCs lower for its total production, firm 2's abatement decreases its effective MCs only for its exports. Thus, it is more likely that firm 1 has more incentive to abate its emissions than firm 2. We can examine if this is actually the case by checking the following sign:

$$\begin{aligned}\Delta\pi_{12}^{\beta} &\equiv (\pi_1^{HFAN\beta} - \pi_1^{HFNN\beta}) - (\pi_2^{HFNA\beta} - \pi_2^{HFNN\beta}) \\ &= [(p_h^{AN\beta} - kt)x_{1hh}^{AN\beta} - (p_h^{NN\beta} - t)x_{1hh}^{NN\beta}] \\ &\quad +[(p_f^{AN\beta} - kt - \tau)x_{1hf}^{AN\beta} - (p_f^{NN\beta} - t - \tau)x_{1hf}^{NN\beta}] \\ &\quad -[(p_h^{NA\beta} - \tau - kt)x_{2fh}^{NA\beta} - (p_h^{NN\beta} - \tau - t)x_{2fh}^{NN\beta}]. \end{aligned} \tag{4.22}$$

If τ is sufficiently small, the first square bracket and the third square bracket are almost equal. Since the second square bracket is positive, we obtain $\Delta\pi_{12}^{\beta} > 0$. Thus, the threshold tax rate between no abatement and abatement is lower for firm 1 than for firm 2 if τ is sufficiently small.

Moreover, the appendix proves that $\Delta\pi_{12}^{\beta} > 0$ holds regardless of the size of τ if $\varepsilon \geq 0$. To elaborate on the abatement decisions by the firms, we focus on linear demands (4.3). First, we can confirm

$$\Delta\pi_{12}^{\beta} = \frac{4t}{9}(1-k)\,(a - t + \tau - kt) > 0, \tag{4.23}$$

for $0 < t < \bar{t}(< \frac{a+\tau}{1+k})$. Thus, letting $t_1^{\beta S}$ denote the lowest t which satisfies $\pi_1^{HFAN\beta} = \pi_1^{HFNN\beta}$, firm 2 would not abate emissions (i.e., $\pi_2^{HFNA\beta} < \pi_2^{HFNN\beta}$) if $t < t_1^{\beta S}$. Firm 1's incentive for abatement investment given no abatement by firm 2 can be seen from the following:

$$g^{\beta}(t) \equiv (\pi_1^{HFAN\beta} + F) - \pi_1^{HFNN\beta} = \frac{4t}{9}\,(1-k)\,(2a - t - \tau - 2kt)\,, \tag{4.24}$$

which is an inverted parabola with the vertex $\left(\frac{2a-\tau}{2(2k+1)}, \frac{(1-k)(2a-\tau)^2}{9(2k+1)}\right)$, implying that $\pi_1^{HFNN\beta} = \pi_1^{HFAN\beta}$ holds twice at $t_1^{\beta S}$and $t_1^{\beta L}$ if $F < \frac{(1-k)(2a-\tau)^2}{9(2k+1)}$. Noting $\bar{t}$, therefore, firm 1 with $F < \frac{(1-k)(2a-\tau)^2}{9(2k+1)}$ would abate its emissions if $t_1^{\beta S} < t < \min\{t_1^{\beta L}, \bar{t}\}$ holds.[16]

Note that once firm 1 adopts the clean technology, firm 2 may change its strategy, that is, firm 2 may also adopt the clean technology. Thus, we need to check firm 2's incentive for the abatement investment given firm 1's investment. We have

$$h^{\beta}(t) \equiv (\pi_2^{HFAA\beta} + F) - \pi_2^{HFAN\beta} = \frac{4t}{9}(1-k)\,(a - t - 2\tau)\,, \tag{4.25}$$

which is an inverted parabola with the vertex $\left(\frac{a-2\tau}{2}, \frac{(1-k)(a-2\tau)^2}{9}\right)$. Thus, if $F < \frac{(1-k)(a-2\tau)^2}{9}$, then there exists the tax rate, $t_2^{\beta}(< \bar{t})$, at which $\pi_2^{HFAA\beta} = \pi_2^{HFAN\beta}$ holds.[17] We can readily verify that $g^{\beta}(t) = h^{\beta}(t)$ holds at $t = \frac{1}{2k}\,(a+\tau)\,(\equiv \widetilde{t})$, which is greater than both $\frac{2a-\tau}{2(2k+1)}$ and $\frac{a-2\tau}{2}$. This

[16]The following is a necessary condition for $t_1^{\beta L} < \bar{t}$: $\frac{2a-\tau}{2(2k+1)} < \bar{t}$ (i.e., $-a - \tau - 4k\tau + 2ka > 0$).

[17]If $F < \frac{(1-k)(a-2\tau)^2}{9}$, there exist two tax rates which lead to $\pi_2^{HFAA\beta} = \pi_2^{HFAN\beta}$. However, the higher tax rate is always greater than $\bar{t}$.

implies that $g^{\beta}(t) > h^{\beta}(t)$ for $t < \widetilde{t}$ and the slopes of $g^{\beta}(t)$ and $h^{\beta}(t)$ are negative at $\widetilde{t}$. Thus, we obtain $t_1^{\beta S} < t_2^{\beta}$, meaning there exists a range of t under which firm 1 would adopt the clean technology but firm 2 would not. In the presence of firm 1's abatement investment, firm 2 would also invest in emission abatement if $t_2^{\beta} < t < \min\{t_1^{\beta L}, \bar{t}\}$.

Conversely, we need to check whether firm 1 would still adopt the clean technology even if firm 2 also adopts the clean technology. For this, we examine firm 1's incentive for the abatement investment given firm 2's investment. We have

$$m^{\beta}(t) \equiv (\pi_1^{HFAA\beta} + F) - \pi_1^{HFNA\beta} = \frac{4t}{9}(1-k)(2a - 2t - \tau - kt). \tag{4.26}$$

Since $m^{\beta}(t) = h^{\beta}(t)$ holds at $t = \frac{a+\tau}{k+1}$, $m^{\beta}(t) > h^{\beta}(t)$ for $0 < t < \bar{t} < \frac{a+\tau}{k+1}$. This implies both firms engage in abatement if firm 2 adopts the clean technology. Thus, unless F is very large, there is a threshold of t below which only firm 1 adopts the clean technology and above which both firms adopt the clean technology.

Just like in the case with an emission tax alone, as a result of the abatement investment by only firm 1, firm 2's emissions decrease but firm 1's emissions and global emissions can increase. With linear demands, we obtain

$$\begin{aligned} E_1^{HFNN\beta} - E_1^{HFAN\beta} &= \frac{1}{3}(1-k)(2a - 3t - \tau - 4kt) < 0 \\ &\Leftrightarrow (2a - 3t - \tau - 4kt) < 0 \qquad (4.27) \\ E^{HFNN\beta} - E^{HFAN\beta} &= \frac{1}{3}(1-k)(2a - t - \tau - 4kt) < 0 \\ &\Leftrightarrow (2a - t - \tau - 4kt) < 0, \qquad (4.28) \end{aligned}$$

for a given t. Compared with (4.15), however, $E^{HFNN\beta} < E^{HFAN\beta}$ is less likely. Moreover, $E_2^{HFAN\beta}$ and $E^{HFAN\beta}$ are decreasing in t, while $E_1^{HFAN\beta}$ is decreasing in t if and only if $k > \frac{1}{4}$.

Firm 2's emission abatement does not affect the outputs for the foreign market, meaning the emissions stemming from firm 1's output for the foreign market are constant while those from firm 2's output for the foreign market decrease. Firm 1's output for the home market decreases while firm 2's output for the home market increase. Although the emissions stemming from firm 1's output for the home market decrease, it is generally ambiguous whether those from firm 2's output for the home market decrease. With linear demands, we can readily verify $E_1^{HFAA\beta} < E_1^{HFAN\beta}$, $E_2^{HFAA\beta} < E_2^{HFAN\beta}$, and $E^{HFAA\beta} < E^{HFAN\beta}$. Moreover, with general demands, $E_1^{HFAA\beta}$ and $E^{HFAA\beta}$ are decreasing in t, while $E_2^{HFAA\beta}$ may or may not be decreasing in t.[18]

Next, comparing between Regimes α and β, we examine how the presence of the carbon-content

[18] With linear demands, $E_2^{HFAA\beta}$ is independent of t.

tariff affects firm 1's incentive for abatement investment. For this, we check the sign of the following:

$$\begin{aligned}\Delta\pi_1^{\alpha\beta} &\equiv (\pi_1^{HFAN\alpha} - \pi_1^{HFNN\alpha}) - (\pi_1^{HFAN\beta} - \pi_1^{HFNN\beta}) \\ &= (p_h^{AN\alpha} - kt)x_{1hh}^{AN\alpha} - (p_h^{NN\alpha} - t)x_{1hh}^{NN\alpha} - ((p_h^{AN\beta} - kt)x_{1hh}^{AN\beta} - (p_h^{NN\beta} - t)x_{1hh}^{NN\beta}). \qquad (4.29)\end{aligned}$$

If this is negative, the range of t, in which firm 1 would engage in abatement investment, expands, that is, firm 1 has an incentive to abate emissions for lower emission taxes with the carbon-content tariff than without it. Compared to the case with an emission tax alone, for a given t, firm 1's output for the home market increases while its output for the foreign market remains unchanged. Thus, it is more likely that firm 1 would abate emissions for smaller emission taxes. The appendix shows $\Delta\pi_1^{\alpha\beta} < 0$ if $\varepsilon \geq 0$. Figure 4.2 illustrates a possible case where $t_1^{\beta S} < t_1^{\alpha S} < t_2^{\beta} < \bar{t} < t_1^{\alpha L}$ holds.

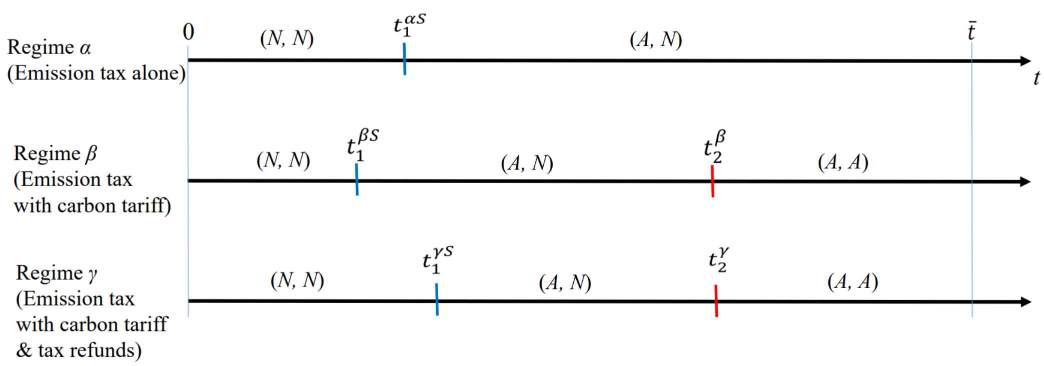

Figure 4.2: Abatement choices with fixed locations.

We now compare the emission level between Regimes α and β when only firm 1 invests in emission abatement (i.e., a comparison between $E^{HFAN\alpha}$ and $E^{HFAN\beta}$). The carbon-content tariff does not affect the emissions stemming from the outputs for the foreign market. With respect to the outputs for the home market, firm 1's output increases but firm 2's output and the total output decrease. This implies that for a given t, $E_1^{HFAN\beta} > E_1^{HFAN\alpha}$, $E_2^{HFAN\beta} < E_2^{HFAN\alpha}$, and $E^{HFAN\beta} < E^{HFAN\alpha}$ hold.

Thus, we obtain the following proposition.

Proposition 4.2 *An emission tax accompanied by the carbon-content tariff can induce firm 2 as well as firm 1 to invest in emission abatement if the investment cost is not too high. Firm 1 has more incentive to invest in emission abatement than firm 2 if τ is sufficiently small or if demands* *are convex (i.e., if $\varepsilon \geq 0$). The introduction of the carbon-content tariff for a given t, if it does not change the abatement decisions, increases firm 1's emissions but decreases both firm 2's emissions and global emissions. An increase in t decreases global emissions if neither firm or both firms adopt the clean technology, but can increase them if only firm 1 adopts the clean technology. Firm 1 has more incentive to invest in emission abatement with carbon-content tariff than without it if demands are convex (i.e., if $\varepsilon \geq 0$).*

4.4.3 Emission Tax Coupled with Tax Refunds at the Border and Carbon-content Tariff (Regime γ)

When the emission-tax refunds are introduced, the effective MCs to serve the foreign market are independent of the home emission tax. Thus, firm 1's disadvantage in the foreign market is offset. Furthermore, cross-border carbon leakage is prevented because firm 2's emissions always decrease in t. However, this does not necessarily result in less global emissions. Since the tax refunds are basically an export subsidy, compared with Regime β, firm 1's output for the foreign market increases while firm 2's output for the foreign market decreases. Since the former effect dominates the latter effect, the total output for the foreign market rises. Thus, without emission abatement, we have $E_1^{HFNN\gamma} > E_1^{HFNN\beta}$, $E_2^{HFNN\gamma} < E_2^{HFNN\beta}$, and $E^{HFNN\gamma} > E^{HFNN\beta}$ for a given t.

We next take emission abatement into account. The profits of each firm with only firm 1's abatement investment are, respectively, given by

$$\pi_1^{HFAN\gamma} = (p_h^{AN\gamma} - kt)x_{1hh}^{AN\gamma} + (p_f^{AN\gamma} - \tau)x_{1hf}^{AN\gamma} - F, \tag{4.30}$$
$$\pi_2^{HFAN\gamma} = (p_h^{AN\gamma} - \tau - t)x_{2fh}^{AN\gamma} + p_f^{AN\gamma} x_{2ff}^{AN\gamma}. \tag{4.31}$$

The profits of each firm with only firm 2's abatement investment are analogous.

$$\pi_1^{HFNA\gamma} = (p_h^{NA\gamma} - t)x_{1hh}^{NA\gamma} + (p_f^{NA\gamma} - \tau)x_{1hf}^{NA\gamma}, \tag{4.32}$$
$$\pi_2^{HFNA\gamma} = (p_h^{NA\gamma} - \tau - kt)x_{2fh}^{NA\gamma} + p_f^{NA\gamma} x_{2ff}^{NA\gamma} - F. \tag{4.33}$$

If both firms invest in emission abatement, the profits of each firm are

$$\pi_1^{HFAA\gamma} = (p_h^{AA\gamma} - kt)x_{1hh}^{AA\gamma} + (p_f^{AA\gamma} - \tau)x_{1hf}^{AA\gamma} - F, \tag{4.34}$$
$$\pi_2^{HFAA\gamma} = (p_h^{AA\gamma} - \tau - kt)x_{2fh}^{AA\gamma} + p_f^{AA\gamma} x_{2ff}^{AA\gamma} - F. \tag{4.35}$$

Whereas firm 1's abatement decreases its effective MCs only for its domestic production from t to kt, firm 2's abatement decreases its effective MCs only for its exports from $t + \tau$ to $kt + \tau$. Firm

1 has more incentive to abate its emissions than firm 2 if the following sign is positive:

$$\begin{aligned}\Delta\pi_{12}^{\gamma} &\equiv (\pi_1^{HFAN\gamma} - \pi_1^{HFNN\gamma}) - (\pi_2^{HFNA\gamma} - \pi_2^{HFNN\gamma}) \\ &= [(p_h^{AN\gamma} - kt)x_{1hh}^{AN\gamma} - (p_h^{NN\gamma} - t)x_{1hh}^{NN\gamma}] \\ &\quad -[(p_h^{NA\gamma} - \tau - kt)x_{2fh}^{NA\gamma} - (p_h^{NN\gamma} - \tau - t)x_{2fh}^{NN\gamma}]. \end{aligned} \tag{4.36}$$

The appendix shows that $\Delta\pi_{12}^{\gamma} > 0$ if $\varepsilon \geq 0$.

With linear demands (4.3), the threshold of the tax rate between no abatement and abatement is lower for firm 1 than for firm 2, because the following holds:

$$\Delta\pi_{12}^{\gamma} = \frac{4t\tau(1-k)}{3} > 0. \tag{4.37}$$

Firm 1's incentive for abatement investment can be seen from the following:

$$g^{\gamma}(t) \equiv (\pi_1^{HFAN\gamma} + F) - \pi_1^{HFNN\gamma} = \frac{4t}{9}\left(1-k\right)\left(a+\tau-kt\right), \tag{4.38}$$

which is an inverted parabola with the vertex $\left(\frac{a+\tau}{2k}, \frac{(1-k)(a+\tau)^2}{9k}\right)$, implying that $\pi_1^{HFNN\gamma} = \pi_1^{HFAN\gamma}$ holds twice at $t_1^{\gamma S}$and $t_1^{\gamma L}$ ($t_1^{\gamma S} < t_1^{\gamma L}$) if $F < \frac{(1-k)(a+\tau)^2}{9k}$. However, $t_1^{\gamma L} > \bar{t}$ holds because $\bar{t} < \frac{a+\tau}{2k}$. Thus, with $F < \frac{(1-k)(a+\tau)^2}{9k}$, firm 1 would abate its emissions if $t_1^{\gamma S} < t < \bar{t}$ holds.

As in Regime β, we need to check firm 2's incentive for the abatement investment given firm 1's investment. With linear demands, we have

$$h^{\gamma}(t) \equiv (\pi_2^{HFAA\gamma} + F) - \pi_2^{HFAN\gamma} = \frac{4t}{9}(1-k)\left(a-t-2\tau\right) = h^{\beta}(t). \tag{4.39}$$

If $F < \frac{(1-k)(a-2\tau)^2}{9}$, then there exit the tax rate $t_2^{\gamma}(< \bar{t})$ at which $\pi_2^{HFAA\beta} = \pi_2^{HFAN\beta}$ holds. We can readily verify that $g^{\gamma}(t) = h^{\gamma}(t)$ holds at $t = \frac{3\tau}{k-1}(< 0)$ which implies that $g^{\gamma}(t) > h^{\gamma}(t)$ for $t > 0$.[19] Thus, we obtain $t_1^{\gamma S} < t_2^{\gamma}$, meaning there exists a range of t under which firm 1 would adopt the clean technology while firm 2 would not. In the presence of firm 1's abatement investment, firm 2 would also invest in emission abatement if $t_2^{\gamma} < t < \min\{t_1^{\gamma L}, \bar{t}\}$.

Conversely, we examine firm 1's incentive for the abatement investment given firm 2's investment. With linear demands, we have

$$m^{\gamma}(t) \equiv (\pi_1^{HFAA\gamma} + F) - \pi_1^{HFNA\gamma} = \frac{4t}{9}\left(1-k\right)\left(a-t+\tau\right). \tag{4.40}$$

[19] The threshold tariff rate between no abatement and abatement for firm 2 is the same between Regimes β and γ, i.e., $t_2^{\gamma} = t_2^{\beta}$ (see Figure 4.2).

Since $m^{\gamma}(t) > h^{\gamma}(t)$ holds for $t > 0$, both firms engage in abatement if firm 2 adopts the clean technology. Thus, unless F is very large, there is a threshold of t below which only firm 1 adopts the clean technology and above which both firms adopt the clean technology.

With linear demands, we can also verify that $E_2^{HFAN\gamma}$ and $E^{HFAN\gamma}$ are decreasing in t, while $E_1^{HFAN\gamma}$ is decreasing in t if and only if $k > \frac{1}{2}$. With the abatement investment by both firms, the emission level is larger in Regime γ than in Regime β (i.e., $E^{HFAA\gamma} > E^{HFAA\beta}$) for a given t, because the supply to the home market remains the same but the supply to the foreign market increases in Regime γ.

Compared with Regime β, whether or not firm 1 engages in emission abatement, firm 1's effective MCs for exports become τ alone. The other MCs are not affected by the introduction of the tax refunds. Thus, for a given t, we obtain

$$\begin{aligned}&(\pi_1^{HFAN\beta} - \pi_1^{HFNN\beta}) - (\pi_1^{HFAN\gamma} - \pi_1^{HFNN\gamma}) \\ &= (p_f^{AN\beta} - kt - \tau)x_{1hf}^{AN\beta} - (p_f^{NN\beta} - t - \tau)x_{1hf}^{NN\beta} > 0,\end{aligned} \tag{4.41}$$

implying that the threshold of the tax rate between no abatement and abatement for firm 1 is larger in Regime γ than in Regime β (see Figure 4.2).[20] This result is intuitive because the tax refunds decrease the benefit of emission abatement. Thus, the tax refunds discourage firm 1's abatement investment. We can also verify

$$(\pi_2^{HFAA\beta} - \pi_2^{HFAN\beta}) - (\pi_2^{HFAA\gamma} - \pi_2^{HFAN\gamma}) = 0, \tag{4.42}$$

meaning that the threshold of the tariff rate between no abatement and abatement for firm 2 is the same between in Regime γ and in Regime β.

However, this does not necessarily mean that for a given t, the emission level with the tax refunds is larger than that without them. With linear demands (4.3), for example, we obtain

$$E^{HFAN\gamma} - E^{HFAN\beta} = \frac{kt}{3}(2k-1) > 0 \Leftrightarrow k > \frac{1}{2}. \tag{4.43}$$

The tax refunds affect the supply to the foreign market alone. In the foreign market, the total supply increases but firm 1's supply (i.e., the supply subject to the emission tax) increases more than the total supply. As a result, it is ambiguous whether the total emissions increase. When k is small, the increase in the total supply in the foreign market is small, but some of firm 2's supply is replaced by firm 1's supply which is subject to low per-unit emissions. Thus, for a given t, the introduction of the tax refunds can decrease the total emissions. However, if both firms adopt the

[20] This result does not depend on linear demands.

clean technology, the introduction of the tax refunds necessarily increases the total emissions, that is, $E_1^{HFAA\gamma} > E_1^{HFAA\beta}$, $E_2^{HFAA\gamma} < E_2^{HFAA\beta}$, and $E^{HFAA\gamma} > E^{HFAA\beta}$ holds for a given t.

Thus, we obtain the following proposition.

Proposition 4.3 *The introduction of the emission-tax refunds for exports in addition to the border carbon-content tariff eliminates cross-border carbon leakage caused by an emission tax. The emission-tax refunds make the threshold tax rate between no abatement and abatement for firm 1 larger but does not change that for firm 2. For a given t at which neither firm or both firms adopt the clean technology, global emissions are larger with the emission-tax refunds than without them (i.e., $E^{HFNN\gamma} > E^{HFNN\beta}$ and $E^{HFAA\gamma} > E^{HFAA\beta}$ hold). However, for a given t at which only firm 1 adopts the clean technology, global emissions can be smaller with the tax refunds than without them (i.e., $E^{HFAN\gamma} < E^{HFAN\beta}$ can hold) if k is small.*

4.5 Endogenous Locations

In this section, we investigate the case where the firms choose their locations. The decision stages are modified as follows. In the first stage, taking home emission policies as given, the firms choose their locations and technologies simultaneously. In the second stage, the firms compete in both home and foreign markets. We assume that the firms do not incur any cost to choose their locations.[21]

Since there are two locations and two technologies, each firm has four strategies in the first stage: HN (Home and no abatement), HA (Home and abatement), FN (Foreign and no abatement), and FA (Foreign and abatement). The complete analysis of endogenous location and technology choices is rather complicated because there are many possible cases to consider. Thus, the purpose of this section is not to provide the complete analysis in the presence of endogenous location and technology choices but to show interesting location patterns.

First of all, we can make the following claim.[22]

Lemma 4.3 *The two firms would not choose the same location without any emission tax if demands are convex (i.e., $\varepsilon \geq 0$).*

We assume that the two firms choose the different locations without any emission tax. We also assume that if the two firms choose the different locations, firms 1 and 2, respectively, choose Home

[21] We can introduce a set-up fixed cost. As long as it is the same between Home and Foreign, however, the essence of our analysis would not change.

[22] The proof is given in the appendix.

and Foreign. Obviously, no firm would invest in the clean technology without any emission tax.

In the following, we first show that there can be a threshold tax rate at which both firms choose Foreign. In Regime α, the emission tax whose rate is above the threshold is not effective at all. In Regimes β and γ, we show that even if both firms choose Foreign for some tax rates, they may choose different locations for higher tax rates.

4.5.1 Tax without Any BTAs (Regime α)

The location pattern that firms 1 and 2, respectively, choose Home and Foreign remains to be realized as long as t is sufficiently small. When t is relatively large, firm 1 may choose locating itself in Foreign or engage in abatement in Home. Without firm 1's abatement, the threshold tax rate at which firm 1 chooses Foreign is less than τ, because firm 1's effective MCs are t for the home market and $t+\tau$ for the foreign market with (HN, FN), but are τ for the home market and 0 for the foreign market with (FN, FN).[23] With firm 1's abatement, the threshold tax rate at which firm 1 chooses Foreign is higher than without it, but is less than τ/k. However, if k is sufficiently close to zero, firm 1 is unlikely to choose Foreign even with high tax rates. Thus, in the following analysis, we focus on the case where the first-stage equilibrium switches from (HN, FN) to (FN, FN) when the tax rate becomes higher.

If both firms choose Foreign, they have no incentive for emission abatement and become identical. The profits are given by

$$\pi_j^{FFNN\alpha} = (p_h^{NN\alpha} - \tau)x_{jfh}^{NN\alpha} + p_f^{NN\alpha}x_{jff}^{NN\alpha}, \quad j = 1, 2. \tag{4.44}$$

As long as both firms are located in Foreign, the emission levels, $E_j^{FFNN\alpha}$and $E^{FFNN\alpha}$ are independent of t. At the threshold tax rate at which firm 1 chooses Foreign, emissions stemming from the production for Home decrease because firm 1's effective MC to serve Home increases from t to τ; and emissions stemming from the production for Foreign increase because firm 1's effective MC to serve Foreign decreases from $\tau + t$ to 0. The appendix shows the following lemma.[24]

Lemma 4.4 *$E^{HFNN\alpha} < E^{FFNN\alpha}$ for $t > 0$ if demands are convex (i.e., $\varepsilon \geq 0$).*

[23] Given that firm 1 chooses Foreign at the threshold tax rate, firm 2 would not choose Home at the tax rate, because the two firms are symmetric.

[24] If the threshold tax rate is sufficiently close to τ, the global emissions increase because $E^{HFNN\alpha} < E^{FFNN\alpha}$ holds at $t = \tau$.

With linear demands, for example, we can verify

$$E^{FFNN\alpha} - E^{HFNN\alpha} = \frac{2t}{3}. \tag{4.45}$$

Thus, if $\varepsilon \geq 0$, the pollution haven effect leads to positive carbon leakage between Home and Foreign and increases global emissions.

We obtain the following proposition.

Proposition 4.4 *The following equilibrium is possible with an emission tax:* (HN, FN) *with low tax rates and* (FN, FN) *with high tax rates. Global emissions are greater with* (FN, FN) *than with* (HN, FN) *(i.e.,* $E^{FFNN\alpha} > E^{HFNN\alpha}$*) if demands are convex (i.e.,* $\varepsilon \geq 0$*).*

4.5.2 Emission Tax with Carbon-content Tariff (Regime β)

The carbon-content tariff is now introduced in addition to the emission tax. Because of the carbon-content tariff, the effective MCs to export to Home from Foreign become higher, implying that the incentive to choose Foreign as the production location is weakened. We can confirm this from the following relationship:

$$\begin{aligned}&(\pi_1^{FFNN\alpha} - \pi_1^{HFNN\alpha}) - (\pi_1^{FFNN\beta} - \pi_1^{HFNN\beta}) \\ &= (p_h^{NN\alpha} - \tau)x_{1fh}^{NN\alpha} - (p_h^{NN\alpha} - t)x_{1hh}^{NN\alpha} - ((p_h^{NN\beta} - t - \tau)x_{1fh}^{NN\beta} - (p_h^{NN\beta} - t)x_{1hh}^{NN\beta}),\end{aligned} \tag{4.46}$$

which is positive for given t. Thus, the (lowest) tax rate with which firm 1 is indifferent between Home and Foreign in Regime β, $t_1^{\beta eS}$, is greater than that in Regime α, $t_1^{\alpha eS}$. Moreover, $E^{HFNN\beta} < E^{HFNN\alpha}$ holds for a given t, because the outputs for the home market decrease but those for the foreign market do not change. Lemma 4.4 is valid in Regime β, that is, $E^{HFNN\beta} < E^{FFNN\beta}$ for $t > 0$ (i.e., global emissions with (FN, FN) are greater than those with (HN, FN)) if $\varepsilon \geq 0$. With linear demands, for example, we can verify

$$E^{FFNN\beta} - E^{HFNN\beta} = \frac{t}{3}. \tag{4.47}$$

Thus, if $\varepsilon \geq 0$, then the carbon-content tariff is effective in reducing global emissions because it makes firm 1 less likely to locate itself in Foreign.

In the rest of this subsection, we specifically show that an increase in t can switch the equilibrium not only from (HN, FN) to (FN, FN) but also from (FN, FN) to (HA, FN). To this end, we assume linear demands.

If both firms choose Foreign as their production locations, the two firms are identical. In Regime α, both firms are independent of t if they produce in Foreign. In Regime β, however, the profits decrease as t increases. At a certain tax rate, t_1^{β}, the firms have an incentive for emission abatement. However, only one of the two firms would adopt the clean technology at t_1^{β}. To see this, we simply assume that if only one firm adopts the clean technology, it is firm 1. Suppose $\pi_1^{FFNN\beta} = \pi_1^{FFAN\beta}$ holds at t_1^{β}. Then we can verify $\pi_2^{FFAA\beta} < \pi_2^{FFAN\beta}$ at t_1^{β}, implying only one firm (firm 1) would invest in emission abatement at t_1^{β}. The other firm (firm 2) would invest in emission abatement at a higher tax rate, t_2^{β}.

It should be pointed out that firm 1 has an incentive not only to adopt the clean technology but also to produce in Home at $t_1^{\beta e+}$ where $\pi_1^{FFNN\beta} = \pi_1^{HFAN\beta}$ holds. More importantly, $t_1^{\beta e+} < t_1^{\beta}$ can hold. Since we obtain

$$\pi_1^{HFAN\beta} - \pi_1^{FFAN\beta} = \frac{4}{9}\left(k^2t^2 + (\tau - ak)\,t + \tau^2\right), \tag{4.48}$$

$\pi_1^{HFAN\beta} > \pi_1^{FFAN\beta}$ holds for any $t(>0)$ if $\tau \geq ak$.[25] Thus, as t rises, the equilibrium can shift from (HN, FN) to (FN, FN) and then to (HA, FN). Figure 4.3 (a) illustrates this case.[26]

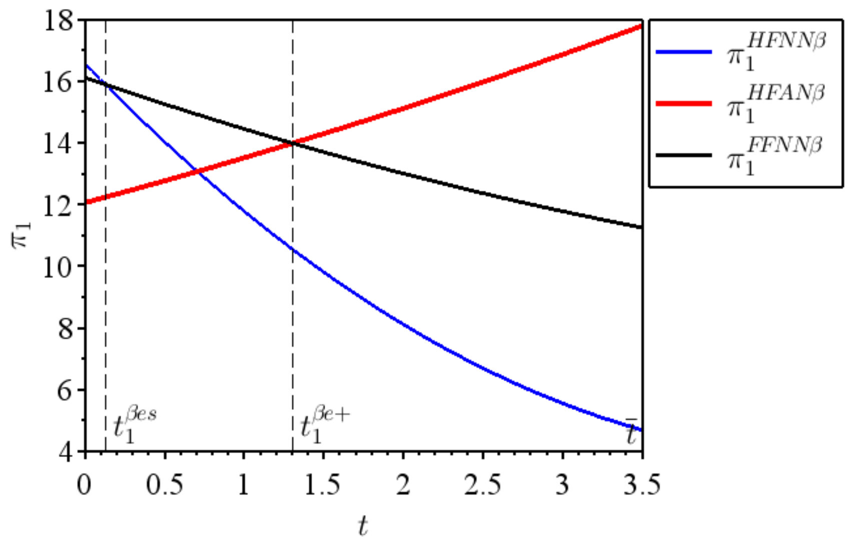

Figure 4.3(a): Regime β: $(HN, FN) \rightarrow (FN, FN) \rightarrow (HA, FN)$.

[25] $\pi_1^{HFAN\beta} > \pi_1^{FFAN\beta}$ holds for any t if $(\tau - ak)^2 - 4k^2\tau^2 < 0$.

[26] In Figure 4.3, we set parameter values as follows: $a = 9$, $\tau = 1$, $k = 1/9$, and $F = 4.5$. Then we obtain $\bar{t} = 3.5$, $t_1^{\beta eS} = 0.127$, $t_1^{\beta S} = 0.706$, $t_1^{\beta e+} = 1.304$, $t_1^{\gamma e} = 1$, $t_1^{\gamma S} = 1.154$, $t_1^{\gamma e+} = 1.174$, and $t_2^{\beta} = t_2^{\gamma} = 2.573$.

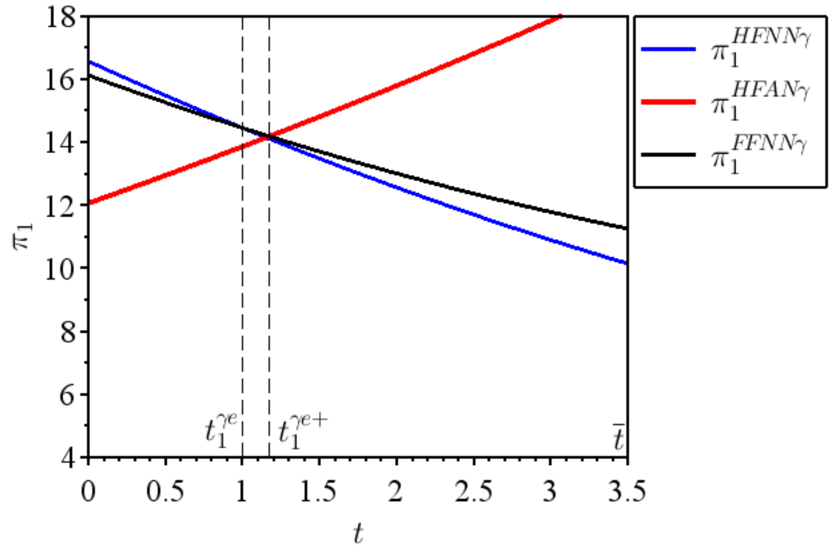

Figure 4.3(b): Regime γ: $(HN, FN) \rightarrow (FN, FN) \rightarrow (HA, FN)$.

We examine how the equilibrium shift from (FN, FN) to (HA, FN) changes emissions. We obtain

$$E^{HFAN\beta} - E^{FFNN\beta} = -\frac{(1-k)(2a-\tau) + k(4k-3)t}{3}. \tag{4.49}$$

Noting $a - 2(t+\tau) > 0$, $E^{HFAN\beta} < E^{FFNN\beta}$ holds for a given t. Thus, the relationship between the tax rate and the emission level is non-monotonic.

It is noteworthy that the equilibrium may switch from (HA, FN) to (FA, FN) as t further increases. This case is illustrated in Figure 4.4.[27] The equilibrium switch from (HA, FN) to (FA, FN) increases firm 1's emissions by $\frac{2k^2t}{3}$ and decreases firm 2's emissions by $\frac{kt}{3}$, leading to

$$E^{HFAN\beta} - E^{FFAN\beta} = \frac{kt(1-2k)}{3}. \tag{4.50}$$

Thus, $E^{HFAN\beta} < E^{FFAN\beta}$ holds for a given t if and only if $k > \frac{1}{2}$. The change in global emissions depends on firm 1's abatement efficiency. If the decrease in firm 2's output is replaced by firm 1's output produced with high abatement efficiency, global emissions decrease.[28]

[27] In Figure 4.4, we set parameter values as follows: $a = 9$, $\tau = 1$, $k = 1/6$, and $F = 4.5$. Then we obtain $\bar{t} = 3.5$, $t_1^{\beta eS} = 0.127$, $t_1^{\beta S} = 0.76$, $t_1^{\beta e+} = 1.521$, $t_1^{\beta e++} = 2.292$, and $t_2^{\beta} = 3.184$. $t_1^{\beta e++}$ is the threshold tax rate between (HA, FN) and (FA, FN).

[28] This result corresponds to negative carbon leakage in Ma and Yomogida (2019).

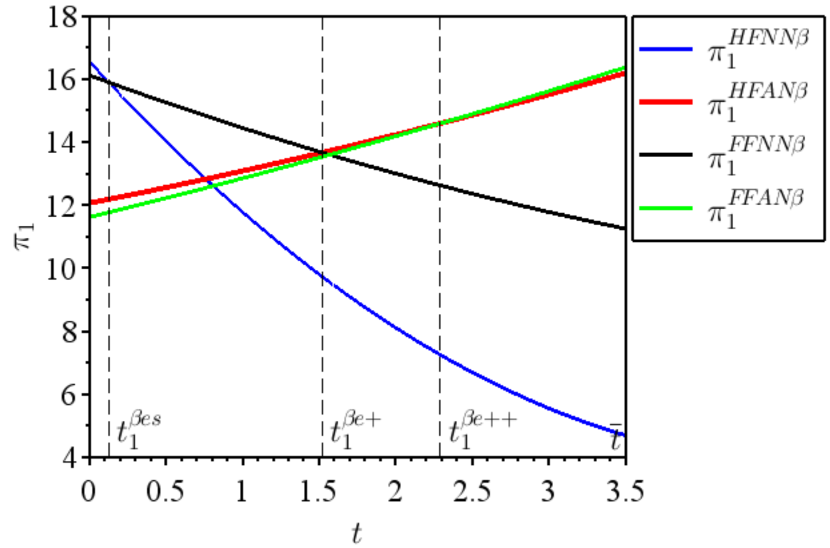

Figure 4.4: Regime β: $(HN, FN) \rightarrow (FN, FN) \rightarrow (HA, FN) \rightarrow (FA, FN)$.

The above analysis establishes the following proposition.

Proposition 4.5 *The following equilibrium is possible if an emission tax is accompanied by the carbon-content tariff:* (HN, FN) *with low tax rates,* (FN, FN) *with medium tax rates, and* (HA, FN) *with high tax rates; and* $E^{HFNN\beta} < E^{FFNN\beta} > E^{HFAN\beta}$*. The carbon-content tariff weakens firm 1's incentive to locate itself in Foreign (i.e.,* $t_1^{\beta eS} > t_1^{\alpha eS}$*). A further increase in* t *may switch equilibrium from* (HA, FN) *to* (FA, FN)*. In this case,* $E^{HFAN\beta} > E^{FFAN\beta}$ *can hold if* k *is small.*

4.5.3 Emission Tax Coupled with Tax Refunds at the Border and Carbon-content Tariff (Regime γ)

The emission-tax refunds are now introduced in addition to the carbon-content tariff. As in Regime β, the equilibrium can switch from (HN, FN) to (FN, FN) and then to (HA, FN) as t increases. Figure 4.3 (b) illustrates this case.

Since firm 1's effective MCs for its exports become just τ, firm 1's incentive to choose Foreign for the production location is weakened. That is, $t_1^{\gamma e} > t_1^{\beta eS} > t_1^{\alpha eS}$ (see Figure 4.3).[29] We can

[29] We can readily verify $t_1^{\gamma e} = \tau$ with linear demands.

confirm this because the following holds for a given t:

$$\begin{aligned}&(\pi_1^{FFNN\beta} - \pi_1^{HFNN\beta}) - (\pi_1^{FFNN\gamma} - \pi_1^{HFNN\gamma}) \\ &= (p_f^{NN\gamma} - \tau)x_{1hf}^{NN\gamma} - (p_f^{NN\beta} - t - \tau)x_{1hf}^{NN\beta} > 0. \end{aligned} \tag{4.51}$$

Although $t_1^{\gamma e} > t_1^{\beta e}$, the total emissions with (HN, FN) are larger in Regime γ than in Regime β for a given t (i.e., $E^{HFNN\gamma} > E^{HFNN\beta}$ for a given t).

When both firms choose Foreign for their production locations, Regime γ and Regime β are equivalent. Thus, $\pi_1^{FFNN\gamma} = \pi_1^{FFAN\gamma}$ at t_1^{β} holds. However, regarding the threshold tax rate at which firm 1 has an incentive not only to engage in emission abatement but also to locate itself in Home, $t_1^{\gamma e+} < t_1^{\beta e+}$ holds, because we have

$$\begin{aligned}&(\pi_1^{FFNN\beta} - \pi_1^{HFAN\beta}) - (\pi_1^{FFNN\gamma} - \pi_1^{HFAN\gamma}) \\ &= (p_f^{AN\gamma} - \tau)x_{1hf}^{AN\gamma} - (p_f^{AN\beta} - kt - \tau)x_{1hf}^{AN\beta} > 0 \end{aligned} \tag{4.52}$$

for a given t (see Figure 4.3).

Note that as in Regime β, the equilibrium may switch from (HA, FN) to (FA, FN) *as* t further increases (see Figure 4.5).[30] With linear demands, we can readily verify

$$E^{HFNN\gamma} = E^{FFNN\gamma} (= E^{FFNN\beta}), \tag{4.53}$$

$$E^{HFAN\gamma} - E^{FFNN\gamma} = -\frac{(1-k)(2a - \tau - 2kt)}{3} < 0, \tag{4.54}$$

$$E^{HFAN\gamma} = E^{FFAN\gamma}. \tag{4.55}$$

We obtain the following proposition.

Proposition 4.6 *The following equilibrium is possible if an emission tax is coupled with the carbon-content tariff and emission-tax refunds for exports: (HN, FN) with low tax rates, (FN, FN) with medium tax rates, and (HA, FN) with high tax rates. However, the introduction of the emission-tax refunds reduces the range of the tax rate with which firm 1 would produce in Foreign. That is, $t_1^{\alpha eS} < t_1^{\beta eS} < t_1^{\gamma e}$ and $t_1^{\gamma e+} < t_1^{\beta e+}$* hold.

[30] In Figure 4.5, we set parameter values as follows: $a = 9$, $\tau = 1$, $k = 3/4$, and $F = 1.3$. Then we obtain $\bar{t} = 3.5$, $t_1^{\gamma e} = 1$, $t_1^{\gamma S} = 1.296$, $t_1^{\gamma e+} = 1.606$, $t_1^{\gamma e++} = 2$, and $t_2^{\gamma} = 2.758$. $t_1^{\gamma e++}$is the threshold tax rate between (HA, FN) and (FA, FN).

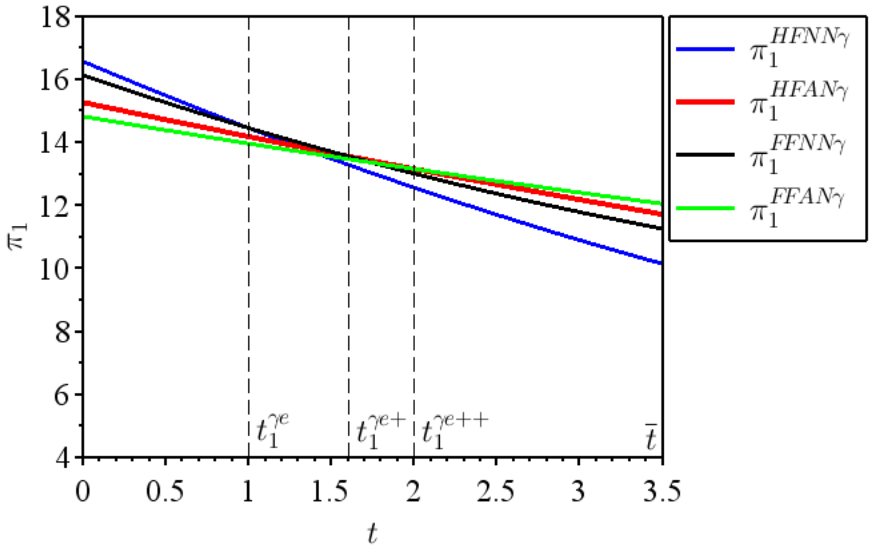

Figure 4.5: Regime γ: $(HN, FN) \to (FN, FN) \to (HA, FN) \to (FA, FN)$.

4.6 Welfare Analysis

In this section, we briefly discuss about the welfare effects of home emission taxes. To this end, we assume that firms 1 and 2 are, respectively, a home and foreign firm. Home welfare consists of consumer surplus, firm 1's profits, tax revenues, and damages from global warming. Similarly, foreign welfare consists of consumer surplus, firm 2's profits, and damages from global warming. The purpose of this section is not to investigate the optimal policies but rather to discuss each welfare component. This is because the optimal policies crucially depend on how to evaluate damages from global warming which in turn crucially depends on a damage function. For example, if the evaluation of GHG emissions is large enough to dominate other positive welfare components, zero emissions are obviously optimal.

We can claim the following with respect to each welfare component. Form Lemmas 4.1 and 4.2, the home emission tax is harmful to firm 1 unless it adopts the clean technology. The introduction of the BTAs for a given tax rate benefits firm 1 if it produces in Home. Global warming is mitigated if and only if global GHG emissions are reduced. The higher tax does not necessarily result in less emissions because the firms may switch their technologies and/or production locations. Unless the technology is switched, less outputs lead to less emissions. However, less outputs hurt either home or foreign consumers, at the very least. The welfare effects of adopting the clean technology are less obvious.

In the following, we discuss each case in more detail. We first consider the case where firm locations are fixed. In Regime α, without emission abatement, a tax increase harms firm 1 and both home and foreign consumers and benefits firm 2. Tax revenues may or may not increase. Although cross-border carbon leakage occurs, global warming is mitigated. If the positive impact of decrease in emissions is large enough to nullify the negative effects, home and foreign welfare improves. Firm 1's abatement investment at the threshold tax rate benefits both home and foreign consumers and harms firm 2.[31] The effects on tax revenues and global warming are ambiguous. If global warming improves, home welfare necessarily improves. Note that the effects of a tax increase on the firms, consumers and home government with emission abatement are qualitatively the same with those without emission abatement, but those on global warming can be different between cases with and without emission abatement. In particular, a tax increase can worsen global warming under the clean technology. If this is the case, a tax increase necessarily worsens home welfare.

The shift from Regime α to Regime β for a given tax rate (i.e., the introduction of the carbon-content tariff) is harmful to home consumers and firm 2 but is beneficial to firm 1 and the home government. Since global emissions decrease, home welfare improves as long as the tax rate is low.[32] In Regime β, an increase in the tax without emission abatement hurts firm 1 and both home and foreign consumers and improves global warming. Cross-border carbon leakage still occurs, but compared with Regime α, it is weakened for a given tax rate. Tax revenues may or may not increase. Firm 2 loses in the home market but gains in the foreign market. In general, it is ambiguous whether firm 2 gains or loses. The effects of firm 1's abatement investment at the threshold tax rate are qualitatively the same with those in Regime α. An increase in the tax with firm 1's emission abatement harms both home and foreign consumers but mitigates global warming. The effects on firms 1 and 2 and tax revenues are ambiguous. Firm 2's abatement investment benefits home consumers and harms firm 1. Tax revenues may or may not decrease. It is also ambiguous whether global warming improves. When both firms adopt the clean technology, a tax increase harms both home and foreign consumers and improves global warming. Tax revenues may or may not increase. The firms may or may not gain.

The shift from Regime β to Regime γ for a given tax rate (i.e., the introduction of the emission-tax refunds for exports) benefits firm 1 and foreign consumers, hurts firm 2 and the home government, and increases global emissions.[33] In Regime γ, cross-border carbon leakage does not occur and foreign consumers are not affected by the home emission tax. Without emission abatement, an increase in the tax hurts firms 1 and 2 and home consumers and improves global warming. The

[31] Firm 1 is indifferent between abatement and non-abatement at the threshold tax rate.

[32] For the welfare effect of an import tariff under international oligopoly, see Brander and Spencer (1984) and Furusawa et al. (2003).

[33] Since the tax refunds are an export subsidy for firm 1, home welfare improves as long as both tax refunds and damages from climate change are sufficiently small. See Brander and Spencer (1985) for the welfare effect of an export subsidy under international oligopoly.

tax revenue may or may not increase. Firm 1's abatement investment at the threshold tax rate is harmful to firm 2 but beneficial to home consumers. The effects on the tax revenue and global warming are generally ambiguous. If global warming is mitigated, Home is better off. An increase in the tax with firm 1's emission abatement harms firm 2 and home consumers but mitigates global warming. The effects on firm 1 and tax revenues are ambiguous.

We next consider the case where firm locations are endogenous. We deal with the case where a tax increase changes the Nash equilibrium in the first stage from (HN, FN) to (FN, FN). We also assume linear demands. In all regimes, the effects of a tax increase with (HN, FN) are the same with those under fixed locations and no-abatement. Moreover, in all regimes, firm 1's location switch from Home to Foreign at the threshold tax rate harms firm 2, home consumers and the home government, benefits foreign consumers, and never improves global warming. Thus, Home is necessarily worse off.

The effects are qualitatively the same between Regimes β and γ. A tax increase with (FN, FN) harms home consumers and both firms, benefits the home government, and improves global warming.[34] Firm 1's location switch to Home and technology switch to the clean one at the threshold tax rate benefit home consumers and mitigate global warming but harm home government and foreign consumers. The effects on firm 2' profits are ambiguous. The effects of a tax increase with (HA, FN) and with (HA, FA) are mentioned above. The effects of firm 2's abatement investment are also mentioned above.

4.7 Conclusion

We have developed a simple two-country, two-firm model to examine how emission taxes with BTAs affect outputs, emissions and locations of firms in the presence of an emission-abatement technology (i.e., a clean technology). The two countries (Home and Foreign) are identical except that only Home introduces carbon pricing. The two firms are also identical. We specifically examined three policy regimes: i) emission taxes alone (Regime α); ii) emission taxes accompanied by carbon-content tariffs (Regime β); and iii) emission taxes coupled with emission-tax refunds for exports and carbon-content tariffs (Regime γ).

If the firm locations are fixed, firm's strategic reaction against an emission tax is whether or not to abate emissions by adopting the clean technology. According to our findings, emission taxes may not be effective in decreasing global emissions. Interestingly, a higher emission tax rate can result in greater global emissions even with fixed firm locations. Also high tax rates may discourage an incentive for the abatement investment. Another important message is that cross-border carbon

[34] Obviously, a tax increase with (FN, FN) has no effect in Regime α.

leakage is completely eliminated in Regime γ (i.e., with full BTAs) but global emissions can be greater than in Regime β (i.e., with partial BTAs) where cross-border carbon leakage is partially eliminated. Thus, from the viewpoint of global emission control, carbon leakage is not necessarily bad. Moreover, the emission-tax refund recovers the competitiveness of the home firm in the foreign market but discourages its abatement investment.

If firm locations are endogenously determined, both firms are likely to produce in Foreign in the presence of a tough emission tax in Home. As a result, global emissions can increase. BTAs induce firms to invest in emission abatement. BTAs also discourage firms from producing in Foreign. This effect is stronger in Regime γ (i.e., with full BTAs) than in Regime β (i.e., with partial BTAs). The effect of carbon pricing on global emissions can be non-monotonic under BTAs.

To avoid rather straightforward results, we assumed that two countries and two firms are symmetric. For example, if firm 2's emissions per unit of output are much greater than firm 1's, carbon leakage from firm 1 to firm 2 should be blocked. In this case, carbon pricing with assisting firm 1 is most likely to be desirable to cope with climate change. Progress in the study regarding carbon pricing is expected in the future.

4.A Appendix

4.A.1 Effective Marginal Costs

The following table shows firm j's effective marginal costs with and without abatement in different policy regimes.

Policy Regime	Abatement Choice	MC_{jhh}	MC_{jhf}	MC_{jfh}	MC_{jff}
α	N	t	$t+\tau$	τ	0
	A	kt	$kt+\tau$	τ	0
β	N	t	$t+\tau$	$t+\tau$	0
	A	kt	$kt+\tau$	$kt+\tau$	0
γ	N	t	τ	$t+\tau$	0
	A	kt	τ	$kt+\tau$	0

Table 4.A.1: Firm j's effective marginal costs

4.A.2 Proof of Lemmas 4.1 and 4.2

Since the home and foreign markets are segmented, we focus on the home market. The profits in the home market are given by

$$\pi_{1h} \equiv (p_h - \lambda_1 kt)x_{1hh},$$
$$\pi_{2h} \equiv (p_h - \tau - \lambda_2 \beta kt)x_{2fh},$$

where $\lambda_j = 1$ if firm j invests in the emission abatement; and $\lambda_j = 1/k$ if firm j does not $(j = 1, 2)$. We have $\beta = 0$ in Regime α; $\beta = 1$ in Regime β and Regime γ. The first order conditions (FOCs) for profit maximization in the home market are

$$p_h - \lambda_1 kt - X_h^{-\varepsilon} x_{1hh} = 0,$$
$$p_h - \tau - \lambda_2 \beta kt - X_h^{-\varepsilon} x_{2fh} = 0.$$

Thus,

$$\pi_{1h} = X_h^{-\varepsilon}(x_{1hh})^2, \pi_{2h} = X_h^{-\varepsilon}(x_{2fh})^2$$

In the following, we drop subscripts h and f.

We first prove Lemma 4.1. For this, we set $\lambda_1 = \lambda_2 = 1/k$ and $\beta = 0$. Suppose that only t

increases. Then, the following holds from FOCs of profit maximization:

$$\begin{pmatrix} -2X^{-\varepsilon}+\varepsilon X^{-\varepsilon-1}x_1 & -X^{-\varepsilon}+\varepsilon X^{-\varepsilon-1}x_1 \\ -X^{-\varepsilon}+\varepsilon X^{-\varepsilon-1}x_2 & -2X^{-\varepsilon}+\varepsilon X^{-\varepsilon-1}x_2 \end{pmatrix}\begin{pmatrix} dx_1 \\ dx_2 \end{pmatrix}=\begin{pmatrix} 1 \\ 0 \end{pmatrix}dt.$$

Thus, noting $\varepsilon<1$, we obtain

$$\begin{aligned}
\frac{dx_1}{dt} &= -X^{\varepsilon}\frac{\varepsilon x_2-2X}{\varepsilon x_1-3X+\varepsilon x_2}=X^{\varepsilon}\frac{\varepsilon\sigma_2-2}{3-\varepsilon}<0,\\
\frac{dx_2}{dt} &= -X^{\varepsilon}\frac{X-\varepsilon x_2}{\varepsilon x_1-3X+\varepsilon x_2}=X^{\varepsilon}\frac{1-\varepsilon\sigma_2}{3-\varepsilon}>0,\\
\frac{dX}{dt} &= -\frac{X^{\varepsilon}}{3-\varepsilon}<0.
\end{aligned}$$

We also have

$$\begin{aligned}
\frac{d\pi_1}{dt} &= -\varepsilon X^{-\varepsilon-1}\frac{dX}{dt}x_1^2+2X^{-\varepsilon}x_1\frac{dx_1}{dt}=\frac{x_1(\varepsilon(2-\sigma_1)-4)}{3-\varepsilon}<0,\\
\frac{d\pi_2}{dt} &= -\varepsilon X^{-\varepsilon-1}\frac{dX}{dt}x_2^2+2X^{-\varepsilon}x_2\frac{dx_2}{dt}=\frac{x_2(2-\varepsilon\sigma_2)}{3-\varepsilon}>0.
\end{aligned}$$

Next we prove Lemma 4.2. For this, we set $\lambda_1=\beta=1$ and $\lambda_2=1/k$. Again suppose that only t increases. Then, the following holds from FOCs:

$$\begin{pmatrix} -2X^{-\varepsilon}+\varepsilon X^{-\varepsilon-1}x_1 & -X^{-\varepsilon}+\varepsilon X^{-\varepsilon-1}x_1 \\ -X^{-\varepsilon}+\varepsilon X^{-\varepsilon-1}x_2 & -2X^{-\varepsilon}+\varepsilon X^{-\varepsilon-1}x_2 \end{pmatrix}\begin{pmatrix} dx_1 \\ dx_2 \end{pmatrix}=\begin{pmatrix} k \\ 1 \end{pmatrix}dt.$$

Thus, we obtain

$$\begin{aligned}
\frac{dx_1}{dt} &= -X^{\varepsilon}\frac{X-\varepsilon x_1-2Xk+k\varepsilon x_2}{\varepsilon x_1-3X+\varepsilon x_2}=X^{\varepsilon}\frac{(1-2k)-\varepsilon\sigma_1+k\varepsilon\sigma_2}{3-\varepsilon},\\
\frac{dx_2}{dt} &= -X^{\varepsilon}\frac{\varepsilon x_1-2X+Xk-k\varepsilon x_2}{\varepsilon x_1-3X+\varepsilon x_2}=-X^{\varepsilon}\frac{(2-k)-\varepsilon\sigma_1+k\varepsilon\sigma_2}{3-\varepsilon},\\
\frac{dX}{dt} &= -\frac{X^{\varepsilon}(k+1)}{3-\varepsilon}<0,
\end{aligned}$$

which implies

$$\begin{aligned}
\frac{dx_1}{dt}<0 &\Longleftrightarrow (1-2k)-\varepsilon\sigma_1+k\varepsilon\sigma_2<0,\\
\frac{dx_2}{dt}<0 &\Longleftrightarrow (2-k)-\varepsilon\sigma_1+k\varepsilon\sigma_2>0
\end{aligned}$$

We also have

$$\frac{d\pi_1}{dt} = -\varepsilon X^{-\varepsilon-1}\frac{dX}{dt}x_1^2 + 2X^{-\varepsilon}x_1\frac{dx_1}{dt} = x_1\frac{\left(\varepsilon\left(\sigma_1+2\sigma_2\right)-4\right)k+\left(2-\varepsilon\sigma_1\right)}{3-\varepsilon}, \tag{4.56}$$

$$\frac{d\pi_2}{dt} = -\varepsilon X^{-\varepsilon-1}\frac{dX}{dt}x_2^2 + 2X^{-\varepsilon}x_2\frac{dx_2}{dt} = x_2\frac{\left(2-\varepsilon\sigma_2\right)k+\left(2\varepsilon\sigma_1+\varepsilon\sigma_2-4\right)}{3-\varepsilon}, \tag{4.57}$$

which implies

$$\frac{d\pi_1}{dt} < 0 \Longleftrightarrow \left(\varepsilon\left(\sigma_1+2\sigma_2\right)-4\right)k+\left(2-\varepsilon\sigma_1\right) < 0,$$
$$\frac{d\pi_2}{dt} < 0 \Longleftrightarrow \left(2-\varepsilon\sigma_2\right)k+\left(2\varepsilon\sigma_1+\varepsilon\sigma_2-4\right) < 0.$$

Note that $\frac{d\pi_1}{dt} < 0$ if both $\frac{dx_1}{dt} < 0$ and $\varepsilon \le 0$ hold; and $\frac{d\pi_2}{dt} < 0$ if both $\frac{dx_2}{dt} < 0$ and $\varepsilon \le 0$ hold.

4.A.3 Signs of $\Delta\pi_{12}^{\beta}$, $\Delta\pi_{12}^{\gamma}$ and $\Delta\pi_{1}^{\alpha\beta}$

First, we show that $\Delta\pi_{12}^{\beta} > 0$ holds if $\varepsilon \ge 0$. For this, we derive

$$\frac{d\Delta\pi_{12}^{\beta}}{dk} = \frac{d\pi_1^{HFAN\beta}}{dk} - \frac{d\pi_2^{HFNA\beta}}{dk}.$$

Noting

$$\begin{pmatrix} -2X^{-\varepsilon}+\varepsilon X^{-\varepsilon-1}x_1 & -X^{-\varepsilon}+\varepsilon X^{-\varepsilon-1}x_1 \\ -X^{-\varepsilon}+\varepsilon X^{-\varepsilon-1}x_2 & -2X^{-\varepsilon}+\varepsilon X^{-\varepsilon-1}x_2 \end{pmatrix}\begin{pmatrix} dx_1 \\ dx_2 \end{pmatrix} = \begin{pmatrix} t \\ 0 \end{pmatrix} dk,$$

we obtain

$$\frac{dx_1}{dk} = -tX^{\varepsilon}\frac{\varepsilon x_2 - 2X}{\varepsilon x_1 - 3X + \varepsilon x_2} = tX^{\varepsilon}\frac{\varepsilon\sigma_2 - 2}{3-\varepsilon},$$
$$\frac{dx_2}{dk} = -tX^{\varepsilon}\frac{X - \varepsilon x_2}{\varepsilon x_1 - 3X + \varepsilon x_2} = tX^{\varepsilon}\frac{1-\varepsilon\sigma_2}{3-\varepsilon},$$
$$\frac{dX}{dk} = -\frac{tX^{\varepsilon}}{3-\varepsilon},$$

$$\frac{d\pi_1}{dk} = -\varepsilon X^{-\varepsilon-1}\frac{dX}{dk}x_1^2 + 2X^{-\varepsilon}x_1\frac{dx_1}{dk} = \frac{tx_1}{3-\varepsilon}(\varepsilon(1+\sigma_2)-4) \tag{4.58}$$

$$\frac{d\pi_2}{dk} = -\varepsilon X^{-\varepsilon-1}\frac{dX}{dk}x_2^2 + 2X^{-\varepsilon}x_2\frac{dx_2}{dk} = \frac{tx_2}{3-\varepsilon}(2-\varepsilon\sigma_2). \tag{4.59}$$

Thus,

$$\frac{d\Delta\pi_{12}^{\beta}}{dk} = \frac{\varepsilon(1+\sigma_{2h}^{AN\beta})-4}{3-\varepsilon}tx_{1hh}^{AN\beta} + \frac{\varepsilon(1+\sigma_{2f}^{AN\beta})-4}{3-\varepsilon}tx_{1hf}^{AN\beta} - \frac{\varepsilon(1+\sigma_{1h}^{NA\beta})-4}{3-\varepsilon}tx_{2fh}^{NA\beta},$$

where σ_{ji} is firm j's market share in country i with the superscripts denoting each firm's status of abatement and policy regime. We have $x_{1hh}^{AN\beta}\Big|_{\tau=0} = x_{2fh}^{NA\beta}\Big|_{\tau=0}$ and $\sigma_{2h}^{AN\beta}\Big|_{\tau=0} = \sigma_{1h}^{NA\beta}\Big|_{\tau=0}$ without trade costs; and $x_{1hh}^{AN\beta} > x_{2fh}^{NA\beta}$and $\sigma_{2h}^{AN\beta} < \sigma_{1h}^{NA\beta}$ with trade costs. Thus, noting $\Delta\pi_{12}^{\beta}\Big|_{k=1} = 0$, we have $\frac{d\Delta\pi_{12}^{\beta}}{dk} < 0$ if $\varepsilon \geq 0$.

Next, we show that $\Delta\pi^{\gamma} > 0$ holds if $\varepsilon \geq 0$. From (4.56), we obtain

$$\begin{aligned}\frac{d\Delta\pi_{12}^{\gamma}}{dk} &= \frac{d\pi_1^{HFAN\gamma}}{dk} - \frac{d\pi_2^{HFNA\gamma}}{dk}\\ &= \frac{\varepsilon(1+\sigma_{2h}^{AN\gamma})-4}{3-\varepsilon}tx_{1hh}^{AN\gamma} - \frac{\varepsilon(1+\sigma_{1h}^{NA\gamma})-4}{3-\varepsilon}tx_{2fh}^{NA\gamma}.\end{aligned}$$

Thus, noting $\Delta\pi_{12}^{\gamma}|_{k=1} = 0$ and $x_{1hh}^{AN\gamma} > x_{2fh}^{NA\gamma}$, we have $\frac{d\Delta\pi_{12}^{\gamma}}{dk} < 0$ if $\varepsilon \geq 0$.

Lastly, we show that $\Delta\pi_1^{\alpha\beta} < 0$ holds if $\varepsilon \geq 0$. From (4.58), we obtain

$$\begin{aligned}\frac{d\Delta\pi_1^{\alpha\beta}}{dk} &= \frac{d(p_h^{AN\beta}-kt)x_{1hh}^{AN\alpha}}{dk} - \frac{d(p_h^{AN\beta}-kt)x_{1hh}^{AN\beta}}{dk}\\ &= \frac{\varepsilon(1+\sigma_{2h}^{AN\alpha})-4}{3-\varepsilon}tx_{1hh}^{AN\alpha} - \frac{\varepsilon(1+\sigma_{2f}^{AN\beta})-4}{3-\varepsilon}tx_{1hh}^{AN\beta}.\end{aligned}$$

Since $x_{1hh}^{AN\beta} > x_{1hh}^{AN\alpha}$ and $\sigma_{2h}^{AN\beta} < \sigma_{2h}^{AN\alpha}$, $\frac{d\Delta\pi^{\beta}}{dk} > 0$ if $\varepsilon \geq 0$. Thus, noting $\Delta\pi_1^{\alpha\beta}\Big|_{k=1} = 0$, $\Delta\pi_1^{\alpha\beta} < 0$ holds if $\varepsilon \geq 0$.

4.A.4 Proof of Lemma 4.3

With $t = 0$, we have

$$\begin{aligned}\pi_1^{HFNN}\big|_{t=0} &= p_h^{NN}x_{1hh}^{NN} + (p_f^{NN}-\tau)x_{1hf}^{NN},\\ \pi_1^{FFNN}\big|_{t=0} &= (p_h^{NN}-\tau)x_{1fh}^{NN} + p_f^{NN}x_{1ff}^{NN}.\end{aligned}$$

We examine the sign of $\Delta\pi_1^{HF}\big|_{t=0} \equiv \pi_1^{HFNN}\big|_{t=0} - \pi_1^{FFNN}\big|_{t=0}$. Noting $\Delta\pi_1^{HF}\big|_{t=0} = 0$ at $\tau = 0$, we check the sign of $\frac{d\Delta\pi_1^{HF}|_{t=0}}{d\tau}$. For this, we consider

$$\begin{pmatrix} -2X^{-\varepsilon}+\varepsilon X^{-\varepsilon-1}x_j & -X^{-\varepsilon}+\varepsilon X^{-\varepsilon-1}x_j \\ -X^{-\varepsilon}+\varepsilon X^{-\varepsilon-1}x_k & -2X^{-\varepsilon}+\varepsilon X^{-\varepsilon-1}x_k \end{pmatrix}\begin{pmatrix} dx_j \\ dx_k \end{pmatrix} = \begin{pmatrix} 1 \\ 0 \end{pmatrix} d\tau \ (j,k=1,2; j\neq k).$$

In view of (4.58) and (4.59), we can readily verify

$$\frac{d\pi_j}{d\tau} = -\varepsilon X^{-\varepsilon-1}\frac{dX}{d\tau}x_j^2 + 2X^{-\varepsilon}x_j\frac{dx_j}{d\tau} = \frac{x_j}{3-\varepsilon}(\varepsilon(1+\sigma_k)-4),$$
$$\frac{d\pi_k}{d\tau} = -\varepsilon X^{-\varepsilon-1}\frac{dX}{d\tau}x_k^2 + 2X^{-\varepsilon}x_k\frac{dx_k}{d\tau} = \frac{x_k}{3-\varepsilon}(2-\varepsilon\sigma_k).$$

We also consider

$$\begin{pmatrix} -2X^{-\varepsilon}+\varepsilon X^{-\varepsilon-1}x_1 & -X^{-\varepsilon}+\varepsilon X^{-\varepsilon-1}x_1 \\ -X^{-\varepsilon}+\varepsilon X^{-\varepsilon-1}x_2 & -2X^{-\varepsilon}+\varepsilon X^{-\varepsilon-1}x_2 \end{pmatrix}\begin{pmatrix} dx_1 \\ dx_2 \end{pmatrix} = \begin{pmatrix} 1 \\ 1 \end{pmatrix} d\tau \ .$$

In view of (4.56) and (4.57), we can readily verify

$$\frac{d\pi_1}{d\tau} = -\varepsilon X^{-\varepsilon-1}\frac{dX}{d\tau}x_1^2 + 2X^{-\varepsilon}x_1\frac{dx_1}{d\tau} = -\frac{2x_1}{3-\varepsilon}(1-\varepsilon\sigma_2),$$
$$\frac{d\pi_2}{d\tau} = -\varepsilon X^{-\varepsilon-1}\frac{dX}{d\tau}x_2^2 + 2X^{-\varepsilon}x_2\frac{dx_2}{d\tau} = -\frac{2x_2}{3-\varepsilon}(1-\varepsilon\sigma_1).$$

Thus, we have

$$\begin{aligned}\frac{d\ \Delta\pi_1^{HF}\big|_{t=0}}{d\tau} &= \frac{d\pi_1^{HFNN}}{d\tau} - \frac{d\pi_1^{FFNN}}{d\tau} \\ &= \frac{x_{1hh}^{HFNN}}{3-\varepsilon}(2-\varepsilon\sigma_{1h}^{HFNN}) + \frac{x_{1hf}^{HFNN}}{3-\varepsilon}(\varepsilon(1+\sigma_{2f}^{HFNN})-4) \\ &\quad + \frac{2x_{1fh}^{FFNN}}{3-\varepsilon}(1-\varepsilon\sigma_{2h}^{FFNN}) \\ &= \frac{x_{1hh}^{HFNN}}{3-\varepsilon}(2-\varepsilon\sigma_{1h}^{HFNN}) + \frac{x_{1fh}^{FFNN}}{3-\varepsilon}(2-2\varepsilon\sigma_{2h}^{FFNN}) \\ &\quad - \frac{x_{1hf}^{HFNN}}{3-\varepsilon}(4-\varepsilon(1+\sigma_{2f}^{HFNN})).\end{aligned}$$

For $\tau > 0$, $x_{1hh}^{HFNN} > x_{1hf}^{HFNN}$, $\sigma_{1h}^{HFNN} = \sigma_{2f}^{HFNN}$ and $\sigma_{2h}^{FFNN} = \frac{1}{2}$ hold. Therefore, $2 - \varepsilon\sigma_{1h}^{HFNN} + 2 - 2\varepsilon\sigma_{2h}^{FFNN} = 4 - \varepsilon(1+\sigma_{2f}^{HFNN})$. Besides, we have $x_{1fh}^{FFNN} > x_{1hf}^{HFNN}$ for $\tau > 0$ if $\varepsilon \geq 0$. To see this, we check the sign of the following:

$$\begin{aligned}\frac{d\left(x_{1fh}^{FFNN} - x_{1hf}^{HFNN}\right)\Big|_{t=0}}{d\tau} &= \frac{d\left(x_{2fh}^{FFNN} - x_{2fh}^{HFNN}\right)\Big|_{t=0}}{d\tau} \\ &= \frac{1}{\left(p_h^{FFNN}\right)'(3-\varepsilon)} - \frac{2-\varepsilon\sigma_{1h}^{HFNN}}{\left(p_h^{HFNN}\right)'(3-\varepsilon)} \\ &= \frac{2-\varepsilon\sigma_{1h}^{HFNN}}{3-\varepsilon}\left(X_h^{HFNN}\right)^{\varepsilon} - \frac{1}{3-\varepsilon}\left(X_h^{FFNN}\right)^{\varepsilon}.\end{aligned}$$

Since $2-\varepsilon\sigma_{1h}^{HFNN} > 1$ and $X_h^{HFNN} > X_h^{FFNN}$, then $\frac{d(x_{1fh}^{FFNN}-x_{1hf}^{HFNN})}{d\tau} > 0$ holds if $\varepsilon \geq 0$. Along with $x_{1fh}^{FFNN}\Big|_{\tau=0} = x_{1hf}^{HFNN}\Big|_{\tau=0}$, we can get $x_{1fh}^{FFNN} > x_{1hf}^{HFNN}$ for $\tau > 0$ if $\varepsilon \geq 0$. Thus, $\Delta\pi_1^{HF}\big|_{t=0} > 0$ for $\tau > 0$ if $\varepsilon \geq 0$.

4.A.5 Proof of Lemma 4.4

To prove Lemma 4.4, we show that the total outputs (demands) are greater with (FN, FN) than with (HN, FN) if $\varepsilon \geq 0$. From FOCs of profit maximization, we have

$$\begin{aligned}
x_{1hh}^{HFNN\alpha} &= (p_h^{HFNN\alpha} - t)(X_h^{HFNN\alpha})^{\varepsilon}, x_{2fh}^{HFNN\alpha} = (p_h^{HFNN\alpha} - \tau)(X_h^{HFNN\alpha})^{\varepsilon},\\
x_{1hf}^{HFNN\alpha} &= (p_f^{HFNN\alpha} - t - \tau)(X_f^{HFNN\alpha})^{\varepsilon}, x_{2ff}^{HFNN\alpha} = (p_f^{HFNN\alpha})(X_f^{HFNN\alpha})^{\varepsilon},\\
x_{1fh}^{FFNN\alpha} &= x_{2fh}^{FFNN\alpha} = (p_h^{FFNN\alpha} - \tau)(X_h^{FFNN\alpha})^{\varepsilon},\\
x_{1ff}^{FFNN\alpha} &= x_{2ff}^{FFNN\alpha} = (p_f^{FFNN\alpha})(X_f^{FFNN\alpha})^{\varepsilon}.
\end{aligned}$$

Noting $x_{1hi}^{HFNN\alpha} + x_{2fi}^{HFNN\alpha} = X_i^{HFNN\alpha}$ $(i = h, f)$ and $x_{1hi}^{FFNN\alpha} + x_{2fi}^{FFNN\alpha} = X_i^{FFNN\alpha}$, we have

$$\begin{aligned}
(X_h^{HFNN\alpha})^{1-\varepsilon} &= 2p_h^{HFNN\alpha} - t - \tau,\\
(X_f^{HFNN\alpha})^{1-\varepsilon} &= 2p_f^{HFNN\alpha} - t - \tau,\\
(X_h^{FFNN\alpha})^{1-\varepsilon} &= 2(p_h^{FFNN\alpha} - \tau),\\
(X_f^{FFNN\alpha})^{1-\varepsilon} &= 2p_f^{FFNN\alpha}.
\end{aligned}$$

Using (4.1), we have

$$\begin{aligned}
p_h^{HFNN\alpha} &= p_f^{HFNN\alpha} = \frac{a(1-\varepsilon) + t + \tau}{3-\varepsilon},\\
p_h^{FFNN\alpha} &= \frac{a(1-\varepsilon) + 2\tau}{3-\varepsilon}, p_f^{FFNN\alpha} = \frac{a(1-\varepsilon)}{3-\varepsilon}.
\end{aligned}$$

Substituting these into the above equations, we obtain

$$\begin{aligned}
X_h^{HFNN\alpha} &= \left(\frac{(2a - t - \tau)(1-\varepsilon)}{3-\varepsilon}\right)^{\frac{1}{1-\varepsilon}},\\
X_f^{HFNN\alpha} &= \left(\frac{(2a - t - \tau)(1-\varepsilon)}{3-\varepsilon}\right)^{\frac{1}{1-\varepsilon}},\\
X_h^{FFNN\alpha} &= \left(\frac{2(a-\tau)(1-\varepsilon)}{3-\varepsilon}\right)^{\frac{1}{1-\varepsilon}},\\
X_f^{FFNN\alpha} &= \left(\frac{2a(1-\varepsilon)}{3-\varepsilon}\right)^{\frac{1}{1-\varepsilon}}.
\end{aligned}$$

Thus, if $\varepsilon \geq 0$, the following holds:

$$\begin{aligned} E^{FFNN\alpha} &= X_h^{FFNN\alpha} + X_f^{FFNN\alpha} \geq 2\left(\frac{2(a-\tau)(1-\varepsilon)}{3-\varepsilon}\right)^{\frac{1}{1-\varepsilon}} \\ &> X_h^{HFNN\alpha} + X_f^{HFNN\alpha} = E^{HFNN\alpha}. \end{aligned}$$

Chapter 5

Border Tax Adjustments with Endogenous Assembly Location

5.1 Introduction

Border tax adjustments (BTAs) have been intensely discussed over a decade. For instance, the American Clean Energy and Security Act of 2009 (also known as Waxman-Markey Bill) proposed a cap-and-trade system requiring that the importers purchase emission permits like domestic producers would have to do. Ursula von der Leyen, the president of the European Commission, promised to propose a European Green Deal and introduce a carbon border tax to avoid carbon leakage in her agenda for Europe. Many studies show that BTAs are more effective to avoid or mitigate carbon leakage compared to some other environmental instruments (e.g., an emission tax alone). Examples are Veenendaal et al. (2008), Elliott et al. (2010), Böhringer et al. (2012) and Fischer and Fox (2012), among others. However, no paper investigates the BTAs issues with vertical linkages.

Vertically related markets deserve more attention in examining the effectiveness of BTAs. First of all, trade of intermediate goods accounts for a large share of total trade (e.g., Feenstra and Hanson, 1996; Hummels et al., 2001). Second, the production of intermediate goods can be dirtier than the production of final goods, e.g., production of tires and bodyshells versus assembly of automobiles. Third, a country may feel easier to regulate direct emissions than indirect emissions due to high administration costs of data collection for emissions embedded in each stage of production, especially when some parts are completed in foreign countries (e.g., Lockwood and Whalley, 2010; Kortum and Weisbach, 2017). Based on the second and third points, producers may escape environmental regulations through exports, FDI or assembly relocation under BTAs.[1] For instance, a final good

[1]The concern on strategic issues under BTAs is also mentioned in Monjon and Quirion (2010) and Cosbey et al. (2019).

producer can assemble the dirty inputs in a country with laxer environmental regulation and then export the clean final goods to the country implementing BTAs, during which process carbon leakage may occur and global emissions may increase. In this chapter, we are going to examine whether it happens.

We build up a two-country model with a number of intermediate good producers and a final good producer. The final good producer is a monopolist in the final good market and chooses its assembly location endogenously, which is the key point in the paper. The production of intermediate goods emits GHG emissions and is subject to oligopolistic competition to capture the fact that some polluting industries, such as chemicals and cement, have a strong feature of oligopoly. The intermediate good producers have identical abatement technology. Their production becomes clean after abatement. This assumption, together with the existence of trade costs of final goods, is meaningful to determine the timing of assembly relocation. To examine the effectiveness of BTAs in preventing carbon leakage and decreasing global emissions, we specifically explore three environmental policy regimes: i) an emission tax alone (Regime α); ii) an emission tax and a carbon-content tariff on the imports of dirty inputs (Regime β); and iii) an emission tax, a carbon-content tariff and a rebate on the exports of dirty inputs (Regime γ). With the simple model, we find that whether BTAs are more effective than an emission tax alone to deal with carbon leakage and global emissions depends on whether assembly relocation happens. If trade costs are high and (or) abatement costs are low, the assembly is always located in the taxing country under BTAs; carbon leakage is eliminated and global emissions decrease. On the other hand, if trade costs are low and (or) abatement costs are high, the final good producer may have an incentive to relocate its assembly to the non-taxing country; the assembly relocation can lead to carbon leakage in Regime β and more emissions in both countries in Regime γ. In this case, global emissions can be higher under BTAs. According to GATT Article XX, the general exceptions clause, countries may be able to impose BTAs if they are "necessary to protect human, animal or plant life or health." Our finding indicates that Regime γ may not be compatible with the related rules.

We mainly follow two strands of literature. The first strand is about examining the effectiveness of BTAs in preventing carbon leakage and controlling emissions (e.g., Yomogida and Tarui, 2013; Jakob et al., 2013; Eichner and Pethig, 2015b; Ishikawa and Okubo, 2017). Yomogida and Tarui (2013) show that carbon leakage can occur under BTAs through trade of dirty goods when the emissions per unit of dirty goods in the taxing country are sufficiently higher than that in the non-taxing country. Jakob et al. (2013) adopt a two-sector two-country model to compare the effectiveness between consumption-based and production-based carbon pricing systems in mitigating carbon leakage. They show that carbon leakage can still occur through terms-of-trade effects and may even be larger under consumption-based carbon pricing (carbon pricing with full BTAs). Eichner and Pethig (2015b) develop a two-period two-country general equilibrium model with fossil fuel as the production input to examine how a carbon tax with full BTAs (also called a consumption-based carbon tax) affects each country's emissions in each period through the changes in the prices of fossil fuel. They find that such a tax in the first period may increase both countries' emissions as long as the income effect is sufficiently strong. Different from the three papers, we focus on how firm relocation leads to carbon leakage under BTAs. Ishikawa and Okubo (2017) extend the footloose capital model to examine the same channel as ours. They show that BTAs do not affect firm locations while decreasing each firm's production in the non-taxing country. Therefore, no carbon leakage exists under BTAs. Opposed to their findings, we find that carbon leakage may still exist under BTAs due to assembly relocation. The second strand is about environmental issues in the presence of vertical linkages. Examples are Hamilton and Requate (2004), Greaker (2006), Bushnell and Mansur (2011) and Wan et al. (2018). Hamilton and Requate (2004) and Wan et al. (2018) introduce an upstream industry consisting of polluting producers as we do, while Greaker (2006) considers an upstream market for environmental innovation. However, they do not take into account endogenous assembly location and BTAs. Bushnell and Mansur (2011) discuss BTA-equivalent policies in vertical markets but with fixed downstream firm locations.

The remaining chapter is organized as follows. Section 5.2 describes the basic ingredients of the model. Sections 5.3, 5.4 and 5.5 examine and compare the three policy regimes respectively. Section 5.6 makes concluding remarks.

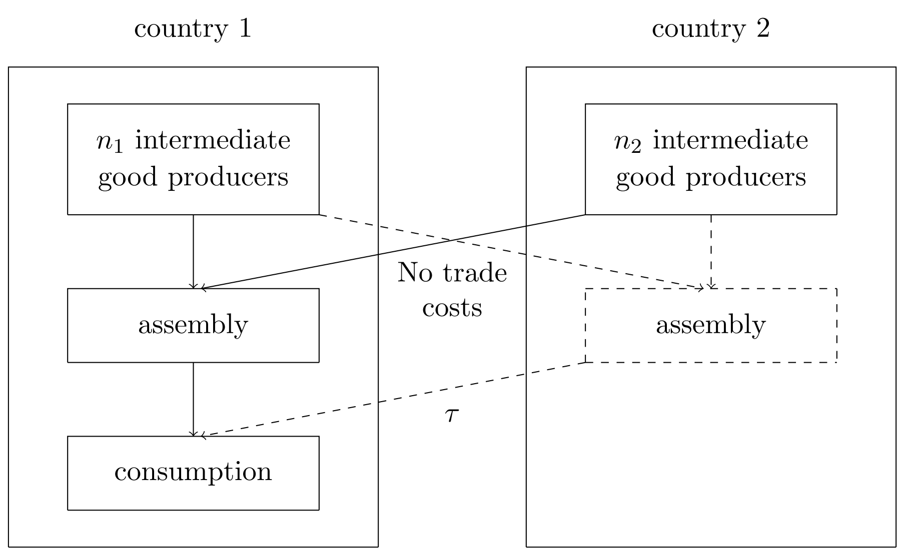

Figure 5.1: The basic setup of the model

5.2 The Basic Model

The basic setup is as shown in Figure 5.1. A final good producer produces homogeneous final goods by assembling a number of homogeneous inputs from country 1 and country 2.[2] The assembly location is endogenous. The numbers of intermediate good producers in country 1 and country 2 are n_1 and n_2 separately with $n_1 + n_2 = N$. The intermediate goods are freely traded across countries; however, each unit of the final goods incurs τ units of trade costs. For simplicity, we assume that only country 1 consumes the final goods and the inverse demand function is linear.

$$P = a - X/2, \tag{5.1}$$

where a is a parameter measuring the market size in country 1 and is assumed to be sufficiently large so that trade conditions are always satisfied throughout this chapter.[3]

The production of final goods is clean, while one unit of intermediate goods emits one unit of GHG during production. To control GHG emissions, country 1 imposes environmental regulations. We specifically explore three environmental policy regimes. Regime α includes an emission tax alone on its domestic production of dirty goods; Regime β also includes a carbon-content tariff on the imports of dirty inputs besides the emission tax; Regime γ includes an emission tax, a carbon-content tariff and a tax rebate on the exports of its dirty goods. The rates of the three instruments are assumed to be the same.

The intermediate goods are produced with labor only. One unit of them needs one unit of labor for production. Labor is supplied at a constant wage rate which is simplified to be zero without loss of generality. Intermediate good producers are identical and subject to oligopolistic Cournot competition. They can do abatement to make their production clean. The unit abatement cost is c. After abatement, producers' marginal cost becomes $1 + c$. Producers will choose to do abatement instead of paying the emission tax if they are regulated and the tax rate is higher than their abatement costs.

One unit of final goods requires only one unit of intermediate goods for assembly. Therefore,

$$C = \begin{cases} z_1 & \text{if } A = 1 \\ z_2 + \tau & \text{if } A = 2 \end{cases}, \tag{5.2}$$

where A denotes the assembly location, C is the unit cost of final goods, z_1 and z_2 are the prices of intermediate goods given the assembly in country 1 and country 2 respectively.

[2] The ownership of the final good producer does not matter in our analysis.

[3] The denominator "2" in the demand function is imposed for simplicity. It has no impact on our results.

The final good producer is a monopolist in the final good market and its profit is

$$\pi = (P - C)X. \tag{5.3}$$

Solving the profit maximization problem of the final good producer gives the supply function of final goods.

$$X = a - C. \tag{5.4}$$

The higher the unit cost is, the fewer the final good producer will supply. With the supply function, the final good producer's profit becomes into

$$\pi = (a - C)^2/2. \tag{5.5}$$

The final good producer chooses its assembly location by comparing its profits with the assembly in country 1 and country 2. And the comparison of profits can be transformed into the comparison of unit costs of final goods equivalently.

$$A = \begin{cases} 1 & \text{if } z_1 \leq z_2 + \tau \\ 2 & \text{if } z_1 > z_2 + \tau \end{cases}. \tag{5.6}$$

The assembly is located in the country with a lower unit cost. If the final good producer decides to locate its assembly in country 1, it saves trade costs. However, it may have an incentive to locate its assembly in country 2 to escape the environmental regulation, especially under BTAs.

To continue, we develop a three-stage game to investigate and compare how the three policy regimes affect assembly location, production, abatement activities and GHG emissions. In the first stage, taking country 1's environmental policies as given, the final good producer decides on its assembly location and production levels of the final goods, as shown in equations (5.6) and (5.4). In the second stage, the intermediate good producers determine whether to do abatement and how much to produce. In the last stage, the final good producer produces and sells its final goods to the consumers in country 1. We solve the game backward and mainly concentrate on the first and second stages.

5.3 Regime α: An Emission Tax Alone

This section introduces the benchmark case. We first analyze the behaviors of intermediate good producers given the assembly in country 1 and country 2 respectively and then show how the final good producer chooses its assembly location endogenously.

Given that the assembly is located in country 1, the inverse demand for intermediate goods is derived as

$$z_1^\alpha = a - (n_1 x_{11}^\alpha + n_2 x_{21}^\alpha). \tag{5.7}$$

x_{11}^α and x_{21}^α are the production of each intermediate good producer in country 1 and country 2, with the first number in the subscripts referring to the location of intermediate good producers and the second number the location of assembly.

For each intermediate good producer in country 1 and country 2, its profit is

$$\pi_{11}^\alpha = [z_1 - \min(t, c)]x_{11}^\alpha; \quad \pi_{21}^\alpha = z_1 x_{21}^\alpha. \tag{5.8}$$

Producers in country 1 choose to do abatement or pay the emission tax directly, depending on the relative values of tax rates and abatement costs. Producers in country 2 face no environmental regulation; therefore, they neither pay the emission tax nor do abatement.

Solving the profit maximization problems, we have the production of intermediate goods of each producer as

$$x_{11}^\alpha = z_1^\alpha - \min(t, c); \quad x_{21}^\alpha = z_1^\alpha. \tag{5.9}$$

Therefore, the price of intermediate goods is

$$z_1^\alpha = \frac{a + n_1 \min(t, c)}{1 + N}. \tag{5.10}$$

An emission tax always increases the price when it is not so high, and does not affect the price when it becomes higher than the abatement cost because producers in country 1 all choose to do abatement.

Given that the assembly is located in country 2, the inverse demand for intermediate goods is derived as

$$z_2^\alpha = a - \tau - (n_1 x_{12}^\alpha + n_2 x_{22}^\alpha). \tag{5.11}$$

x_{12}^α and x_{22}^α are the production of each intermediate good producer in country 1 and country 2 respectively.

The profits of producers are

$$\pi_{12}^\alpha = [z_2^\alpha - \min(t, c)]x_{12}^\alpha; \quad \pi_{22}^\alpha = z_2^\alpha x_{22}^\alpha. \tag{5.12}$$

Producers in country 1 are still regulated by the emission tax. Solving the profit maximization problems, we have the production of intermediate goods of each producer as

$$x_{11}^{\alpha} = z_2^{\alpha} - \min(t, c); \quad x_{22}^{\alpha} = z_2^{\alpha}. \tag{5.13}$$

Taking production levels back to the first order conditions gives the price of intermediate goods as

$$z_2^{\alpha} = \frac{a - \tau + n_1 \min(t, c)}{1 + N}. \tag{5.14}$$

Note that

$$C_2^{\alpha} = z_2^{\alpha} + \tau > z_1^{\alpha} \tag{5.15}$$

always holds. Therefore, the assembly is always located in the taxing country under Regime α. The intuition behind this finding is shown as follows. By locating its assembly in country 1, the final good producer can save trade costs. On the other hand, even if the assembly is located in country 2, the intermediate good producers in country 1 still have to pay the emission tax.

Based on the price levels, we can derive the production of intermediate goods and the corresponding emissions.[4] The dashed lines in Figures 5.2 and 5.3 describe the relationship between an emission tax and GHG emissions.[5] When the emission tax is not high, an increase in the tax rate decreases country 1's emissions while increasing country 2's emissions, which verifies the existence of carbon leakage. When the emission tax becomes sufficiently high, it has no impact on the emissions because production in country 1 becomes clean.

5.4 Regime β: An Emission Tax + A Carbon Tariff

Different from the regime with an emission tax alone, the final good producer may have an incentive to escape the tax by locating its assembly in country 2 in Regime β because the intermediate goods in country 2 can avoid the carbon tariff.

Given that the final good producer locates its assembly in country 1, intermediate good producers in both countries face the same environmental regulation. The inverse demand for the intermediate goods is

$$z_1^{\beta} = a - (n_1 x_{11}^{\beta} + n_2 x_{21}^{\beta}). \tag{5.16}$$

[4] See the Appendix.

[5] Figures 5.2 and 5.3 are drawn with the variable values $a = 3$, $N = 1$, $n_1 = 0.3$, $n_2 = 0.7$, $c = 0.5$. Trade costs are manipulated to derive different cases: $\tau = 0.25$ in Figure 5.2; $\tau = 0.4$ in Figure 5.3.

The profit of an intermediate good producer in country 1 and country 2 becomes

$$\pi_{11}^{\beta} = [z_1^{\beta} - \min(t, c)]x_{11}^{\beta}; \quad \pi_{21}^{\beta} = [z_1^{\beta} - \min(t, c)]x_{21}^{\beta}. \tag{5.17}$$

The intermediate good producers in country 2 also choose to do abatement or pay the tariff directly in Regime β.

The production of intermediate goods is the same across producers:

$$x_{11}^{\beta} = x_{21}^{\beta} = z_1^{\beta} - \min(t, c). \tag{5.18}$$

The price of intermediate goods depends on whether producers do abatement.

$$z_1^{\beta} = \frac{a + N\min(t, c)}{1 + N}. \tag{5.19}$$

Given that the final good producer locates its assembly in country 2, the analysis becomes totally the same as in Regime α because only the intermediate good producers in country 1 are regulated by the emission tax.

If trade costs are high and (or) abatement costs are low, i.e., $\tau \geq n_2 c/N$, then $z_2^{\beta} + \tau \geq z_1^{\beta}$ holds. The assembly is always located in country 1. Carbon leakage is prevented because the dirty inputs from country 2 face a carbon-content tariff. As a result, global emissions become lower than that in Regime α. If trade costs are low and (or) abatement costs are high, i.e., $\tau < n_2 c/N$, then $z_2^{\beta} + \tau < z_1^{\beta}$ holds for $t > t_1^{\beta} \equiv N\tau/n_2$. The final good producer relocates its assembly to country 2 at $t = t_1^{\beta}$. As shown in Figure 5.2, carbon leakage occurs for $t_1^{\beta} \leq t < c$ because the intermediate good producers in country 2 do not pay the carbon tariff anymore which makes them more competitive. on the other hand, global emissions are still lower than that in Regime α due to the existence of trade costs.

Proposition 5.1 *If $\tau \geq n_2 c/N$, Regime β is more effective than Regime α to prevent carbon leakage; if $\tau < n_2 c/N$, carbon leakage occurs due to the assembly relocation in Regime β. Global emissions are always lower in Regime β than that in Regime α.*

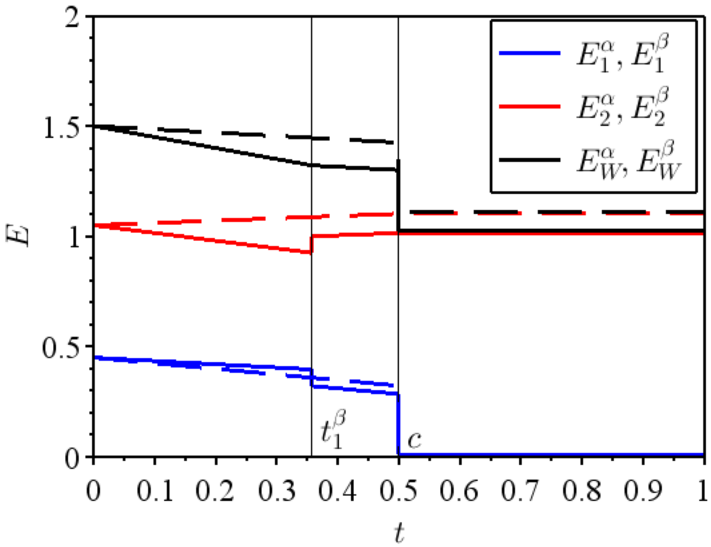

Figure 5.2: Comparison of the effects on emissions under Regime β (solid lines) and Regime α (dashed lines) for $\tau \leq n_2 c/N$.

5.5 Regime γ: An Emission Tax + A Carbon Tariff + A Tax Rebate

Given that the assembly in country 1, the analysis becomes totally the same as in Regime β. In the case with the assembly in country 2, the inverse demand for the intermediate goods becomes

$$z_2^\gamma = a - \tau - (n_1 x_{12}^\gamma + n_2 x_{22}^\gamma)\,. \tag{5.20}$$

The profits of intermediate good producers in country 1 and country 2 are

$$\pi_{12}^\gamma = z_2^\gamma x_{12}^\gamma; \quad \pi_{22}^\gamma = z_2^\gamma x_{22}^\gamma. \tag{5.21}$$

Solving the profit maximization problem gives

$$x_{12}^\gamma = x_{22}^\gamma = z_2^\gamma. \tag{5.22}$$

Taking the first order conditions back to the demand function gives the price of intermediate goods as

$$z_2^\gamma = \frac{a-\tau}{1+N}. \tag{5.23}$$

The unit cost of the final goods given $A = 2$ is

$$z_2^\gamma + \tau = \frac{a + N\tau}{1 + N}. \tag{5.24}$$

When deciding on the assembly location, the final good producer faces a tradeoff between trade costs and higher input costs due to environmental regulation. If $\tau \geq c$, the final good producer always locates its assembly in country 1. This case is more likely to occur especially when abatement costs are low and (or) trade costs are high. The intuition is that the final good producer saves trade costs greatly when they are high and benefits from lower production costs of inputs after producers' abatement, and producers are willing to do so when their abatement costs are low. In this case, carbon leakage is prevented and global emissions are lower in Regime γ than in Regime α. If $\tau < c$, the assembly is relocated to country 2 before abatement. The threshold tax rate is

$$t_2^\gamma = \tau. \tag{5.25}$$

This case is more likely to occur when trade costs are low and (or) abatement costs are high. In Regime γ, the final good producer has a stronger incentive to locate the assembly in country 2 (i.e., $t_2^\gamma < t_1^\beta$) because the intermediate goods exported from country 1 are exempt from environmental regulation due to a rebate.

The solid lines in Figure 5.3 describe the effect of Regime γ on GHG emissions when trade costs are sufficiently low. As the assembly is relocated to country 2, production of each producer in country 1 and country 2 does not change; therefore, the emissions do not change at the threshold tax rate, implying that there is no carbon leakage. This finding is based on the assumption that intermediate goods can be freely transported across countries. Suppose there exist trade costs for intermediate goods, carbon leakage can also occur in Regime γ. Besides, we find that global emissions can be higher in Regime γ than in Regime α. Given an emission tax rate which is higher than the abatement costs, Regime γ releases the production of intermediate goods in country 1 from environmental regulation by inducing the assembly to be located in country 2. Intermediate good producers in country 1 become more competitive and produce more without abatement. Therefore, Regime γ increases country 1's emissions and decreases country 2's emissions. Consequently, global emissions may be higher if the former effect dominates.

Conclude the findings in the following proposition.

Proposition 5.2 *If $\tau \geq c$, Regime γ is more effective than Regime α to deal with carbon leakage and global emissions. If $\tau < c$, the final good producer has a stronger incentive to locate the assembly in country 2 in Regime γ than in Regime β; global emissions can be higher in Regime γ than in*

Regime α.

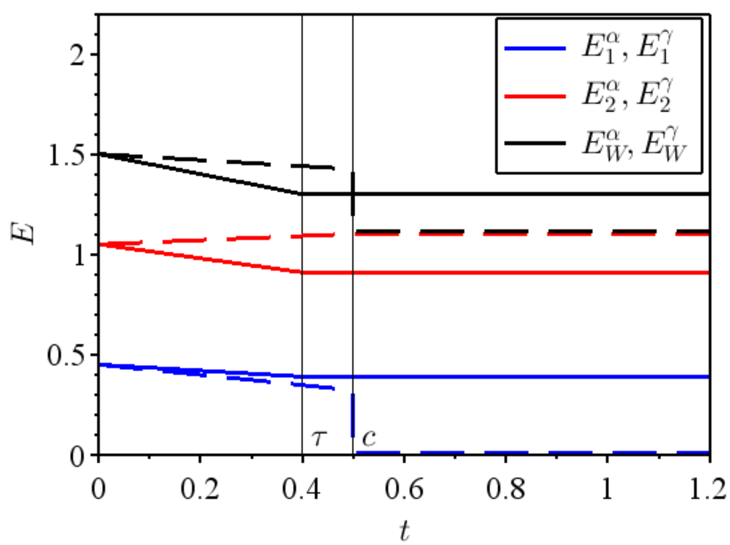

Figure 5.3: Comparison of the effects on emissions under Regime γ (solid lines) and Regime α (dashed lines) for $\tau \leq c$.

5.6 Conclusion

We developed a simple model to examine and compare how BTAs affect production and GHG emissions in the presence of intermediate goods and endogenous assembly location. Specifically, we explored three policy regimes. In Regime α, there is an emissions tax alone on the domestic production of dirty intermediate goods; in Regime β, a carbon-content tariff is also introduced; in Regime γ, the government imposes a tax rebate on its exports of dirty goods besides the two environmental instruments. We found that BTAs avoid carbon leakage and decrease global emissions when the assembly is in the taxing country. However, carbon leakage can still occur due to assembly relocation in Regime β. Besides, an introduction of a tax rebate in Regime γ can lead to more global emissions than the other regimes. Our findings imply that BTAs may not be more effective to deal with carbon leakage and control global emissions compared to an emission tax alone when the assembly location is endogenous. However, as long as the assembly is always kept in the taxing country, BTAs become more effective. To make it happen, the taxing country can subsidize abatement activities and encourage technology transfer across countries so that production costs decline even without assembly relocation.

Our analysis also shows how globalization affects the effectiveness of BTAs. Globalization has two crucial features. One is the decline in trade costs, the other is the upgrade of technologies. In this chapter, the two kinds of globalization affect the effectiveness of BTAs in opposite directions. On the one hand, as trade costs decline, the assembly is more likely to be located in country 2, which may cause carbon leakage or increase global emissions. On the other hand, as abatement technologies become better, the assembly is more likely to be located in country 1, which decreases global emissions and avoids carbon leakage.

To conclude this paper, two final remarks are in order. First, although the assumption that only country 1 consumes the final goods is useful for us to concentrate on the tradeoff between trade costs and abatement investment as shown in equation (5.6), one might wonder how our results would change if country 2 also consumes final goods. Actually, the essence of our paper still holds. That is, the effectiveness of BTAs still depends on the assembly location: BTAs are more effective if the assembly is always located in country 1 and may not if it is located in country 2. Note that the existence of country 2's consumption affects the timing of assembly relocation. If the market size in country 2 is sufficiently small, the analysis is very similar to the main part. If it is sufficiently large, the assembly is likely to be always located in country 2 to save trade costs in the three policy regimes. In the latter case, Regime β is the same as Regime α; however, global emissions are higher in Regime γ than in the other two regimes.

Second, we assumed that environmental policies are imposed only on direct emissions, which incentivizes the final good producer to relocate its assembly to country 2. If the indirect emissions were also regulated, the incentive would be eliminated with the assembly always located in country 1. Therefore, a carbon-footprint tax is more effective to prevent carbon leakage and decrease global emissions in our model.[6] However, it is not always the case if some model settings are adjusted. Carbon leakage may still exist if intermediate good producers can locate their production in country 2. A carbon-footprint tax would decrease country 1's consumption and induce producers to relocate to and serve country 2 if country 2's market size is sufficiently large. As a consequence, global emissions are likely to increase. The design of more effective environmental tax regimes in the presence of strategic behaviors of producers and fragmentation of production process is left for future research.

[6]Refer to McAusland and Najjar (2015) for more discussions of carbon-footprint taxes.

5.A Appendix

5.A.1 Production and Emissions

Regime α

In Regime α, the assembly is always located in country 1, each producer's production of intermediate goods is

$$x_{11}^{\alpha} = \frac{a-(1+n_2)\min(t,c)}{1+N}; \quad x_{21}^{\alpha} = \frac{a+n_1\min(t,c)}{1+N}$$

When the emission tax is low, as t increases, producers in country 1 produce less due to higher production costs; producers in country 2 provide more dirty inputs because they are not regulated by the emission tax, which makes them more competitive. When the emission tax is high, production is independent of t because producers in country 1 all do abatement.

Each country's and global emissions are derived as

$$E_1^{\alpha} = \begin{cases} \frac{n_1[a-(1+n_2)t]}{1+N} \\ 0 \end{cases}, \quad E_2^{\alpha} = \begin{cases} \frac{n_2(a+n_1 t)}{1+N} \\ \frac{n_2(a+n_1 c)}{1+N} \end{cases}, \quad E_W^{\alpha} = \begin{cases} \frac{Na-n_1 t}{1+N} & \text{if } t \le c \\ \frac{n_2(a+n_1 c)}{1+N} & \text{if } t > c \end{cases}.$$

Regime β

Given the assembly in country 1, production of producers in countries 1 and 2 is

$$x_{11}^{\beta} = x_{21}^{\beta} = \frac{a-\min(t,c)}{1+N}.$$

Given the assembly in country 2, production of producers in countries 1 and 2 is

$$x_{11}^{\beta} = \frac{a-\tau-(1+n_2)\min(t,c)}{1+N}; \quad x_{21}^{\beta} = \frac{a-\tau+n_1\min(t,c)}{1+N}$$

For $\tau > n_2c/N$, the assembly is always located in country 1. Each country's and global emissions are derived as follows.

$$E_1^{\beta} = \begin{cases} \frac{n_1(a-t)}{1+N} \\ 0 \end{cases}, \quad E_2^{\beta} = \begin{cases} \frac{n_2(a-t)}{1+N} \\ 0 \end{cases}, \quad E_W^{\beta} = \begin{cases} \frac{N(a-t)}{1+N} & \text{if } t \le c \\ 0 & \text{if } t > c \end{cases}.$$

For $\tau \le n_2c/N$, the assembly is relocated to country 2 at $t = t_1^{\beta}$. Each country's and global emissions are derived as follows.

$$E_1^{\beta\prime} = \begin{cases} \dfrac{n_1(a-t)}{1+N} \\ \dfrac{n_1[a-\tau-(1+n_2)t]}{1+N} \\ 0 \end{cases}, \quad E_2^{\beta\prime} = \begin{cases} \dfrac{n_2(a-t)}{1+N} \\ \dfrac{n_2(a-\tau+n_1 t)}{1+N} \\ \dfrac{n_2(a-\tau+n_1 c)}{1+N} \end{cases}, \quad E_W^{\beta\ \prime} = \begin{cases} \dfrac{N(a-t)}{1+N} & \text{if } t \le t_1^\beta \\ \dfrac{N(a-\tau)}{1+N} & \text{if } t_1^\beta < t \le c \\ \dfrac{n_2(a-\tau+n_1 c)}{1+N} & \text{if } t > c \end{cases}.$$

Regime γ

Given the assembly in country 2, the production of each producer is

$$x_{12}^\gamma = x_{22}^\gamma = \frac{a-\tau}{1+N}.$$

An emission tax with a carbon tariff and a tax rebate has no effect on the production of intermediate goods.

For $\tau > c$, the assembly is always located in country 1. Each country's and global emissions are derived as follows.

$$E_1^\gamma = \begin{cases} \dfrac{n_1(a-t)}{1+N} \\ 0 \end{cases}, \quad E_2^\gamma = \begin{cases} \dfrac{n_2(a-t)}{1+N} \\ 0 \end{cases}, \quad E_W^\gamma = \begin{cases} \dfrac{N(a-t)}{1+N} & \text{if } t \le c \\ 0 & \text{if } t > c \end{cases}.$$

For $\tau \le c$, the assembly is relocated to country 2 at $t = t_2^\gamma$. Each country's and global emissions are derived as follows.

$$E_1^{\gamma\prime} = \begin{cases} \dfrac{n_1(a-t)}{1+N} \\ \dfrac{n_1(a-\tau)}{1+N} \end{cases}, \quad E_2^{\gamma\prime} = \begin{cases} \dfrac{n_2(a-t)}{1+N} \\ \dfrac{n_2(a-\tau)}{1+N} \end{cases}, \quad E_W^{\gamma\ \prime} = \begin{cases} \dfrac{N(a-t)}{1+N} & \text{if } t \le t_2^\gamma \\ \dfrac{N(a-\tau)}{1+N} & \text{if } t > t_2^\gamma \end{cases}.$$

Chapter 6

General Conclusion

6.1 Concluding Remarks of the Essays

We have answered several old questions in the literature on trade and the environment with new perspectives. Specifically, we considered a new production pattern under current globalization (Chapter 2), a new externality rather than production pollution (Chapter 3) and a new policy topic to deal with carbon leakage and global emissions (Chapter 4 and Chapter 5). In the following, we made brief concluding remarks on the essays.

Chapter 2 analyzed socially optimal environmental tax in global value chains and showed that desirable environmental regulations may drastically vary before and after the current globalization where spatial unbundling of production processes is possible. In the pre-globalized world with high unbundling costs, environmental tax harmonization prevents distorting efficient location choices and maximizes global welfare, irrespective of heterogeneity among countries. In the globalized world with low unbundling costs, environmental tax harmonization leads to the concentration of pollution in one country and almost never maximizes global welfare. The second unbundling calls for careful international coordination beyond naive harmonization.

Chapter 3 studied the relationship between trade liberalization, GHG emissions from consumption and consumption taxes with the footloose capital model. We found a non-monotonic effect of trade liberalization on global emissions. That is, as trade costs decline, global emissions initially decrease and then rise. We also showed that an increase in the consumption tax in one country reduces its emissions while raising the other country's emissions, which implies that carbon leakage can occur under consumption pollution. In the welfare analysis, we found that the social planner never has an incentive to change firm locations; particularly, identical consumption taxes are globally desirable regardless of market sizes if firms initially disperse across countries under no environmental regulation.

Chapter 4 developed a simple two-country, two-firm model to examine how emission taxes with BTAs affect outputs, emissions and locations of firms in the presence of an emission-abatement technology. The two countries are identical except that only a country introduces environmental policies. The two firms are also identical. We specifically examined three policy regimes: i) emission taxes alone, ii) emission taxes accompanied by carbon-content tariffs, and iii) emission taxes coupled with emission-tax refunds and carbon-content tariffs. When an emission-abatement technology is available, an emission tax may lead firms to adopt it. However, even if some tax rates induce the firm's emission abatement, higher tax rates do not necessarily induce it. Moreover, as a result of emission abatement, global emissions may increase. The emission-tax refund is more effective than the carbon-content tariff in eliminating carbon leakage. Whereas the carbon-content tariff encourages emission abatement, the emission-tax refund discourages it. If firm locations are endogenously determined, both firms may locate themselves in the non-taxing country in the presence of the taxing country's emission tax. As a result, global emissions can increase. The BTAs may induce firms to invest in emission abatement. Moreover, the BTAs encourage a firm to locate itself in the taxing country. This effect is stronger with the tax refund than without it.

Chapter 5 re-examined the effectiveness of BTAs in preventing carbon leakage and decreasing global emissions in the presence of intermediate goods and endogenous assembly location. We explored the same three policy regimes as in Chapter 4. In Regime α, there is an emissions tax alone; in Regime β, a carbon-content tariff is also introduced; in Regime γ, the government imposes a tax rebate on its exports of dirty goods besides the two environmental instruments. It was shown that BTAs avoid carbon leakage and decrease global emissions when the assembly is in the taxing country. However, carbon leakage can still occur due to assembly relocation in Regime β. Besides, global emissions can be higher in Regime γ than in Regime α. Our findings implied that BTAs may not be more effective than an emission tax alone when vertical linkages are introduced.

6.2 Future Research

We end this dissertation by providing several directions for future research.[1]

6.2.1 International Emissions Trading

According to World Bank (2020a) and the Carbon Pricing Dashboard, there are now 28 implemented ETSs and 3 scheduled ETSs. On January 1, 2020, the Swiss ETS and the EU ETS became linked, allowing covered entities in the Swiss ETS to be able to use emissions permits from the EU ETS for compliance, and vice versa. Besides, the UK is considering to construct its own ETS and

[1] The part of future research benefits a lot from the RA job for Professor Jota Ishikawa.

link it to the EU ETS.[2] The link between emissions trading markets seems to be an irreversible trend to deal with carbon emissions. Therefore, it is worthwhile to investigate how the link (or international emissions trading) would affect trade patterns, welfare and global emissions especially when countries are differentiated in their production technologies and permit levels.

There have been numerous papers investigating emissions trading issues. Examples are Copeland and Taylor (1995a, 2005a), Ishikawa and Kiyono (2006), Abe et al. (2012), Ishikawa et al. (2012), Marschinski et al. (2012), Kiyono and Ishikawa (2013), Konishi and Tarui (2015). However, two key points are neglected in the literature. The first is strategic firm organizations in the emissions trading. As a direction, we can investigate how international emissions trading affects the locations and (or) sourcing patterns of firms and whether carbon leakage is prevented. The second extension is emissions trading with border adjustments. Suppose a country imposes an emission cap (which is fixed) and requires that the importers purchase the emission permits as the domestic firms do. Initially, this country's emissions decrease and its market shrinks, which may induce the firms to relocate to the other country. Note that firm relocation may increase both countries' emissions because it may decrease the commodity prices in the two countries. In the country with an emission cap, the permit price may decrease due to lower demand for permits, leading to a lower commodity price. In the other country, the commodity price may decrease due to harsher competition.

6.2.2 Transportation Pollution

Transportation has contributed a lot to global GHG emissions. According to the US Environmental Protection Agency, GHG emissions from the transportation sector were the highest, about 28.9%, among all economic sectors in 2017, even higher than the industry and electricity production. The Japanese Ministry of the Environment announced that the transportation sector generated about 17.9% of CO_2 emissions in 2016, and the ratio was a little higher than that of the commercial sector. According to the Third IMO GHG Study 2014, shipping and international shipping accounted, on average, for approximately 3.1% and 2.6% of annual global CO_2 emissions for the period 2007-2012. These numbers are not small. In 2012, international shipping emitted about 796 million tonnes of CO_2, while the total CO_2 emissions in Germany were 745 million tonnes.[3] Besides, IMO predicts that the growth of the world maritime trade could increase the CO_2 emissions from international shipping between 50% and 250% by 2050.

The empirical papers also provide supportive evidence that international transportation contributed a lot to the global emissions (e.g., Olsthoorn, 2001; Cadarso et al., 2010; Cristea et al.,

[2] Source: Government of the United Kingdom, Legislation for a UK Emissions Trading System, March 11, 2020, https://www.gov.uk/government/publications/legislation-for-a-uk-emissions-trading-system/legislation-for-a-uk-emissions-trading-system.

[3] The German data is from the international energy agency (IEA).

2013; Vöhringer et al., 2013 among others). Olsthoorn (2001) estimates that CO_2 emissions from international aviation may increase by 200% to 500% between 1995 and 2050. Cristea et al. (2013) suggest that international transport accounts for 33% of global trade-related emissions and more than 75% of emissions for major manufacturing categories.

To our knowledge, only a few theoretical papers investigate environmental issues of transportation in trade (e.g., Abe et al., 2014; Takarada et al., 2014; Shapiro, 2016; Forslid, 2020). The previous papers have investigated environmental issues of transportation from the following perspectives: strategic trade and environmental policies (Abe et al., 2014), the introduction of both production and transportation pollution with different emission intensities (Shapiro, 2016; Forslid, 2020), comparison between domestic and international emissions trading (Takarada et al., 2014). A common point of the papers is that they all focus more on welfare analysis rather than firms' behaviors. Based on the background and previous literature, there are three potential points to emphasize for future research.

Environmental policies. The previous papers usually assume that the transport firms are regulated on the basis of their flag and ownership. That is, the firms have to pay the emission tax to or purchase the emission permits from the countries they belong to. However, the firms might avoid the regulation by registering the ships in the non-taxing countries. An alternative environmental policy is to impose an emission tax at the border. The international carriers need to pay the emission tax for the transportation of exports, irrespective of ownership. Besides, a country can also impose a carbon-content tariff on the transportation of imports.

Abatement activities. Transport firms can do abatement through speed optimization, adoption of energy-efficient technologies and usage of low- and zero-carbon fuels. The international carriers may prefer speed reduction which is easy to operate, but they may face profit loss due to longer delivery time.[4] There is no evidence that low- and zero-carbon fuels are used in international shipping now. Upgrading energy-efficient technologies seems practical in the short term. To do so, firms can do R&D by themselves or together in the form of an R&D joint venture; besides, they can use the better (engine) technologies of their rivals through licensing.

Transportation in global value chains. Globalization allows for global sourcing, which implies that intermediate goods can be transported between countries multiple times before assembled into final goods. Therefore, transportation pollution deserves more attention, especially in global value

[4] Corbett, Wang, and Winebrake (2009) show that halving the speed of international shipping can reduce emissions by 70%.

chains. By conjecture, stringent environmental regulations on international transport would induce the input-producers to co-locate with the final-good producers and the final-good producers to co-locate with the market so as to avoid international shipping.

6.2.3 Firm Heterogeneity

After Melitz (2003), more and more attention was paid to firm heterogeneity and researchers tended to emphasize how firms with different productivity respond to environmental regulations. For instance, Cherniwchan (2017) investigates the impacts of NAFTA on pollution emissions with the data of the USA manufacturing plants and finds that NAFTA played an important role in reducing the pollution of the USA manufacturing plants. He shows that the reduction in pollution emissions is attributed to the changes in the emission intensity of production rather than the changes in outputs. Then the author examines the channels through which the emission intensity might change and finds that this kind of change can be explained by within plant adjustments (within plant reorganization effect), increased imports of dirty intermediate input from Mexico (offshoring effect) and adoption of better technologies (technique effect). All these findings emphasize the importance of firm-level analysis in the issue of trade liberalization and environmental pollution, while it has not been adequately exploited, especially in the theoretical field.

We are going to extend the models in Melitz (2003) and Cherniwchan et al. (2017) to investigate how firms with different productivity and abatement technologies behave in the presence of pollution and environmental policies and how countries decide on their environmental policies with international interactions. We will concentrate on within-industry adjustments since the previous research has demonstrated that there is remarkable heterogeneity in emissions and emission intensities across firms. Based on Melitz (2003), firms with higher productivity tend to own cleaner technology and do not need to invest more in abatement as emission taxes go higher. On the other hand, firms with middle productivity choose to invest more and firms with low productivity may exit directly due to high production costs. However, based on the traditional models without firm heterogeneity, all firms invest more in abatement as environmental regulation becomes more stringent, leading to lower emission intensity. The aggregate emission intensities both decrease in the two models while through different channels. We will also reexamine the relationship between the pollution haven effect (PHE) and the pollution haven hypothesis (PHH) with firm heterogeneity. PHE means that stricter environmental regulation increases the import of dirty goods. PHH refers to the phenomenon where trade liberalization shifts dirty production to countries with laxer environmental regulation. The empirical papers find strong evidence for PHE while little for PHH. We aim to solve this open question with firm-level analysis. One potential reason is the existence of reshoring of dirty goods. When trade costs are high, firms with high productivity in developed countries tend to offshore the assembly and parts production to developing countries. Some capital-intensive and dirty parts production co-locates with the assembly and also shifts to developing countries to save trade costs. As trade costs decline, the co-location effect becomes weaker; consequently, the capital-intensive and dirty parts are reshored to developed countries that have comparative advantages of capital-intensive goods. Firm heterogeneity plays an important role among the analyses because firms with different productivity may do offshoring or reshoring at the same time which explains why PHH is weak.

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