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Carbon Tariffs, Emissions Leakage, and Production Relocation*

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Abstract

We study whether carbon tariffs can prevent emissions leakage which occurs when firms relocate production across countries. We extend a segmented market model of international trade to a North-South setting with polluting firms. A northern firm may relocate its plant to the South to avoid the higher carbon costs imposed on its domestic production relative to those on its offshored production. To prevent emissions leakage through the firm's relocation, the North can adopt a carbon tariff and an export rebate that can offset its gap in carbon taxes with the South. We find that the North's carbon tariff and export rebate prevent emissions leakage, which causes an increase in global emissions, if the northern firm uses less emissions-intensive technology relative to the southern firm and its emissions intensity exceeds fifty percent of that of the southern firm. However, if the northern firm's emissions intensity is less than fifty percent of that of the southern firm, the North's carbon tariff fails to prevent emissions leakage even with its export rebate. We also find that the North's optimal carbon tax regime includes its carbon tariff and export rebate. Furthermore, we show that the North's optimal carbon tax regime actually benefits the South through a reduction in global emissions.

Keywords: carbon tax, carbon tariffs, carbon leakage, production relocation
JEL classification: F18, Q54, Q56, Q58

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1 Introduction

The Paris Agreement on climate change requires nations to take actions for enhancing the global effort to tackle climate change. One such action is carbon pricing, an important instrument that can help countries achieve their targets for carbon emissions reduction. A number of countries have priced carbon but these prices exhibit regional heterogeneity.[1] These disparities can lead to carbon leakage: that is, carbon emissions reduction in countries that adopt stringent carbon prices could be offset, or more than offset by an increase in carbon emissions in countries that adopt lenient carbon regulations. Possible channels of carbon leakage include trade and firm relocation. Products of countries with stringent carbon prices could be replaced by more carbon-intensive imports, and firms based in countries having high carbon prices could relocate their plants to countries with low carbon prices.[2]

Carbon tariffs address this risk of carbon leakage. Since January 2026, the European Union (EU) has officially imposed carbon tariffs on imports of carbon-intensive goods through its carbon border adjustment mechanism (CBAM). This mechanism places a price on carbon emitted during the production of goods imported into EU, ensuring that the carbon price of imports is equivalent to the carbon price of EU products.[3]

Export rebates of carbon prices can also address carbon leakage. Although the EU CBAM does not include export rebates as of now, the EU Commission announced plans to mitigate carbon leakage risk for exports in July 2025. While some expert critics argue for export measures to deal with carbon leakage with respect to exported goods,[4] others oppose the inclusion of export rebates in the CBAM because such rebates could be inconsistent with World Trade Organization (WTO) rules or contradict the polluters pay principle.[5]

[1] High-income countries tend to have higher carbon taxes and Emissions Trading System (ETS) prices than middle-income countries (World Bank, 2023).

[2] In addition, carbon leakage could occur through an energy price channel. A country that increases its carbon price reduces the demand for fossil fuels and, thus, its carbon emissions. The decrease in demand for fossil fuels leads to a corresponding decline in their world price. As a result, in countries with lenient climate regulations, the demand for fossil fuels increases and, accordingly, their carbon emissions expand.

[3] The EU CBAM covers energy-intensive and trade-exposed sectors such as cement, iron and steel, aluminum, fertilizers, electricity, and hydrogen (European Commission, 2023). On October 1, 2023, CBAM entered its transitional phase. During the transitional phase, importers of CBAM goods are asked to report the amounts of greenhouse gases (GHGs) emitted during the production of imports. The CBAM has been applied in its definitive regime since January 2026. Under the definitive regime, importers of over 50 tonnes of CBAM-covered goods are required to buy and submit a certain number of CBAM certificates according to GHG emissions embedded in goods imported into the EU. The price of CBAM certificates is determined in accordance with the EU ETS allowance price.

[4] For instance, Marcu et al. (2022) state that "failure to address the impact of the carbon costs on EU products exported to global markets incurs a high likelihood of carbon leakage."

[5] Export rebates could be inconsistent with WTO rules if they are considered to be export subsidies that are strictly prohibited under WTO rules (Cosbey et al. 2019). Tamellin (2025) states that exporters of CBAM goods should pay for their emissions in line with the polluter pays principle and the internalization of social costs of pollution.

Then, how do carbon tariffs prevent carbon leakage? Does the adoption of export rebates complement carbon tariffs? How can we evaluate carbon tariffs and export rebates in terms of social welfare and global emissions? We examine these questions by constructing a model with firm's choice on production location. We extend a segmented market model of international trade to a North-South setting with polluting firms. A northern firm may relocate its plant to the South to avoid the higher carbon costs imposed on its domestic production relative to those on its offshored production. To prevent emissions leakage through the firm's relocation, the North can adopt a carbon tariff and an export rebate that can offset its gap in carbon taxes with the South.

We examine the effects of the North's carbon tariff on the incentive for the northern firm to relocate its plant to the South. One the one hand, the North's carbon tariff negatively affects the incentive for relocation of the northern firm. This is because it raises carbon costs imposed on the northern firm's imports from its offshored plant in the South. On the other hand, the carbon tariff positively affects the incentive for the firm's relocation. That is, the northern firm's lower emissions intensity relative to that of the southern firm offers a competitive advantage for the northern firm, and its competitive advantage is enhanced owing to the firm's relocation. We determine whether the negative effect of the North's carbon tariff outweighing the positive effect depends on the magnitude of the gap in emissions intensities between the northern and southern firms.[6]

We analyze the effects of the North's carbon tariff on emissions leakage that could occur owing to the unilateral carbon tax of the North. We show that, if the northern firm uses less emissions-intensive technology relative to the southern firm and its emissions intensity exceeds fifty percent of that of the southern firm, then the North's carbon tariff prevents emissions leakage through northern firm's relocation as long as its export rebate is implemented together. In this case, the carbon tariff also prevents an expansion of global emissions that would occur if emissions leakage arose. Meanwhile, if the northern firm's emissions intensity is less than fifty percent of that of the southern firm, then the North's carbon tariff fails to prevent emissions leakage even with its export rebate. Nonetheless, in this case, we show that emissions leakage through relocation does not worsen the global environment because it contributes to a reduction in global emissions.

We further investigate the North's optimal carbon tax regime. We show that when the North sets its carbon tax rate to maximize its social welfare, its optimal tax regime incorporates both a carbon tariff and an export rebate. This is because its carbon tariff and export rebate prevent emissions leakage, which would then increase global emissions. In addition, they alleviate the negative effect of the North's carbon tax on the northern firm's production efficiency. We also examine the impact of the North's optimal carbon

[6] A recent report of the EU Commission shows that there are significant differences in CO2 emission intensities in iron and steel industry between developed and developing countries. In terms of Scope 1 emissions, the CO2 emission intensity of EU is 1.04 tonne CO2 per tonne steel and that of Japan is 1.55, which are lower than that of China 1.58 and that of India 2.70 (Koolen and Vidovic, 2022).

tax regime on the South, revealing that it can benefit the South as well. This result is obtained when the North's optimal carbon tax provides a sufficiently large gain for the South owing to a reduction in global emissions.

The rest of this article is organized as follows. Section 2 reviews the literature. Section 3 presents our model. Section 4 explains how the North's carbon tariff affects the production location of the northern firm under each carbon tax regime. Section 5 evaluates the effects of the North's carbon tariff on emissions leakage and global emissions. Section 6 analyzes the North's optimal carbon tax regime and examines its impact on the South's welfare. Section 7 concludes this article.

2 Related Literature

Our study is related to several strands of the literature. Existing studies on border carbon adjustments (BCAs) that include carbon tariffs and export rebates explore different channels of carbon leakage theoretically and quantitatively. Fontagné and Schubert (2023) presents a recent survey on the development in the economics of BCA. Quantitative studies that consider trade channels include those by McKibben and Wilcoxen (2009), Elliott et al. (2010), Böhringer et al. (2012, 2017), Takeda et al. (2012), Mattoo et al. (2013), and Takeda and Arimura (2024). These scholars use computable general equilibrium (CGE) models to examine the effects of BCAs on carbon leakage under various scenarios of climate policies.[7] Larch and Wanner (2017) develop a structural gravity model of international trade to examine the quantitative effects of carbon tariffs.

Theoretical studies that use general equilibrium models include those by Jakob et al. (2013) and Eichner and Pethig (2015). Jakob et al. (2013) consider leakage caused through a change in the terms of trade, while Eichner and Pethig (2015) focus on an intertemporal channel of leakage. Yomogida and Tarui (2013) use a partial equilibrium model to explore the effects of BCA on emissions leakage through trade in oligopolistic sectors. They also show how BCA affects a welfare-maximizing emissions tax when the emission tax is implemented unilaterally. Hecht and Peters (2019) extend Yomogida and Tarui's (2013) analysis and examine a non-cooperative game in emissions tax between countries. They show that BCA could support more stringent environmental policy. Kim (2025) uses a heterogeneous firms model of trade to examine the effects on welfare and the environment of unilateral environmental policy with BCA.

Among studies that consider firm relocation as a channel of leakage, empirical findings show mixed evidence on the relocation effect of climate policies. On the one hand, Dechezleprêtre et al. (2022) examine the impact of the EU ETS on relocation by multinational firms and do not find significant evidence in the period 2007–2014. On the other

[7] Fischer and Fox (2012) examine the effects of BCA on competitiveness and leakage in a given sector by using a partial equilibrium model parameterized with simulations of a CGE model.

hand, Ben-David et al. (2021) explore the impact of climate policies on multinational firms based in 48 countries and find strong evidence of the relocation effect. Babiker (2005) use a CGE model with oligopoly in energy-intensive sectors and find that unilateral climate policies in developed countries can cause significant carbon leakage through relocation of energy-intensive sectors. Sanna-Randaccio et al. (2017) use a partial equilibrium model with multi-plant oligopoly and show that a unilateral climate policy can cause leakage through firm relocation. Richter et al. (2021) examine the strategic effects of non-cooperative choice of emissions taxes by using a model with imperfect competition and mobile polluting firms. Although these studies do not consider BCA as a policy tool, Ishikawa and Okubo (2017) and Cheng and Ishikawa (2021) theoretically examine the effects of emissions tax on firm relocation under BCA by using a footloose capital model and a two-country oligopoly model, respectively. Elboghdadly and Finus (2022) examine the effects of BCAs on strategic emissions tax competition between countries with a model of endogenous plant location.

Recent works also explore the effects of BCA under bilateral or multilateral climate policies. Keen and Kotsogiannis (2014) examine the role of BCA in achieving a Pareto-efficient outcome when countries cooperatively establish their trade and climate policies. Helm et al. (2012) and Sanctuary (2018) determine whether BCA induces a trade partner to adopt more stringent climate policy. Studies that explore the effects of BCAs on self-enforcing cooperation in climate policies include those by Eyland and Zaccoury (2014), Anouliès, (2015), Helm and Schmidt (2015), Bakski and Chaudhuri (2017, 2025), and Al Khourdajie and Finus (2020). Hagen and Schopf (2024) examine the effects of industrial lobbying on international climate agreement when coalition countries use BCAs.

Our study is the closest to those by Cheng and Ishikawa (2021) and Elboghdadly and Finus (2022) in that it examines the effects of BCA with a model that incorporates firm's choice on production location. Our study complements existing works in the following respects. While Ishikawa and Chen (2021) consider the case in which carbon taxes are exogenous and countries are symmetric, we examine how one country's adoption of BCA affects its optimal carbon tax in a setting with asymmetric countries. Elboghdadly and Finus (2022) focus on a carbon tariff as a BCA policy measure and do not consider an export rebate of carbon tax. In contrast, we introduce an export rebate to deal with emissions leakage through exports. Our analysis on the effect of an export rebate is relevant to the recent policy debate on whether the EU CBAM should include a measure to deal with a risk of carbon leakage for exports. In addition, unlike Elboghdadly and Finus (2022), our model allows asymmetric emissions intensity between northern and southern firms. We show that this asymmetry plays a crucial role in the effects of a carbon tariff on emissions leakage through firm's relocation.

3 The Model

Consider a partial equilibrium model with two countries, N (North) and S (South). The industry is a homogeneous product duopoly with a northern firm (firm 1) and a southern firm (firm 2) based in country N and S, respectively.[8] Both countries have segmented markets wherein one firm competes with the other.[9] The inverse demand function in the market of country K is linear and written as follows:

$$p_K = a - b(q_{iK} + q_{jK}),\ a, b > 0,$$

with $i, j = 1, 2$, $i \neq j$, $K = N, S$, and q_{iK} denotes firm i's output sold to the market of country K.

Firm production emits carbon dioxide, which is a primary driver of global warming. Carbon emissions per output of each firm are constant, e_i $(i = 1, 2)$. The northern firm has a lower emissions intensity than the southern firm, $e_1 < e_2$, because the northern firm has adopted low-carbon technology, but the southern firm continues to use high-carbon technology. The northern firm produces in the North or relocates its plant to the South. Under domestic production in the North, the northern firm produces with a constant marginal cost, c_{1N}. If the northern firm relocates its plant to the South, it incurs a fixed cost, f_1, and produces with a constant marginal cost, c_{1S}. We assume that its marginal cost in the South is lower than that in the North, $c_{1S} < c_{1N}$. The southern firm produces with a constant marginal cost, c_{2S}, in the South.

We focus on a unilateral carbon tax imposed by the North. We consider three different regimes of a carbon tax in the North: (1) a carbon tax, (2) a carbon tax with a carbon tariff, and (3) a carbon tax with a carbon tariff and an export rebate of a carbon tax. The timing of decision-making is as follows: First, the government of the North makes a commitment to one of the carbon tax regimes. Second, it chooses an optimal carbon tax that maximizes the welfare of the North. Third, the northern firm chooses to produce in the North or relocate its plant to the South. Fourth, firms compete in each country's market à la Cournot.

Let τ_i denote a carbon tax per unit of carbon emissions in country K $(K = N, S)$. Suppose that the North's carbon tax is higher than that of the South, $\tau_N > \tau_S$. Then, the government of the North can impose a carbon tariff on imports from the South. Let t_N denote a carbon tariff per unit of embedded carbon emissions of goods imported from the South. In addition, the government of the North can rebate a carbon tax to firms exporting goods to the South. Let r_N denote a carbon tax rebate per unit of embedded emissions of goods exported to the South.

[8] Our framework is based on the reciprocal dumping model developed by Brander and Krugman (1983).

[9] To simplify the analysis, we assume that the firms do not incur transportation costs to ship their products across borders, but such costs are prohibitively high for any third-party arbitragers.

The profit of the northern firm depends on its plant location and the carbon tax regime of the North. If the northern firm produces in the North, its profit will be

$$\pi_1 = (p_N - c_{1N} - e_1\tau_N)q_{1N} + [p_S - c_{1N} - e_1(\tau_N - r_N)]q_{1S}.$$

If the northern firm relocates its plant to the South, its profit will be

$$\pi_1 = [p_N - c_{1S} - e_1(t_N + \tau_S)]q_{1N} + (p_S - c_{1S} - e_1\tau_S)q_{1S} - f_1.$$

When the North implements neither a carbon tariff nor an export rebate, $t_N = r_N = 0$. In this case, for the northern firm, an increase in the carbon tax of the North would raise carbon-emissions costs of domestic production relative to those under plant relocation to the South. This could induce the northern firm to move its plant to the South and result in carbon leakage. The carbon tariff of the North t_N could reduce the northern firm's incentive to relocate its plant by increasing the embedded-carbon emissions cost of imported goods from the South. The export rebate of the North r_N could increase the northern firm's incentive to produce in the North by reducing the carbon-emissions cost of goods exported to the South. Then, the profit of the southern firm will be

$$\pi_2 = (p_S - c_{2S} - e_2\tau_S)q_{2S} + [p_N - c_{2S} - e_2(t_N + \tau_S)]q_{2N}.$$

When the carbon tariff and export rebate exactly offset the difference in carbon taxes between the North and the South, i.e., $t_N = r_N = \tau_N - \tau_S$, firms will face the same carbon tax on their sales to each country's market. For their sales to the northern market, the carbon tax imposed on either firm becomes τ_N regardless of their production location. Similarly, for their sales to the southern market, either firm incurs the same carbon tax τ_S regardless of their production location. In the following analysis, we will focus on the case in which the carbon tariff and export rebate achieve a level playing field, namely, $t_N = \tau_N - \tau_S$ if the carbon tariff is implemented and $r_N = \tau_N - \tau_S$ if the export rebate is implemented. For simplification of the analysis, we also assume that the carbon tax of the South is fixed at zero, $\tau_S = 0$.

We can derive the equilibrium output of each firm by using the first order conditions of profit maximization. If the northern firm produces in the North, its output sold for the northern market and the southern market can be derived, respectively, as

$$q_{1N}(c_{1N}, \tau_N, t_N) = \frac{a - 2c_{1N} + c_{2S} + e_2 t_N - 2e_1\tau_N}{3b}, \tag{1}$$

$$q_{1S}(c_{1N}, \tau_N, r_N) = \frac{a - 2c_{1N} + c_{2S} - 2e_1(\tau_N - r_N)}{3b}. \tag{2}$$

The output of the southern firm for each country's market can be derived as

$$q_{2N}(c_{1N}, \tau_N, t_N) = \frac{a - 2c_{2S} + c_{1N} + e_1\tau_N - 2e_2 t_N}{3b}, \tag{3}$$

$$q_{2S}(c_{1N}, \tau_N, r_N) = \frac{a - 2c_{2S} + c_{1N} + e_1(\tau_N - r_N)}{3b}. \tag{4}$$

If the northern firm relocates its plant to the South, its output for the northern market and the southern market can be obtained, respectively, as

$$q_{1N}(c_{1S}, t_N) = \frac{a - 2c_{1S} + c_{2S} + (e_2 - 2e_1)t_N}{3b}, \tag{5}$$

$$q_{1S}(c_{1S}) = \frac{a - 2c_{1S} + c_{2S}}{3b}. \tag{6}$$

The output of the southern firm for each country's market can be obtained as

$$q_{2N}(c_{1S}, t_N) = \frac{a - 2c_{2S} + c_{1S} + (e_1 - 2e_2)t_N}{3b}, \tag{7}$$

$$q_{2S}(c_{1S}) = \frac{a - 2c_{2S} + c_{1S}}{3b}. \tag{8}$$

If the North adopts the carbon tax regime without the carbon tariff and export rebate, the North will choose τ_N subject to the constraints $t_N = r_N = 0$. In this regime, the North's carbon tax affects each firm's output as long as the northern firm produces in the North. If the North adopts the carbon tax regime with the carbon tariff, it will choose τ_N subject to the constraints $t_N = \tau_N$ and $r_N = 0$. In this regime, the North's carbon tax affects each firm's output sold in the northern market regardless of northern firm's production location but also affects their output sold in the southern market only under the northern firm's production in the North. If the North adopts the carbon tax regime with the carbon tariff and the export rebate, it will choose τ_N subject to the constraints $t_N = r_N = \tau_N$. In this regime, regardless of the northern firm's production location, the North's carbon tax affects each firm's output sold in the northern market but does not affect their output sold in the southern market.

4 Effects of Carbon Tariffs on Firm's Plant Location

Let us consider how the North's carbon tax affects the northern firm's choice on domestic production or relocation to the South in each carbon tax regime. If the northern firm produces in the North, its profit can be derived as

$$\pi_1(c_{1N}, \tau_N, t_N, r_N) = b[q_{1N}(c_{1N}, \tau_N, t_N)]^2 + b[q_{1S}(c_{1N}, \tau_N, r_N)]^2. \tag{9}$$

If the northern firm chooses to relocate to the South, its profit can be obtained as

$$\pi_1(c_{1S}, t_N) = b[q_{1N}(c_{1S}, t_N)]^2 + b[q_{1S}(c_{1S})]^2 - f_1. \tag{10}$$

The northern firm's variable profit increases with its output sold in each country's market. The northern firm would shift its production plant to the South if $\pi_1(c_{1S}, t_N) > \pi_1(c_{1N}, \tau_N, t_N, r_N)$. If the North adopts the carbon tax regime without the carbon tariff and export rebate, the northern firm's gain from relocation to the South is

$$\pi_1(c_{1S}, 0) - \pi_1(c_{1N}, \tau_N, 0, 0).$$

An increase in the North's carbon tax reduces the northern firm's profit under domestic production and induces plant relocation to the South.

If the North implements the carbon tax regime with the carbon tariff, the northern firm's gain from production relocation to the South is

$$\pi_1(c_{1S}, t_N) - \pi_1(c_{1N}, \tau_N, t_N, 0).$$

An increase in the North's carbon tax τ_N negatively affects the northern firm's profit under its domestic production. At the same time, an accompanied increase in its carbon tariff t_N positively affects the northern firm's profit from its sales to the domestic market. This is because a carbon tariff provides a competitive advantage to the northern firm relative to the southern firm in the northern market. We can show that the total effects of the North's carbon tax and carbon tariff on the northern firm's profit depends on a gap in emissions intensities between the northern and southern firms. If the North raises τ_N and t_N under the constraint that $t_N = \tau_N$, the northern firm's profit obtained from sales to the domestic market would *increase* if and only if $e_1 \in (0, e_2/2)$, which implies that the northern firm's emissions intensity is less than fifty percent of that of the southern firm.[10] This is because firm's profit increases with its output and the positive effect of the carbon tariff on northern firm's output exceeds the negative effect of the carbon tax on its output. A similar result is obtained when the northern firm relocates its production to the South. If the North imposes the carbon tariff on imports from both northern and southern firms, then the carbon tariff increases the import from the northern firm at the expense of the import from the southern firm if and only if $e_1 \in (0, e_2/2)$. Thus, the North's carbon tariff can positively affect the northern firm's profit under its production in the South. We can state the results in the following proposition.[11]

[10] The critical level of the northern firm's emissions intensity is fifty percent of that of the southern firm. The fifty percent comes from symmetry of the number of firms in each country, i.e., there is one firm headquartered in each country.

[11] For the derivations of the results, see Appendix A.

Proposition 1 *Suppose that the North raises its carbon tax and carbon tariff by the same amount. Then, the northern firm's profit obtained from its domestic sales increases regardless of its production location if and only if the northern firm's emissions intensity is less than fifty percent of that of the southern firm,* $e_1 \in (0, e_2/2)$.

In addition, the impact on the northern firm's profit of the North's carbon tax with its carbon tariff is greater under its production in the South than that under its production in the North. The northern firm can expand its output by relocating its plant to the South because its marginal production cost decreases from c_{1N} to c_{1S}. The northern firm's profit gain owing to the carbon tax and the carbon tariff increases with its output scale. Thus, if the northern firm's emissions intensity is less than fifty percent of that of the southern firm, $e_1 \in (0, e_2/2)$, the North's carbon tax with its carbon tariff would provide a larger profit gain under the northern firm's production relocation as compared to that under its domestic production. This result is somewhat surprising because the North's carbon tariff aims to prevent relocation to the South, but implementing the carbon tariff can positively affect the northern firm's incentive to relocate its plant to the South.

Meanwhile, if the northern firm's emissions intensity exceeds fifty percent of that of southern firm, $e_1 \in (e_2/2, e_2)$, then an increase in the North's carbon tax with its carbon tariff *decreases* the northern firm's profit obtained from its domestic sales regardless of its production location. In addition, its impact on the northern firm's profit is magnified under northern firm's production in the South as compared to that under its production in the North. Thus, if $e_1 \in (e_2/2, e_2)$, the carbon tax with the carbon tariff would have a larger negative effect on the northern firm's profit under its production relocation relative to that under its domestic production. This implies that an increase in the North's carbon tax with its carbon tariff would reduce the northern firm's incentive to relocate its plant to the South if $e_1 \in (e_2/2, e_2)$.

When the North implements the carbon tax with the carbon tariff, it also imposes a carbon tax on the northern firm's emissions from its output exported to the South. An increase in the North's carbon tax reduces the northern firm's export to the South, negatively affecting its profit obtained from the southern market. The negative effect on the northern firm's export would increase its incentive to relocate production to the South. Note that this effect holds regardless of the size of the difference in emissions intensities between the northern and southern firms.

The above results imply that the North's carbon tariff on imports from the South does not necessarily reduce the northern firm's incentive to relocate its plant to the South. If the northern firm's emissions intensity is less than fifty percent of that of the southern firm, then the North's carbon tax with its carbon tariff has two positive effects on the northern firm's relocation to the South. One is an increase in its profit from sales to the northern market and another is an increase in its profit from sales to the southern market. Thus, an increase in the North's carbon tax with its carbon tariff would increase

the incentive for plant relocation to the South. Meanwhile, if the northern firm's emissions intensity exceeds fifty percent of that of the southern firm, then the North's carbon tax and its carbon tariff have both negative and positive effects on the incentive to relocate the plant to the South. The negative effect arises due to a decrease in its profit from sales to the northern market and the positive effect occurs due to an increase in its profit from sales to the southern market. Thus, an increase in the carbon tax with the carbon tariff could reduce the northern firm's gain from plant relocation to the South if the negative effect more than offsets the positive effect. The results are stated as follows.[12]

Proposition 2 *Suppose that the North implements a carbon tax with a carbon tariff. If the northern firm's emissions intensity is less than fifty percent of that of the southern firm,* $e_1 \in (0, e_2/2)$*, then an increase in the North's carbon tax with its carbon tariff positively affects the incentive of the northern firm to relocate its plant to the South. If the northern firm's emissions intensity exceeds fifty percent of that of the southern firm,* $e_1 \in (e_1/2, e_2)$*, an increase in the carbon tax with the carbon tariff may or may not reduce the incentive of the norther firm to relocate its plant to the South.*

When the North implements the carbon tax regime with the carbon tariff and the export rebate, the northern firm's gain from plant relocation to the South is

$$\pi_1(c_{1S}, t_N) - \pi_1(c_{1N}, \tau_N, t_N, r_N).$$

The North's carbon tax affects the northern firm's profit from its domestic sales in the same way as in the carbon tax regime with the carbon tariff. However, unlike the regime with the carbon tariff, implementing the export rebate eliminates the negative effect of the carbon tax on the northern firm's profit from its export to the South. Thus, in the carbon tax regime with the carbon tariff and the export rebate, the North's carbon tax affects the northern firm's incentive to relocate to the South only through its effects on the northern firm's profit from its domestic sales. We can state the results as follows.[13]

Proposition 3 *Suppose that North adopts a carbon tax regime with a carbon tariff and an export rebate. If the northern firm's emissions intensity is less than fifty percent of that of the southern firm,* $e_1 \in (0, e_2/2)$*, then an increase in the North's carbon tax with its carbon tariff and its export rebate would raise the northern firm's incentive to relocate its plant to the South. If the northern firm's emissions intensity exceeds fifty percent of that of the southern firm,* $e_1 \in (e_2/2, e_2)$*, an increase in the North's carbon tax with its carbon tariff and its export rebate would reduce the northern firm's incentive to relocate its production to the South.*

[12] See Appendix A for the derivations of the results.
[13] See Appendix A for the derivations of the results.

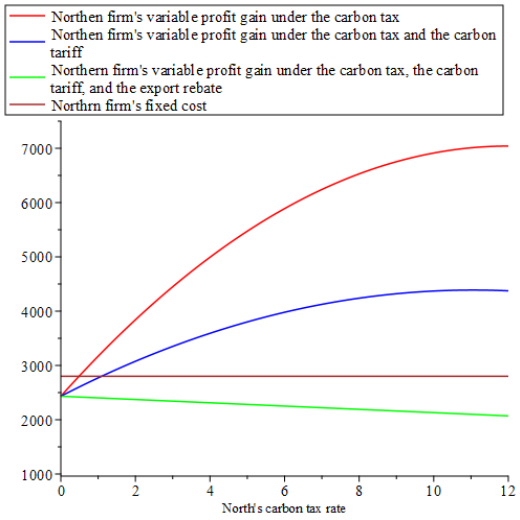

Figure 1: Northern firm's variable profit gain from its plant relocation under the condition that the northern firm's emissions intensity is more than fifty percent of that of the southern firm

Let us compare the impacts of its carbon tax on the northern firm's incentive to relocate its plant to the South under different carbon tax regimes. Figure 1 shows the case with a condition that the northern firm's emissions intensity exceeds fifty percent of that of the southern firm, $e_1 \in (e_2/2, e_2)$.[14] In each carbon tax regime, the northern firm would relocate its plant to the South if an increase in its variable profit is greater than its fixed cost, f_1. Given a level of the carbon tax, a gain from production relocation for the northern firm is largest under the carbon tax regime without the carbon tariff and the export rebate. If the North adopts its carbon tariff, it reduces the northern firm's gain from production relocation to the South. However, it cannot prevent the northern firm's relocation. If the North adopts its export rebate with its carbon tariff, the northern firm stays in the North. Thus, in this regime, the North can increase its carbon tax without inducing the northern firm's relocation to the South.

Figure 2 shows the case with a condition that the northern firm's emissions intensity is less than fifty percent of that of the southern firm, $e_1 \in (0, e_2/2)$. The carbon tariff reduces a variable-profit gain for the northern firm from production relocation but an increase in the North's carbon tax with its carbon tariff would induce the northern firm to shift its plant to the South. Meanwhile, unlike the previous case, if the North adopts its carbon tariff and export rebate, an increase in the North's carbon tax would raise a variable-profit gain for the northern firm from plant relocation to the South. This implies that a unilateral increase in the North's carbon tax results in the northern firm's plant relocation to the South even if it implements its carbon tariff and its export rebate.

[14] See Appendix D for the details of the numerical example.

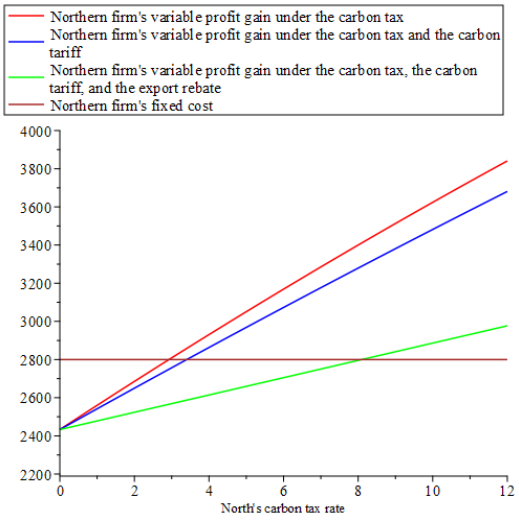

Figure 2: Northern firm's variable profit gain from its plant relocation under the condition that the northern firm's emissions intensity is less than fifty percent of that of the southern firm

5 Impacts of Carbon Tariffs on Emissions

We have examined the effects of the North's carbon tax on the northern firm's choice for production location. In this section, let us turn to how the North's carbon tax affects global emissions under a possibility of plant relocation to the South. Let E_K denote a country K's carbon emissions and E_G denote global emissions, i.e., $E_G = E_N + E_S$. If the northern firm produces in the North, the emissions of each country can be derived as

$$E_N(c_{1N}, \tau_N, t_N, r_N) = e_1 \left[q_{1N}(c_{1N}, \tau_N, t_N) + q_{1S}(c_{1N}, \tau_N, r_N)\right],$$
$$E_S(c_{1N}, \tau_N, t_N, r_N) = e_2 \left[q_{2N}(c_{1N}, \tau_N, t_N) + q_{2S}(c_{1N}, \tau_N, r_N)\right].$$

If the northern firm relocates its plant to the South, the emissions of each country can be obtained as

$$E_N(c_{1S}, t_N) = 0,$$
$$E_S(c_{1S}, t_N) = e_1 \left[q_{1N}(c_{1S}, t_N) + q_{1S}(c_{1S})\right] + e_2 \left[q_{2N}(c_{1S}, t_N) + q_{2S}(c_{1S})\right].$$

If the North does not adopt its carbon tariff and export rebate, global emissions under the northern firm's domestic production can be derived as

$$E_G(c_{1N}, \tau_N, 0, 0) = E_N(c_{1N}, \tau_N, 0, 0) + E_S(c_{1N}, \tau_N, 0, 0).$$

An increase in the North's carbon tax reduces its emissions but increases those of the South. The effect on global emissions depend on the gap in emissions intensities be-

tween the firms. If the northern firm's emissions intensity exceeds fifty percent of that of the southern firm, $e_1 \in (e_2/2, e_2)$, global emissions decrease because a reduction in the emissions of the North exceeds an increase in those of the South. However, if the northern firm's emissions intensity is less than fifty percent of that of the southern firm, $e_1 \in (0, e_2/2)$, global emissions increase because the negative impact on the North's emissions falls short of the positive impact on those of the South. In the latter case, the North's carbon tax results in an increase in global emissions owing to emissions leakage through international trade. If the northern firm relocates its plant to the South, global emissions can be derived as

$$E_G(c_{1S}, 0) = E_S(c_{1S}, 0).$$

The impact of the northern firm's relocation on global emissions depends on the gap in emissions intensities between the firms. If the northern firm relocates to the South, its output produced with its low-carbon technology expands, but southern firm's output produced with its high-carbon technology decreases. If the northern firm's emissions intensity exceeds fifty percent of that of the southern firm, $e_1 \in (e_2/2, e_2)$, global emissions expand because an increase in northern firm's emissions exceeds a decrease in southern firm's emissions. However, if the northern firm's emissions intensity is less than fifty percent of that of the southern firm, $e_1 \in (0, e_2/2)$, global emissions shrink because an expansion of northern firm's emissions falls short of a reduction in those of the southern firm. The results are stated as follows.[15]

Proposition 4 *Suppose the North adopts a carbon tax regime without a carbon tariff and an export rebate. If the northern firm's emissions intensity exceeds fifty percent of that of the southern firm, $e_1 \in (e_2/2, e_2)$, then an increase in the carbon tax decreases global emissions under the northern firm's domestic production. In addition, the northern firm's relocation to the South expands global emissions. If the northern firm's emissions intensity is less than fifty percent of that of the southern firm's, $e_1 \in (0, e_2/2)$, then an increase in the carbon tax expands global emissions under the northern firm's domestic production. Moreover, the northern firm's relocation to the South reduces global emissions.*

Next, suppose that the North adopts the carbon tax regime with the carbon tariff. Global emissions under northern firm's domestic production is

$$E_G(c_{1N}, \tau_N, t_N, 0) = E_N(c_{1N}, \tau_N, t_N, 0) + E_S(c_{1N}, \tau_N, t_N, 0).$$

Under this carbon tax regime, both firms would incur the same carbon tax τ_N (or carbon tariff $t_N = \tau_N$) on emissions released from producing goods sold in the northern market. Then, regardless of the gap in emissions intensities between the firms, an increase in the North's carbon tax and its carbon tariff reduces emissions of either firm's output sold

[15] See Appendix B for the derivations of the results.

in the northern market. Meanwhile, in the southern market, the North's carbon tax is imposed only on the northern firm's emissions of its exported good. This implies that an increase in the North's carbon tax reduces emissions of the northern firm but increases those of the southern firm. As to their output sold in the southern market, the sum of northern and southern firms' emissions increases if the northern firm's emissions intensity is less than fifty percent of that of the southern firm's, $e_1 \in (0, e_2/2)$. Meanwhile, it decreases if the northern firm's emissions intensity exceeds fifty percent of that of the southern firm, $e_1 \in (e_2/2, e_2)$. In sum, under the carbon tax regime with the carbon tariff, an increase in the North's carbon tax reduces firms' emissions in producing their output sold in the northern market but it may increase or decrease the sum of their emissions from producing their output sold in the southern market, depending on the gap in emissions intensities. We can show that, regardless of the gap in emissions intensities between the firms, global emissions decrease under our assumption that consumers of the countries have identical demand functions.

In the North's carbon tax regime with its carbon tariff, if the northern firm shifts its production to the South, global emissions can be derived as

$$E_G(c_{1S}, t_N) = E_S(c_{1S}, t_N).$$

The impact of the northern firm's relocation on global emissions depends on the gap in emissions intensities. Global emissions increase if the northern firm's emissions intensity exceeds fifty percent of that of the southern firm, $e_1 \in (e_2/2, e_2)$. Meanwhile, they decrease if the northern firm's emissions intensity is less than fifty percent of that of the southern firm's, $e_1 \in (0, e_2/2)$. The reason is the same as that in the carbon tax regime without the carbon tariff and the export rebate.

Imposing a carbon tariff on imports from the South, the North can affect the South's emissions even in the case of the northern firm's relocation to the South. An increase in the North's carbon tariff reduces imports from both firms if $e_1 \in (e_2/2, e_2)$. Thus, global emissions decrease. If $e_1 \in (0, e_2/2)$, an increase in the North's carbon tariff increases imports from the northern firm at the expense of those from the southern firm. Again, the northern firm's output produced with its low-carbon technology expands and the southern firm's output produced with its high-carbon technology shrinks. Thus, global emissions decrease. In sum, regardless of the gap in emissions intensities, an increase in the North's carbon tariff reduces global emissions under the northern firm's production in the South. We can summarize the results as follows.[16]

Proposition 5 *Suppose the North adopts a carbon tax regime with its carbon tariff. If the northern firm produces in the North, an increase in its carbon tax with its carbon tariff reduces global emissions. The northern firm's relocation to the South expands global*

[16] See Appendix B for the derivations of these results.

emissions if its emissions intensity exceeds fifty percent of that of the southern firm, $e_1 \in (e_2/2, e_2)$*. However, it reduces global emissions if northern firm's emissions intensity is less than fifty percent of that of the southern firm,* $e_1 \in (0, e_2/2)$*. Under the northern firm's production in the South, an increase in the North's carbon tariff reduces global emissions.*

If the North adopts the carbon tax regime with its carbon tariff and its export rebate, global emissions under the northern firm's domestic production can de derived as

$$E_G(c_{1N}, \tau_N, t_N, r_N) = E_N(c_{1N}, \tau_N, t_N, r_N) + E_S(c_{1N}, \tau_N, t_N).$$

In this regime, the North implements the export rebate; thus, the northern firm does not incur any carbon tax on emissions released from producing its output exported to the southern market. The North's carbon tax and its carbon tariff affect only the emissions of either firm's output sold in the northern market. As in the carbon tax regime with the carbon tariff, an increase in the North's carbon tax and its carbon tariff reduces global emissions. However, the marginal effects of the North's carbon tax on global emissions are different between these two carbon tax regimes. As compared to the carbon tax regime with the carbon tariff, an increase in the carbon tax leads to a smaller reduction in global emissions if $e_1 \in (e_2/2, e_2)$. This is because the export rebate of the carbon tax reduces the marginal effect of the carbon tax on global emissions. However, if $e_1 \in (0, e_2/2)$, the export rebate leads to a larger marginal reduction in global emissions.

If the northern firm relocates its plant to the South, global emissions can be derived as

$$E_G(c_{1S}, t_N) = E_S(c_{1S}, t_N).$$

The impact of the northern firm's relocation on global emissions is the same as that in the carbon tax regime with the carbon tariff. The results are summarized as follows.[17]

Proposition 6 *Suppose the North adopts a carbon tax with its carbon tariff and its export rebate. If the northern firm produces in the North, an increase in the carbon tax reduces global emissions. If the northern firm's emissions intensity is less than fifty percent of that of the southern firm,* $e_1 \in (0, e_2/2)$*, then the northern firm's relocation decreases global emissions. An increase in the North's carbon tariff reduces global emissions under the northern firm's production in the South.*

We can compare the effects of the North's carbon tax on global emissions under different carbon tax regimes. Figure 3 shows the case in which the northern firm's emissions intensity exceeds fifty percent of that of the southern firm.[18] In the carbon tax regime

[17] See Appendix B for the derivations of the results.

[18] We use the same numerical example as in the previous section.

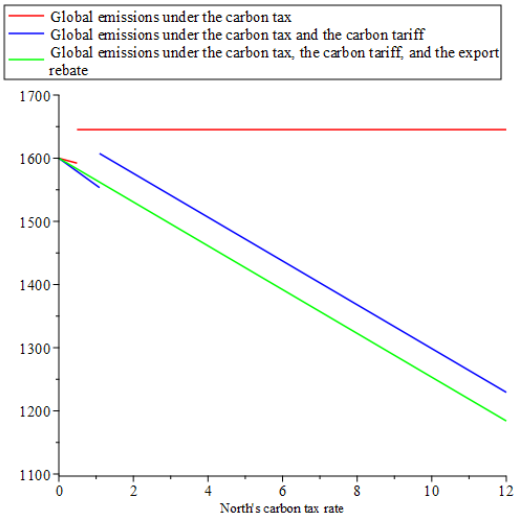

Figure 3: The effects of the North's carbon tax on global emissions under the condition that the northern firm's emissions intensity is more than fifty percent of that of the southern firm

without the carbon tariff and the export rebate, an increase in the North's carbon tax causes emissions leakage through the northern firm's plant relocation to the South, leading to an increase in global emissions. Even if the North implements the carbon tariff, it cannot prevent emissions leakage, which results in an increase in global emissions. However, after relocation to the South, the North's carbon tariff reduces global emissions unlike the case with the carbon tax only. If the North implements the carbon tariff and the export rebate, then it can achieve the lowest level of global emissions by preventing emissions leakage through the northern firm's relocation to the South.

Figure 4 shows the case in which the northern firm's emissions intensity is less than fifty percent of that of the southern firm. In contrast to the previous case, global emissions decrease owing to emissions leakage caused by the northern firm's plant relocation to the South. In addition, under the northern firm's production in the South, the lowest level of global emissions is attained in the carbon tax regime with the carbon tariff or with the carbon tariff and the export rebate.

6 North's Optimal Carbon Tax Regime

We now analyze the North's optimal carbon tax regime. We show that when the North sets its optimal carbon tax rate to maximize its social welfare, the optimal tax regime incorporates both a carbon tariff and an export rebate. We analyze the impact of this regime on the South, revealing that it can yield positive welfare benefits for the South as well.

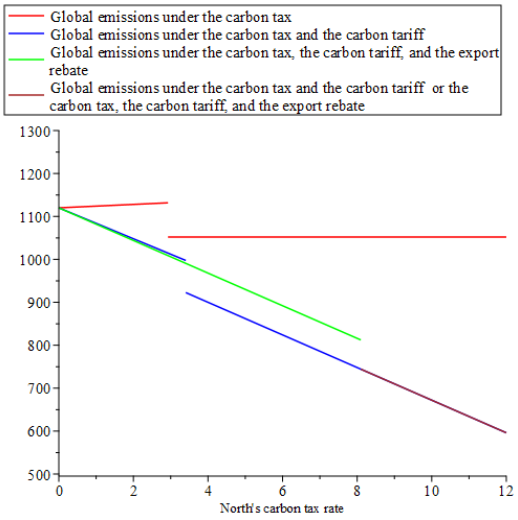

Figure 4: The effects of the North's carbon tax on global emissions under the condition that the northern firm's emissions intensity is less than fifty percent of that of the southern firm

The utility function of each country is quadratic and quasi-linear,

$$u_K = aq_K - \frac{b}{2}q_K^2 + q_{K0} - \delta_K E_G,\ K = N, S,$$

where q_K denotes the country K's consumption of goods produced in the duopoly sector, q_{K0} denotes its consumption of a numeraire good, and δ_K denotes its constant marginal damage from global carbon emissions. We assume that consumers regard damages caused by carbon emissions as external costs. The numeraire good sector is competitive and it is produced with labor. In country $K = N, S$, the production of the nemeraire good requires a_K units of labor. We assume that $a_S > a_N$, i.e., the North has higher productivity than the South and the unit labor requirement of the North equals one, $a_N = 1$. We also assume that each country has a sufficiently large amount of labor, so that both countries produce the nemeraire good in equilibrium. Since the nemeraire good is tradable and its price is normalized to one, the competitive conditions imply that $\omega_N a_N = 1 = \omega_S a_S$, where ω_K denotes the wage rate of country $K = N, S$. These conditions imply that the North has higher wages than the South, $\omega_N > \omega_S$, i.e., the northern wage equals one, $\omega_N = 1$ and the southern wage is smaller than one, $\omega_S = 1/a_S < 1$ because of $a_S > a_N = 1$.[19] Then, the social welfare of the North can be derived as follows:

$$w_N = CS_N + \pi_1 + g_N + L_N - \delta_N E_G,$$

where CS_N denotes its consumer surplus, g_N denotes its government budget surplus, and

[19] We assume that the production of the numeraire good does not release carbon emissions.

L_N denotes its labor endowment.[20] The consumer surplus is

$$CS_N = aq_N - \frac{b}{2}q_N^2 - p_N q_N.$$

In equilibrium, $q_N = q_{1N} + q_{2N}$. Under the northern firm's production in the North, the North's government budget surplus is

$$g_N = \tau_N e_1(q_{1N} + q_{1S}) + t_N e_2 q_{2N} - r_N e_1 q_{1S}.$$

If the northern firm produces in the South, its government budget surplus is

$$g_N = t_N(e_1 q_{1N} + e_2 q_{2N}).$$

The North's social welfare depends on northern firm's production location and the North's carbon tax regime. We can denote the North's welfare as $w_N = w_N(c_{1N}, \tau_N, t_N, r_N)$ under the northern firm's domestic production. Suppose that the North adopts the carbon tax regime without the carbon tariff and the export rebate, i.e. $t_N = r_N = 0$. Then, under the northern firm's domestic production, the effects of the North's carbon tax on its social welfare can be derived as follows:[21]

$$\frac{\partial w_N(c_{1N}, \tau_N, 0, 0)}{\partial \tau_N} = \underbrace{-q_{2N}\frac{\partial p_N}{\partial \tau_N}}_{\text{terms of trade effect in imports}} + \underbrace{(p_N - c_{1N})\frac{\partial q_{1N}}{\partial \tau_N}}_{\text{production efficiency effect in domestic sales}} + \underbrace{q_{1S}\frac{\partial p_S}{\partial \tau_N}}_{\text{terms of trade effect in exports}} + \underbrace{(p_S - c_{1N})\frac{\partial q_{1S}}{\partial \tau_N}}_{\text{production efficiency effect in exports}} - \underbrace{\delta_N \frac{\partial E_G}{\partial \tau_N}}_{\text{external cost effect}}.$$

On the right hand side (RHS), the first term is the terms of trade effect in imports, the second term is the production efficiency effect of output sold in the northern market, the third term is the terms of trade effect in exports, the fourth term is the production efficiency effect of output exported to the southern market, and the last term is the external cost effect of global emissions. An increase in the North's carbon tax raises the domestic price and reduces the northern firm's output sold in the domestic market. Thus, the first and second terms on the RHS negatively affect the North's social welfare. An increase in the carbon tax also raises the price in the southern market because it reduces the northern firm's output exported to the South. Thus, the third term is positive, but the fourth term is negative. We can show that the negative effect of a worsening in the production efficiency exceeds the positive impact of an improvement in the terms of trade.

[20] See Appendix C for the derivation of the social welfare of the North.

[21] We derive the effects of the carbon tax on the North's welfare by applying the method used for deriving a welfare change owing to trade policies (Helpman and Krugman, 1989 and Feenstra, 2016). See Appendix C for the derivation.

The external cost effect depends on the gap in emissions intensities between the northern and southern firms. If $e_1 \in (e_2/2, e_2)$, the North's carbon tax reduces global emissions and the external cost effect has a positive impact on the social welfare. Meanwhile, if $e_1 \in (0, e_2/2)$, the external cost effect negatively affects the North's social welfare owing to an increase in global emissions.

In sum, under the northern firm's domestic production, the North may not have an incentive to impose a positive carbon tax on domestic emissions even if its carbon tax reduces global emissions. This result holds because deteriorations in its production efficiency outweigh a gain from a decreasing external cost of global emissions. This outcome is obtained when the northern firm's emissions intensity exceeds fifty percent of that of the southern firm and the North's marginal damage is not large enough. Meanwhile, if the northern firm's emissions intensity is less than fifty percent of the southern firm's, a small carbon tax of the North worsens its production efficiency and increases its external cost of global emissions. Thus, under this situation, the North would not adopt a positive carbon tax.

If the northern firm relocates its plant to the South, the welfare of the North can be denoted as $w_N = w_N(c_{1S}, t_N)$. Under the North's carbon tax regime without the carbon tariff and the export rebate, the impact of the northern firm's plant relocation on the North's welfare becomes

$$w_N(c_{1S}, 0) - w_N(c_{1N}, \tau_{N1}, 0, 0),$$

where τ_{N1} denotes the critical level of the carbon tax that causes the northern firm's plant relocation to the South, i.e., $\pi_1(c_{1S}, 0) = \pi_1(c_{1N}, \tau_{N1}, 0, 0)$. Relocation by the northern firm has a positive effect on its consumer surplus owing to a reduction in the price and a negative effect on its government budget surplus owing to a reduction in its carbon tax revenue. The effect on the external cost depends on the gap in emissions intensities between the firms. If $e_1 \in (e_2/2, e_2)$, the external cost increases due to an expansion in global emissions. However, if $e_1 \in (0, e_2/2)$, the external cost decreases owing to a reduction in global emissions.

In sum, the northern firm's relocation has a positive effect on the North's consumer surplus, a negative effect on its tax revenue, and a positive or negative impact on its external cost of emissions. Thus, the North's marginal damage to global emissions is key to the welfare impact of relocation by the northern firm. If the marginal damage is sufficiently large, the change in the external cost could be a crucial factor that determines the welfare impact of the northern firm's relocation. Namely, if $e_1 \in (e_2/2, e_2)$, the northern firm's relocation to the South can worsen the North's welfare due to an increase in global emissions. However, if $e_1 \in (0, e_2/2)$, the northern firm's relocation can improve the welfare of the North due to a reduction in global emissions. The results could be

stated as follows.[22]

Proposition 7 *Suppose that the North adopts a carbon tax regime without a carbon tariff and an export rebate. If the northern firm's emissions intensity exceeds fifty percent of that of the southern firm,* $e_1 \in (e_2/2, e_2)$*, then, under the northern firm's domestic production, the North may not impose a positive carbon tax on domestic emissions. This result arises if the worsening in its production efficiency outweighs the gain from a reduction in its external cost of global emissions. If the northern firm's emissions intensity is less than fifty percent of that of the southern firm,* $e_1 \in (0, e_2/2)$*, then a positive carbon tax definitely reduces the welfare of the North. The welfare impact of the northern firm's relocation depends on the marginal damage of the North and the gap in emissions intensities between the firms. If the North's marginal damage is sufficiently large, then the northern firm's relocation to the South negatively affects the North's welfare under the condition that* $e_1 \in (e_2/2, e_2)$*. However, it positively affects the North's welfare under the condition that* $e_1 \in (0, e_2/2)$*.*

Next, suppose that the North implements the carbon tax regime with the carbon tariff. Under the northern firm's domestic production, the North's welfare can be denoted as $w_N = w_N(c_{1N}, \tau_N, t_N, 0)$. The effects of the North's carbon tax with its carbon tariff on the North's welfare can be derived as

$$\begin{aligned}
&\frac{\partial w_N(c_{1N}, \tau_N, t_N, 0)}{\partial \tau_N} + \frac{\partial w_N(c_{1N}, \tau_N, t_N, 0)}{\partial t_N} \\
&= \underbrace{-q_{2N}\left(\frac{\partial p_N}{\partial \tau_N} + \frac{\partial p_{2N}}{\partial t_N}\right)}_{\text{terms of trade effect in imports}} + \underbrace{t_N e_2\left(\frac{\partial q_{2N}}{\partial \tau_N} + \frac{\partial q_{2N}}{\partial t_N}\right)}_{\text{consumption distortionary effect}} + \underbrace{(p_N - c_{1N})\left(\frac{\partial q_{1N}}{\partial \tau_N} + \frac{\partial q_{1N}}{\partial t_N}\right)}_{\text{production efficiency effect in domestic sales}} \\
&+ \underbrace{q_{1S}\frac{\partial p_S}{\partial \tau_N}}_{\text{terms of trade effect in exports}} + \underbrace{(p_S - c_{1N})\frac{\partial q_{1S}}{\partial \tau_N}}_{\text{production efficiency effect in exports}} \underbrace{-\delta_N\left(\frac{\partial E_G}{\partial \tau_N} + \frac{\partial E_G}{\partial t_N}\right)}_{\text{external cost effect}},
\end{aligned}$$

where p_{2N} denotes the producer price of the southern firm in the northern market, $p_{2N} = p_N - e_2\tau_N$. We evaluate the welfare effects of the carbon tax under the constraint, $\tau_N = t_N$. On the RHS, the first term is the terms of trade effect in imports. Although the carbon tax worsens the terms of trade for the North, the carbon tariff improves it. The positive effect of the carbon tariff outweighs the negative effect of the carbon tax because the northern firm's emissions intensity is lower than that of the southern firm. Thus, the terms of trade effect in imports positively affects the welfare of the North. The second term is the consumption distortionary effect due to the carbon tariff. This term negatively affects the North's welfare because the carbon tax with the carbon tariff reduces the volume of

[22] See Appendix C for the derivations of the results.

imports from the South.[23] The third term is the production efficiency effect of output sold in the northern market. The carbon tariff increases the northern firm's domestic sales while the carbon tax decreases them. If the northern firm's emissions intensity is less than fifty percent of that of the southern firm, $e_1 \in (0, e_2/2)$, then the positive effect of the carbon tariff exceeds the negative effect of the carbon tax. This implies that the production efficiency effect improves the welfare of the North. Meanwhile, if the northern firm's emissions intensity exceeds fifty percent of that of the southern firm, $e_1 \in (e_2/2, e_2)$, then the positive effect of the carbon tariff falls short of the negative effect of the carbon tax. Thus, the production efficiency effect negatively affects the welfare of the North. The fourth term is the terms of trade effect in exports and the fifth term is the production efficiency effect of output exported to the South. These two terms are the same as those in the carbon tax regime without the carbon tariff and the export rebate. As we have shown, their sum has a negative effect on the North's welfare. The last term is the external cost effect. Unlike the regime with the carbon tax only, the external cost effect improves the North's welfare because the carbon tax with the carbon tariff reduces global emissions.

In sum, the carbon tariff alleviates the North's welfare loss from the carbon tax. It improves the terms of trade in imports and the production efficiency of output for domestic sales. In addition, the external cost effect positively affects the North's welfare regardless of the gap in emissions intensities between the firms. Meanwhile, as in the carbon tax regime without the carbon tariff, the carbon tax on exported output negatively affects the North's welfare due to the deteriorations in its terms of trade and production efficiency. For a small carbon tariff, the consumption distortionary effect is negligible. These results imply that, under the northern firm's domestic production, a carbon tariff would raise the North's incentive to adopt a positive carbon tax because it improves the terms of trade in imports, alleviates the negative effects of the carbon tax on production efficiency, and reduces the external costs of global emissions.

Suppose that the northern firm relocates its plant to the South. Then, the welfare of the North would be denoted as $w_N = w_N(c_{1S}, t_N)$ under the North's carbon tax regime with the carbon tariff. The welfare impact of the northern firm's relocation can be derived as

$$w_N(c_{1S}, t_{N2}, 0) - w_N(c_{1N}, \tau_{N2}, t_{N2}, 0),$$

where τ_{N2} denotes the critical level of the carbon tax that causes the northern firm to shift its plant to the South, i.e., $\pi_1(c_{1S}, t_{N2}, 0) = \pi_1(c_{1N}, \tau_{N2}, t_{N2}, 0)$. Note that $\tau_{N2} = t_{N2}$. The impact of the northern firm's relocation on consumers surplus is positive due to a reduction in the price. The effect on government budget surplus is not clear because

[23] Note that the carbon tax imposed on the northern firm increases the volume of imports from the southern firm, but the carbon tariff on imports from the South reduces the volume of imports from the southern firm. The total effect on the volume of imports can be shown to be negative. See Appendix C for the details.

the North would lose its revenue from the carbon tax imposed on the northern firm's domestic emissions but it would obtain its new revenue from the carbon tariff imposed on the embedded emissions of northern firm's output produced in the South. The effect on the external cost of global emissions depends on the gap in the emissions intensities between the firms. As in the case of the carbon tax only, the North's marginal damage is key to the welfare impact of the northern firm's relocation. If the marginal damage is sufficiently large, the effect on the North's welfare is determined by the change in the external cost of global emissions. Namely, the northern firm's plant relocation to the South would negatively affect the North's welfare if $e_1 \in (e_2/2, e_2)$. However, it would positively affect its welfare if $e_1 \in (0, e_2/2)$.

Under the northern firm's production in the South, the effects of the North's carbon tariff on its welfare can be derived as

$$\frac{\partial w_N(c_{1S}, t_N)}{\partial t_N} = \underbrace{-q_{2N}\frac{\partial p_{2N}}{\partial t_N}}_{\text{terms of trade effect in imports}} + \underbrace{t_N e_2 \frac{\partial q_{2N}}{\partial t_N}}_{\text{consumption distortionary effect}} + \underbrace{(p_N - c_{1S})\frac{\partial q_{1N}}{\partial t_N}}_{\text{production efficiency effect}} - \underbrace{\delta_N \frac{\partial E_G}{\partial t_N}}_{\text{external cost effect}}.$$

On the RHS, the first term is the terms of trade effect in imports from the southern firm. The terms of trade effect positively affects the welfare because the carbon tariff reduces the southern firm's export price. As compared to the case of the northern firm's domestic production, the terms of trade effect is smaller. This is because the volume of import from the southern firm is smaller under the northern firm's production in the South. The second term is the consumption distortionary effect that negatively affects the northern welfare. Its magnitude is the same as that under the northern firm's domestic production. The third term is the production efficiency effect of the northern firm's output exported to the northern market. If $e_1 \in (0, e_2/2)$, the production efficiency effect is positive because the carbon tariff expands the import volume from the northern firm. Meanwhile, if $e_1 \in (e_2/2, e_2)$, it is negative because the import volume from the northern firm decreases due to the carbon tariff. In either case, the production efficiency effect has a greater effect on the North's welfare as compared to the case of the northern firm's domestic production. This is because the northern firm has a lower marginal production cost under its production in the South. The last term is the external cost effect of global emissions. The external cost effect positively affects the North's welfare due to a reduction in global emissions. Moreover, unlike the case of the northern firm's production in the North, the terms of trade effect of exports and the production efficiency effect of export sales disappear, which positively affects a North's welfare gain from the carbon tax with the carbon tariff because the sum of these two effects is negative. We can show that

increasing the carbon tariff by a small amount improves the welfare of the North under the northern firm's production in the South. The results are summarized as follows.[24]

Proposition 8 *Suppose that the North adopts a carbon tax regime with a carbon tariff. The carbon tariff alleviates the North's welfare loss from the carbon tax because it improves the terms of trade in imports from the South and alleviates the worsening in the production efficiency of the northern firm. It also reduces the external cost of global emissions regardless of the gap in emissions intensities between the firms. The North can improve its welfare with a small amount of the carbon tax with the carbon tariff regardless of the northern firm's production location. If the marginal damage of the North is sufficiently large, the northern firm's production relocation negativity affects the North's welfare under the condition that* $e_1 \in (e_2/2, e_2)$*, but positively affects its welfare under the condition that* $e_1 \in (0, e_2/2)$*.*

Suppose that the North adopts the carbon tax regime with the carbon tariff and the export rebate. Under the northern firm's domestic production, the welfare of the North can be denoted as $w_N = w_N(c_{1N}, \tau_N, t_N, r_N)$. Then, the effects of the carbon tax with the carbon tariff and the export rebate on the North's welfare can be derived as

$$\begin{aligned}
&\frac{\partial w_N(c_{1N},\tau_N,t_N,r_N)}{\partial \tau_N} + \frac{\partial w_N(c_{1N},\tau_N,t_N,r_N)}{\partial t_N} + \frac{\partial w_N(c_{1N},\tau_N,t_N,r_N)}{\partial r_N} \\
&= \underbrace{-q_{2N}\left(\frac{\partial p_N}{\partial \tau_N} + \frac{\partial p_{2N}}{\partial t_N}\right)}_{\text{terms of trade effect in imports}} + \underbrace{t_N e_2\left(\frac{\partial q_{2N}}{\partial \tau_N} + \frac{\partial q_{2N}}{\partial t_N}\right)}_{\text{consumption distortionary effect}} + \underbrace{(p_N - c_{1N})\left(\frac{\partial q_{1N}}{\partial \tau_N} + \frac{\partial q_{1N}}{\partial t_N}\right)}_{\text{production efficiency effect in domestic sales}} \\
&\underbrace{-\delta_N\left(\frac{\partial E_G}{\partial \tau_N} + \frac{\partial E_G}{\partial t_N} + \frac{\partial E_G}{\partial r_N}\right)}_{\text{external cost effect}}.
\end{aligned}$$

We evaluate the welfare effects of the North's carbon tax under the constraint, $\tau_N = t_N = r_N$. On the RHS, the first three terms are the same as those in the case of the carbon tax regime with the carbon tariff. Unlike the carbon tax regime with the carbon tariff, the terms of trade effect in exports and the production efficiency effect of output for export sales disappear. This is because the export rebate of the carbon tax exactly offsets the carbon tax imposed on emissions of output exported to the South. Without these two terms, increasing the carbon tax by a small amount would lead to a greater improvement in the North's welfare. This is because the sum of these two terms has a negative effect on the North's welfare. The external cost effect that is the last term on the RHS has a positive effect on the welfare of the North because global emissions decline due to an increase in the carbon tax with the carbon tariff and the export rebate. Moreover, the external cost effect can have a larger positive effect on the North's welfare as compared

[24] See Appendix C for the derivations of the results.

to the carbon tax regime with the carbon tariff. This occurs under the condition that $e_1 \in (0, e_2/2)$ because the export rebate of the carbon tax prevents emissions leakage that could result in an increase in global emissions. Meanwhile, if $e_1 \in (e_2/2, e_2)$, the external cost effect leads to a smaller improvement in the North's welfare under the carbon tax regime with the carbon tariff and the export rebate as compared to the carbon tax regime with the carbon tariff. This is because the export rebate weakens the negative effect of the carbon tax on global emissions.

In sum, under the northern firm's domestic production, the North can improve its welfare by increasing its carbon tax with its carbon tariff and its export rebate by a small amount. Its positive effect on the North's welfare can be greater as compared to the carbon tax regime with the carbon tariff. This is because the export rebate eliminates the negative effect of the carbon tax on production efficiency in the northern firm's export sales to the South.

If the northern firm relocates to the South, the welfare of the North can be denoted as $w_N = w_N(c_{1S}, t_N)$. The impact on the North's welfare of the northern firm's relocation can be derived as

$$w_N(c_{1S}, t_{N3}) - w_N(c_{1N}, \tau_{N3}, t_{N3}, r_{N3}),$$

where τ_{N3} denotes a critical level of the carbon tax that causes the northern firm's relocation to the South under the condition that $e_1 \in (0, e_2/2)$, i.e., $\pi_1(c_{1N}, \tau_{N3}, t_{N3}, r_{N3}) = \pi_1(c_{1S}, t_{N3})$. Note that $\tau_{N3} = t_{N3} = r_{N3}$. We can easily confirm that the impact of the northern firm's relocation on the welfare of the North is positive if the marginal damage is greater than the critical level of the carbon tax τ_{N3}. The northern firm's relocation has a positive impact on consumer surplus of the North due to a decrease in the price and a negative effect on the northern government's tax and tariff revenue due to a reduction in emissions covered by the carbon tax and the carbon tariff. In addition, the external cost effect of global emissions is positive because of a reduction in global emissions covered by the carbon tax and the carbon tariff. If the marginal damage δ_N is greater than the critical level of the carbon tax τ_{N3}, the positive effect of a reduction in the external cost exceeds the negative effect of a decrease in the revenue of the carbon tax and the carbon tariff. Thus, the northern firm's relocation to the South has a positive impact on the North's welfare. Note that, under the northern firm's production in the South, the effects of the carbon tariff on the North's welfare are the same as those in the carbon tax regime with the carbon tariff. The results are stated as follows.[25]

Proposition 9 *Suppose that the North adopts a carbon tax regime with a carbon tariff and an export rebate. Under the northern firm's domestic production, the North can improve its welfare by raising the carbon tax with the carbon tariff and the export rebate by a small amount. Its welfare improvement can be greater as compared to the carbon tax*

[25] See Appendix C for the derivations of the results.

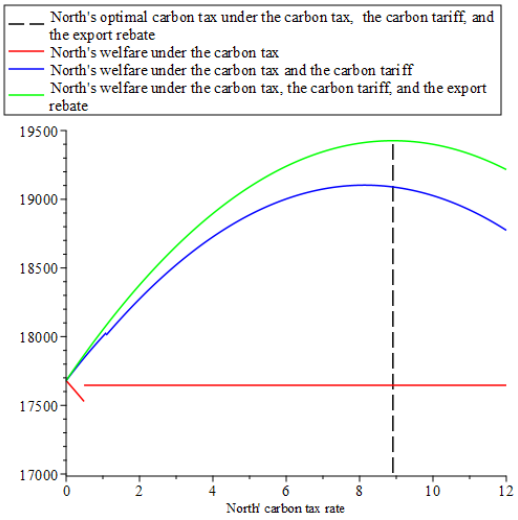

Figure 5: The effects of the North's carbon tax on its welfare under the condition that the northern firm's emissions intensity is more than fifty percent of that of the southern firm

regime with the carbon tariff because the export rebate eliminates the negative effect of the carbon tax on production efficiency in its export to the South. Under the condition that the northern firm's emissions intensity is less than fifty percent of that of the southern firm, $e_1 \in (0, e_2/2)$*, the northern firm's relocation to the South has a positive impact on the North's welfare if its marginal damage is larger than the critical level of the carbon tax that causes the northern firm's relocation to the South. Under the northern firm's production in the South, the effects on the North's welfare of the carbon tariff are the same as those in the carbon tax regime with the carbon tariff.*

We can compare the effects of the carbon tax on the North's welfare under different carbon tax regimes[26]. Figure 5 shows the case in which the northern firm's emissions intensity exceeds fifty percent of that of the southern firm, $e_1 \in (e_2/2, e_2)$. In the carbon tax regime without the carbon tariff and the export rebate, it is optimal for the North not to impose a positive carbon tax because its welfare is maximized under the zero carbon tax. In the carbon tax regime with the carbon tariff, the northern firm's relocation negatively affects the North's welfare. The welfare is maximized when the carbon tax is high enough for the northern firm to relocate its plant to the South. In the carbon tax regime with the carbon tariff and the export rebate, the northern firm's relocation to the South does not occur. Thus, the North can attain the maximum level of its welfare under northern firm's production in the North. Furthermore, in this regime, the North achieves the maximum welfare among the three carbon tax regimes.[27] Recall that the carbon tariff alleviates

[26] We use the same numerical example as in the previous section.

[27] The optimal carbon tax rate is smaller than the prohibitive carbon tariff rate that eliminates the import from the southern firm. See Appendix D for the details.

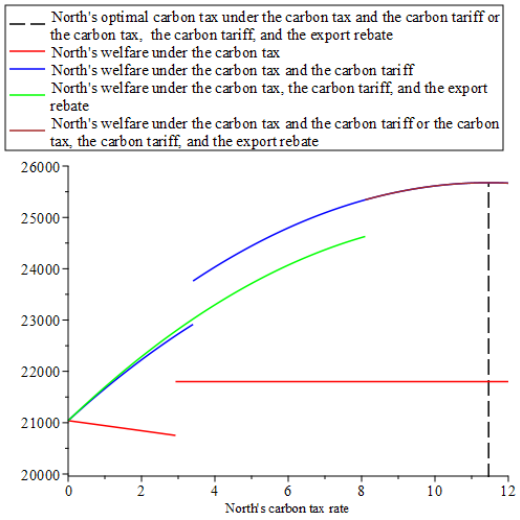

Figure 6: The effects of the North's carbon tax on its welfare under the condition that the northern firm's emissions intensity is less than fifty percent of that of the southern firm

the North's welfare loss from the carbon tax because of an improvement in the terms of trade in imports from the southern firm and an increase in the production efficiency of the northern firm's domestic sales. These positive effects of the carbon tariff on the North's welfare are greater under the northern firm's domestic production as compared to its production relocation to the South. In addition, the export rebate eliminates the negative effect of the North's carbon tax on its production efficiency in its export sales to the South. These results imply that the North can achieve the maximum welfare under the northern firm's domestic production by implementing the export rebate with the carbon tariff.

Figure 6 shows the case with the condition that the northern firm's emissions intensity is less than fifty percent of that of the southern firm, $e_1 \in (0, e_2/2)$. In the regime with the carbon tax only, the North would not rase its carbon tax above zero under the northern firm's domestic production. However, the northern firm's relocation has a positive welfare impact. Thus, it is optimal for the North to choose the carbon tax at the level just inducing the northern firm to relocate its plan to the South. In the carbon tax regime with the carbon tariff, the North can attain the maximum welfare by inducing the northern firm to relocate its plant to the South. If the North adopts its export rebate in addition to its carbon tariff, it can attain the same maximum welfare as in the carbon tax regime with the carbon tariff. Unlike the case with the condition that $e_1 \in (e_2/2, e_2)$, the welfare is maximized under the northern firm's production in the South. This is because the impact of northern firm's relocation on the North's welfare is positive due to a reduction in global emissions. Moreover, the production efficiency effect on northern firm's domestic sales is positive and the magnitude of the production efficiency effect is larger under the northern

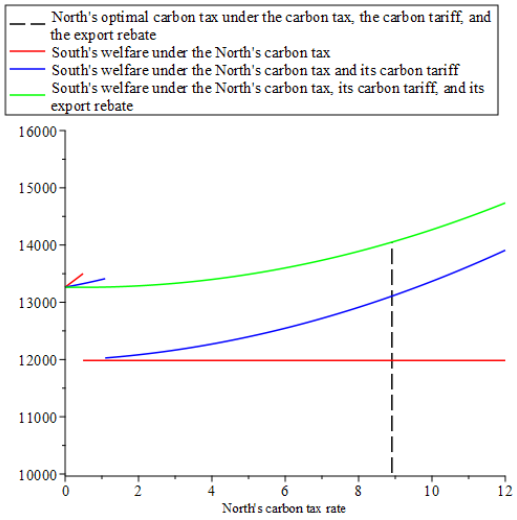

Figure 7: The effects of the North's carbon tax on the welfare of the South under the condition that the northern firm's emissions intensity is more than fifty percent of that of the southern firm

firm's production in the South as compared to that under its production in the North. In addition, among the carbon tax regimes, the North achieves the highest welfare in either the carbon tax regime with the carbon tariff or with the carbon tariff and the export rebate.

Proposition 10 *Suppose that the North sets its optimal carbon tax rate to maximize its social welfare. If the northern firm's emissions intensity exceeds fifty percent of that of the southern firm,* $e_1 \in (e_2/2, e_2)$*, then the North's optimal carbon tax can attain the highest welfare with the carbon tariff and the export rebate by inducing the northern firm to stay in the North. If the northern firm's emissions intensity is less than fifty percent of that of the southern firm,* $e_1 \in (0, e_2/2)$*, then the North's optimal carbon tax can achieve the highest welfare of the North with the carbon tariff or with the carbon tariff and the export rebate by inducing the northern firm to relocate its plant to the South.*

This proposition implies that the North's optimal carbon tax regime incorporates both a carbon tariff and an export rebate.

Let us turn to the impact of the North's optimal carbon tax regime on the South. The welfare of the South can be derived as

$$w_S = CS_S + \pi_2 + \omega_S L_S - \delta_S E_G.$$

The South's welfare depends on the northern firm's production location and the North's carbon tax regime. If the northern firm produces in country K, $(K = N, S)$, the welfare of the South can be denoted as $w_S = w_S(c_{1K}, \tau_N, t_N, r_N)$.

We can show the effects of the North's carbon tax on the South's welfare by using the numerical example. Figure 7 shows the case in which $e_1 \in (e_2/2, e_2)$. Suppose that the northern firm produces in the North. Then, an increase in the North's carbon tax positively affects the welfare of the South through two different channels. One is an increase in the southern firm's profit and the other is a decrease in the external cost of global emissions. Meanwhile, an increase in the North's carbon tax negatively affects the South's welfare through a decrease in the consumer surplus of the South. We can show that the positive effect on the southern firm's profit more than offsets the negative effect on the consumer surplus. Figure 7 shows the case in which a small increase in the North's carbon tax raises the welfare of the South under any carbon tax regimes of the North. The magnitude of an increase in the South's welfare is largest under the North's carbon tax regime without the carbon tariff and the export rebate. This is because the North's carbon tariff reduces the southern firm's profit obtained from its export to the northern market. If the North adopts the export rebate in addition to the carbon tariff, the magnitude of an increase in the South's welfare becomes much smaller due to the negative effect of the North's export rebate on the southern firm's profit obtained in the southern market.

Suppose that the northern firm relocates to the South. One the one hand, there is a positive effect of relocation on the welfare of the South due to a decrease in the price in the southern market. On the other hand, there are negative effects of relocation on the welfare of the South due to an increase in the external cost of global emissions and a decrease in the southern firm's profit. Figure 7 shows the case in which the latter negative effects more than offset the former positive effect. Namely, the northern firm's relocation reduces the welfare of the South. This implies that the North's carbon tariff and export rebate can benefit the South by preventing the northern firm's relocation to the South. Furthermore, the South's welfare increases with the North's carbon tax because the positive effect of a decrease in the external cost of emissions outweighs the negative effect of a decrease in the southern firm's profit obtained from the northern market. Figure 7 shows that when the North sets its optimal carbon tax rate to maximize its welfare, its optimal carbon tax regime can benefit the South as well.

Figure 8 shows the case in which $e_1 \in (0, e_2/2)$. Suppose that the northern firm produces in the North. If the North adopts the carbon tax only, a small increase in the North's carbon tax positively affects the welfare of the South through an increase in the profit of the southern firm. Meanwhile, it negatively affects the welfare of the South due to a decrease in its consumer surplus and an increase in the external cost of global emissions. Thus, whether a small increase in the North's carbon tax increases or decreases the welfare of the South remains ambiguous. Figure 8 shows the case in which a small carbon tax of the North benefits the South under its regime with its carbon tax only. If the North adopts the carbon tariff or both the carbon tariff and the export rebate, then, unlike the previous

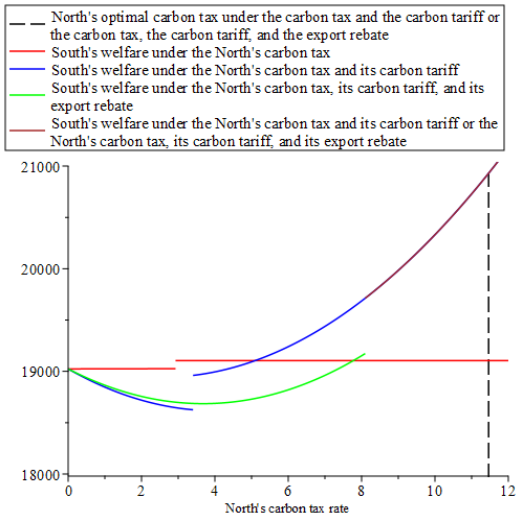

Figure 8: The effects of the North's carbon tax on the welfare of the South under the condition that northern firm's emissions intensity is less than fifty percent of that of the southern firm

case, a small carbon tax of the North negatively affects the welfare of the South. This is because the negative effect of the carbon tariff on the southern firm's profit outweighs the positive effect of a decrease in the external cost of global emissions. Furthermore, if the northern firm relocates its plant to the South, the South's welfare increases under the carbon tax regime with or without its carbon tariff. The northern firm's relocation positively affects the welfare of the South through a decrease in its external cost and an increase in its consumer surplus while it negatively affects the South's welfare through a decrease in the profit of the southern firm. Figure 8 shows the case in which the South benefits from the northern firm's relocation to the South because the sum of the positive effects outweighs the negative impact. Under northern firm's production in the South, an increase in the North's carbon tariff raises the South's welfare because the positive effect of a decrease in the external cost outweighs the negative effect of a decrease in the southern firm's profit. These results imply that the North's optimal carbon tax regime can benefit the South.

Proposition 11 *Regardless of the gap in the emissions intensities between the northern and southern firms, the North's optimal carbon tax regime can benefit the South.*

7 Concluding Remarks

We examined the effects of the carbon tax under different carbon tax regimes by using the North-South duopoly model. If the northern firm's emissions intensity exceeds fifty percent of that of the southern firm, then the North's carbon tariff with its export rebate can prevent emissions leakage caused by the northern firm's plant relocation to the South.

As a result, the North's optimal carbon tax that maximizes its social welfare reduces global emissions. If the northern firm's emissions intensity is less than fifty percent of that of the southern firm, then the North's optimal carbon tax leads to emissions leakage through plant relocation to the South even in the carbon tax regime with the carbon tariff and export rebate. However, emissions leakage does not result in an increase in global emissions because plant relocation expands the northern firm's low-carbon output at the expense of the southern firm's high-carbon output.

We analyze an optimal carbon tax regime for the North. When the North chooses its optimal carbon tax rate to maximize its social welfare, the optimal carbon tax regime incorporates both a carbon tariff and an export rebate. Moreover, this carbon tax regime can benefit the South we well. That is, both measures alleviate the negative effects of the carbon tax on the northern firm's production efficiency and prevent emissions leakage that increases global emissions.

We can modify our model in several directions. First, we assume that firms conduct Cournot competition. As is well known in the literature on trade policy in oligopoly, the market structure affects the policy outcomes. We need to examine how our results would be modified when we use a model with Bertrand competition. Second, we focus on the case of the unilateral carbon tax by the North. One of the aims of carbon tariffs is to encourage trade partners with lax carbon regulation to raise their carbon prices. We can extend our model to examine how the North's carbon tariff affects the South's optimal choice on its carbon tax. Last, we assume that the gap in emissions intensity between the firms is exogenous. We can examine the effects of the carbon tariff on the northern firm's investment in low-carbon technology and its spillover to southern firms. These tasks are left for our future work.

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Appendix A: Incentives to Northern Firm's Plant Relocation

In this appendix, we derive the effects of the carbon tax, carbon tariff, and export rebate on the northern firm's incentive to relocate its plant to the South. By using (9), we can derive the change of the northern firm's profit under the northern firm's domestic production,

$$d\pi_1 = 2b\left[q_{1N}\left(\frac{\partial q_{1N}}{\partial \tau_N}d\tau_N + \frac{\partial q_{1N}}{\partial t_N}dt_N\right) + q_{1S}\left(\frac{\partial q_{1S}}{\partial \tau_N}d\tau_N + \frac{\partial q_{1S}}{\partial r_N}dr_N\right)\right].$$

In the carbon tax regime without the carbon tariff and export rebate, the northern firm's profit change due to the North's carbon tax is

$$\frac{\partial \pi_1(c_{1N}, \tau_N, 0, 0)}{\partial \tau_N} = 2b\left(q_{1N}\frac{\partial q_{1N}}{\partial \tau_N} + q_{1S}\frac{\partial q_{1S}}{\partial \tau_N}\right) = -\frac{4e_1(q_{1N}+q_{1S})}{3} < 0,$$

where the second equality holds because the output change due to the carbon tax is

$$\frac{\partial q_{1K}}{\partial \tau_N} = -\frac{2e_1}{3b},\ (K = N, S).$$

This profit change implies that a small carbon tax increases the northern firm's gain from relocation to the South.

In the carbon tax regime with the carbon tariff, the northern firm's profit change due to the North's carbon tax and carbon tariff is

$$\begin{aligned}\frac{\partial \pi_1(c_{1N}, \tau_N, t_N, 0)}{\partial \tau_N} + \frac{\partial \pi_1(c_{1N}, \tau_N, t_N, 0)}{\partial t_N} &= 2b\left[q_{1N}\left(\frac{\partial q_{1N}}{\partial \tau_N} + \frac{\partial q_{1N}}{\partial t_N}\right) + q_{1S}\frac{\partial q_{1S}}{\partial \tau_N}\right] \\ &= \frac{2(e_2 - 2e_1)q_{1N} - 4e_1 q_{1S}}{3},\end{aligned}$$

where the second equality holds because the output change due to the carbon tariff is

$$\frac{\partial q_{1N}}{\partial t_N} = \frac{e_2}{3b}.$$

The North's carbon tax with the carbon tariff increases the northern firm's profit from domestic sales if and only if the positive effect of the carbon tariff exceeds the negative effect of the carbon tax, i.e. $e_2/2 > e_1$. The effect of the North's carbon tax on the northern firm's profit from export sales is negative.

In the carbon tax with the carbon tariff and export rebate, the northern firm's profit change due to the North's carbon tax with the carbon tariff and the export rebate is

$$\begin{aligned}&\frac{\partial \pi_1(c_{1N}, \tau_N, t_N, r_N)}{\partial \tau_N} + \frac{\partial \pi_1(c_{1N}, \tau_N, t_N, r_N)}{\partial t_N} + \frac{\partial \pi_1(c_{1N}, \tau_N, t_N, r_N)}{\partial r_N} \\ &= 2b\left[q_{1N}\left(\frac{\partial q_{1N}}{\partial \tau_N} + \frac{\partial q_{1N}}{\partial t_N}\right) + q_{1S}\left(\frac{\partial q_{1S}}{\partial \tau_N} + \frac{\partial q_{1S}}{\partial r_N}\right)\right] \\ &= \frac{2(e_2 - 2e_1)q_{1N}}{3},\end{aligned}$$

where the last equality holds because the change in the output exported to the South due to the export rebate exactly cancels out the change due to the carbon tax,

$$\frac{\partial q_{1S}}{\partial r_N} = \frac{2e_1}{3b}.$$

If the North adopts the export rebate, its carbon tax with the carbon tariff increases the

northern firm's profit if and only if the positive effect of the carbon tariff exceeds the negative effect of the carbon tax, i.e. $e_2/2 > e_1$.

Suppose that the northern firm produces in the South. By using (10), we can derive a change in its profit due to the North's carbon tariff,

$$d\pi_1 = 2bq_{1N}\frac{\partial q_{1N}}{\partial t_N}dt_N.$$

Note that the effects of the carbon tariff on the northern firm's profit in the carbon tax regime with the carbon tariff is the same as those in the carbon tax regime with the carbon tariff and export rebate. The profit change can be written as

$$\frac{\partial \pi_1(c_{1S}, t_N)}{\partial t_N} = 2bq_{1N}\frac{\partial q_{1N}}{\partial t_N} = \frac{2(e_2 - 2e_1)q_{1N}}{3},$$

where the second equality holds because the output change due to the carbon tariff is

$$\frac{\partial q_{1N}}{\partial t_N} = \frac{e_2 - 2e_1}{3b}.$$

In the carbon tax regime with the carbon tariff, the effect of the carbon tax with the carbon tariff on the northern firm's gain from plant relocation can be derived as

$$\frac{\partial \pi_1(c_{1S}, t_N)}{\partial t_N} - \left(\frac{\partial \pi_1(c_{1N}, \tau_N, t_N, 0)}{\partial \tau_N} + \frac{\partial \pi_1(c_{1N}, \tau_N, t_N, 0)}{\partial t_N}\right) = \frac{2(e_2 - 2e_1)(c_{1N} - c_{1S})}{9b} + \frac{4e_1 q_{1S}}{3},$$

where the equality holds because

$$q_{1N}(c_{1S}, t_N) - q_{1N}(c_{1N}, \tau_N, t_N, 0) = \frac{c_{1N} - c_{1S}}{3b},$$

given that $\tau_N = t_N$. If the northern firm's emissions intensity is less than fifty percent of that of the southern firm, $e_1 \in (0, e_2/2)$, then the effect of the carbon tax with the carbon tariff on the northern firm's gain from its plant relocation is positive. Meanwhile, if the northern firm's emissions intensity exceeds fifty percent of that of the southern firm, $e_1 \in (e_2/2, e_2)$, then the effect depends on the negative effect on its profit change in domestic sales relative to the positive effect on its profit change in export sales.

In the carbon tax regime with the carbon tariff and export rebate, the change of a northern firm's profit gain from relocation to the South can be derived as

$$\frac{\partial \pi_1(c_{1S}, t_N)}{\partial t_N} - \left(\frac{\partial \pi_1(c_{1N}, \tau_N, t_N, r_N)}{\partial \tau_N} + \frac{\partial \pi_1(c_{1N}, \tau_N, t_N, r_N)}{\partial t_N} + \frac{\partial \pi_1(c_{1N}, \tau_N, t_N, r_N)}{\partial r_N}\right)$$
$$= \frac{2(e_2 - 2e_1)(c_{1N} - c_{1S})}{9b}.$$

The carbon tax with the carbon tariff and export rebate reduces the northern firm's profit

gain from its relocation to the South if and only if $e_1 \in (e_2/2, e_2)$.

Appendix B: Impacts on Carbon Emissions

In this appendix, we derive the effects of the carbon tax, carbon tariff, and export rebate on carbon emissions. Under the northern firm's domestic production, the change in carbon emissions of each country can be derived as,

$$dE_N = e_1 \left(\frac{\partial q_{1N}}{\partial \tau_N} d\tau_N + \frac{\partial q_{1N}}{\partial t_N} dt_N + \frac{\partial q_{1S}}{\partial \tau_N} d\tau_N + \frac{\partial q_{1S}}{\partial r_N} dr_N \right),$$
$$dE_S = e_2 \left(\frac{\partial q_{2N}}{\partial \tau_N} d\tau_N + \frac{\partial q_{2N}}{\partial t_N} dt_N + \frac{\partial q_{2S}}{\partial \tau_N} d\tau_N + \frac{\partial q_{2S}}{\partial r_N} dr_N \right).$$

In the carbon tax regime without the carbon tariff and export rebate, the effect of the North's carbon tax on global emissions is

$$\begin{aligned} \frac{\partial E_G(c_{1N}, \tau_N, 0, 0)}{\partial \tau_N} &= e_1 \left(\frac{\partial q_{1N}}{\partial \tau_N} + \frac{\partial q_{1S}}{\partial \tau_N} \right) + e_2 \left(\frac{\partial q_{2N}}{\partial \tau_N} + \frac{\partial q_{2S}}{\partial \tau_N} \right) \\ &= \frac{2e_1(e_2 - 2e_1)}{3b}, \end{aligned}$$

where the second equality is obtained by using the southern firm's output change,

$$\frac{\partial q_{2K}}{\partial \tau_N} = \frac{e_1}{3b}, \ (K = N, S).$$

Global emissions decrease due to the carbon tax if and only if the northern firm's emissions intensity exceeds fifty percent of that of the southern firm, $e_1 \in (e_2/2, e_2)$. In the carbon tax regime with the carbon tariff, the change in global emissions is

$$\begin{aligned} &\frac{\partial E_G(c_{1N}, \tau_N, t_N, 0)}{\partial \tau_N} + \frac{\partial E_G(c_{1N}, \tau_N, t_N, 0)}{\partial t_N} \\ &= e_1 \left(\frac{\partial q_{1N}}{\partial \tau_N} + \frac{\partial q_{1N}}{\partial t_N} + \frac{\partial q_{1S}}{\partial \tau_N} \right) + e_2 \left(\frac{\partial q_{2N}}{\partial \tau_N} + \frac{\partial q_{2N}}{\partial t_N} + \frac{\partial q_{2S}}{\partial \tau_N} \right) \\ &= \frac{2e_1(e_2 - 2e_1) + e_2(e_1 - 2e_2)}{3b}, \end{aligned}$$

where the second equality is obtained by using the southern firm's output change,

$$\frac{\partial q_{2N}}{\partial t_N} = -\frac{2e_2}{3b}.$$

The carbon tax with the carbon tariff reduces global emissions regardless of the difference in emissions intensities because

$$\frac{2e_1(e_2-2e_1)+e_2(e_1-2e_2)}{3b}=-\frac{2(e_2-e_1)^2+e_1(2e_1+e_2)}{3b}<0.$$

In the carbon tax regime with the carbon tariff and export rebate, the change in global emissions due to the carbon tax, carbon tariff, and export rebate is

$$\begin{aligned}&\frac{\partial E_G(c_{1N},\tau_N,t_N,r_N)}{\partial \tau_N}+\frac{\partial E_G(c_{1N},\tau_N,t_N,r_N)}{\partial t_N}+\frac{\partial E_G(c_{1N},\tau_N,t_N,r_N)}{\partial r_N}\\&=e_1\left(\frac{\partial q_{1N}}{\partial \tau_N}+\frac{\partial q_{1N}}{\partial t_N}+\frac{\partial q_{1S}}{\partial \tau_N}+\frac{\partial q_{1S}}{\partial r_N}\right)+e_2\left(\frac{\partial q_{2N}}{\partial \tau_N}+\frac{\partial q_{2N}}{\partial t_N}+\frac{\partial q_{2S}}{\partial \tau_N}+\frac{\partial q_{2S}}{\partial r_N}\right)\\&=\frac{e_1(e_2-2e_1)}{3b}+\frac{e_2(e_1-2e_2)}{3b},\end{aligned}$$

where the second equality is derived by using the output change due to the export rebate,

$$\begin{aligned}\frac{\partial q_{1S}}{\partial r_N}&=\frac{2e_1}{3b},\\\frac{\partial q_{2S}}{\partial r_N}&=-\frac{e_1}{3b}.\end{aligned}$$

Global emissions decrease due to the carbon tax with the carbon tariff and export rebate regardless of the gap in emissions intensities,

$$\frac{e_1(e_2-2e_1)}{3b}+\frac{e_2(e_1-2e_2)}{3b}=-\frac{2\left[(e_1-e_2)^2+e_2e_2\right]}{3b}<0.$$

An increase in the carbon tax with with the carbon tariff and the export rebate leads to a smaller reduction in global emissions as compared to the case without the export rebate.

Under the northern firm's production in the South, the change in carbon emissions of each country can be derived as,

$$\begin{aligned}dE_N&=0,\\dE_S&=e_1\frac{\partial q_{1N}}{\partial t_N}dt_N+e_2\frac{\partial q_{2N}}{\partial t_N}dt_N.\end{aligned}$$

In the carbon tax regime with the carbon tariff, the change in global emissions is

$$\begin{aligned}\frac{\partial E_G(c_{1S},t_N)}{\partial t_N}&=e_1\frac{\partial q_{1N}}{\partial t_N}+e_2\frac{\partial q_{2N}}{\partial t_N}\\&=\frac{e_1(e_2-2e_1)}{3b}+\frac{e_2(e_1-2e_2)}{3b},\end{aligned}$$

where the second equality is obtained by using the southern firm's output change,

$$\frac{\partial q_{2N}}{\partial t_N} = \frac{e_1 - 2e_2}{3b}.$$

The effects of the carbon tariff on global emissions are the same as those of the carbon tax with the carbon tariff and export rebate under the northern firm's domestic production. This implies that the carbon tariff reduces global emissions regardless of the gap in emissions intensities. Note that, under the northern firm's production in the South, the effects of the carbon tariff on global emissions in the carbon tax regime with the carbon tariff are the same as those in the carbon tax regime with the carbon tariff and export rebate. This implies that, in the carbon tax regime with the carbon tariff and export rebate, an increase in the carbon tariff under the northern firm's production in the South leads to the same reduction in global emissions as that of the carbon tax under the northern firm's domestic production.

The impact on global emissions of the northern firm's relocation to the South can be derived as

$$\begin{aligned} &E_G(c_{1S}, t_N) - E_G(c_{1S}, \tau_N, t_N, r_N) \\ &= \frac{(2e_1 - e_2)\left[2(c_{1N} - c_{1S}) + e_1(\tau_N - t_N) + e_1(\tau_N - r_N)\right]}{3b}. \end{aligned}$$

If the northern firm's emissions intensity is more (less) than fifty percent of that of the southern firm, $e_1 \in (e_2/2, e_2)$ ($e_1 \in (0, e_2/2)$), then the northern firm's relocation to the South expands (reduces) global emissions in all the carbon tax regimes. The increase (decrease) in emissions is the smallest under the carbon tax regime with the carbon tariff and export rebate, $\tau_N = t_N = r_N$. In the carbon tax regime with the carbon tariff ($\tau_N = t_N > 0 = r_N$), the expansion (reduction) of emissions is smaller than that under the carbon tax regime without the carbon tariff and export rebate ($\tau_N > t_N = r_N = 0$) but larger than that under the carbon tax regime with the carbon tariff and export rebate ($\tau_N = t_N = r_N > 0$).

Appendix C: Effects on Northern Welfare

In this appendix, we derive the effects of the North's carbon tax, carbon tariff, and export rebate on the North's social welfare. In the equilibrium with the northern firm's domestic production, the total demand and the price in the northern market can be

derived respectively as

$$q_N = \frac{2a - c_{1N} - e_1\tau_N - c_{2S} - e_2 t_N}{3b},$$
$$p_N = \frac{a + c_{1N} + e_1\tau_N + c_{2S} + e_2 t_N}{3}.$$

In the southern market, the total demand and the price are respectively

$$q_S = \frac{2a - c_{1N} - e_1(\tau_N - r_N) - c_{2S}}{3b},$$
$$p_S = \frac{a + c_{1N} + e_1(\tau_N - r_N) + c_{2S}}{3}.$$

The income of the North can be derived as

$$I_N = \pi_1 + g_N + L_N.$$

The budget constraint for the North is

$$p_N q_N + q_{N0} = I_N.$$

Using the budget constraint with the utility function, the social welfare of the North can be written as

$$w_N = aq_N - \frac{b}{2}q_N^2 - p_N q_N + \pi_1 + g_N + L_N - \delta_N E_G.$$

Under the northern firm's domestic production, the change in the social welfare can be derived as

$$dw_N = -q_{2N}dp_N + e_2 q_{2N} dt_N + t_N e_2 dq_{2N} + q_{1S}dp_S + (p_N - c_{1N})dq_{1N} + (p_S - c_{1N})dq_{1S} - \delta_N dE_G.$$

In the carbon tax regime without the carbon tariff and the export rebate, the effect of the carbon tax on the social welfare is

$$\begin{aligned}\frac{\partial w_N(c_{1N}, \tau_N, 0, 0)}{\partial \tau_N} &= -q_{2N}\frac{\partial p_N}{\partial \tau_N} + (p_N - c_{1N})\frac{\partial q_{1N}}{\partial \tau_N} + q_{1S}\frac{\partial p_S}{\partial \tau_N} + (p_S - c_{1N})\frac{\partial q_{1S}}{\partial \tau_N} - \delta_N \frac{\partial E_G}{\partial \tau_N}, \\ &= -\frac{q_{2N}e_1}{3} - \frac{2e_1(p_N - c_{1N})}{3b} + \frac{q_{1S}e_1}{3} - \frac{2e_1(p_S - c_{1N})}{3b} - \frac{2e_1(e_2 - 2e_1)\delta_N}{3b}.\end{aligned}$$

On the RHS, the sum of the first four terms is negative because the third term can be written as

$$\frac{q_{1S}e_1}{3} = \frac{e_1(p_S - c_{1N} - e_1\tau_N)}{3b}.$$

The last term that is the external cost effect positively (negatively) affects the welfare if the northern firm's emissions intensity is more (less) than fifty percent of that of the southern firm, $e_1 \in (e_2/2, e_2)$ ($e_1 \in (0, e_2/2)$).

In the carbon tax regime with the carbon tariff, the change in the North's welfare can be derived as

$$\begin{aligned}
&\frac{\partial w_N(c_{1N},\tau_N,t_N,0)}{\partial \tau_N}+\frac{\partial w_N(c_{1N},\tau_N,t_N,0)}{\partial t_N}\\
&=-q_{2N}\frac{\partial p_N}{\partial \tau_N}-q_{2N}\frac{\partial p_{2N}}{\partial t_N}+t_Ne_2\left(\frac{\partial q_{2N}}{\partial \tau_N}+\frac{\partial q_{2N}}{\partial t_N}\right)+(p_N-c_{1N})\left(\frac{\partial q_{1N}}{\partial \tau_N}+\frac{\partial q_{1N}}{\partial t_N}\right)\\
&+q_{1S}\frac{\partial p_S}{\partial \tau_N}+(p_S-c_{1N})\frac{\partial q_{1S}}{\partial \tau_N}-\delta_N\left(\frac{\partial E_G}{\partial \tau_N}+\frac{\partial E_G}{\partial t_N}\right),\\
&=\frac{q_{2N}(2e_2-e_1)}{3}-\frac{t_Ne_2(2e_2-e_1)}{3b}+\frac{(e_2-2e_1)(p_N-c_{1N})}{3b}\\
&+\frac{q_{1S}e_1}{3}-\frac{2e_1(p_S-c_{1N})}{3b}-\left[\frac{2e_1(e_2-2e_1)}{3b}+\frac{e_2(e_1-2e_2)}{3b}\right]\delta_N,
\end{aligned}$$

where the second equality is derived by using the southern firm's producer (export) price in the northern market, $p_{2N}=p_N-t_Ne_2$. We now evaluate the welfare effects of the carbon tax under the constraint, $\tau_N=t_N$. On the RHS, the first term that is the terms of trade effect of imports is positive, the second term that is the consumption distortionary effect is negative, and the third term that is the production efficiency effect in domestic sales is negative (positive) if the northern firm's emissions intensity is more (less) than fifty percent of that of the southern firm, $e_1\in(e_2/2,e_2)$ ($e_1\in(0,e_2/2)$). The first term on the RHS can be written as

$$\frac{q_{2N}(2e_2-e_1)}{3}=\frac{(2e_2-e_1)(p_N-c_{2S}-e_2t_N)}{3b},$$

by using

$$\frac{q_{2N}}{3}=\frac{p_N-c_{2S}-e_2t_N}{3b}.$$

For a small carbon tax and carbon tariff, the consumption distortionary effect is negligible. In addition, even if the northern firm's emissions intensity exceeds fifty percent of that of the southern firm, $e_1\in(e_2/2,e_2)$, then the following inequality holds,

$$\frac{(2e_2-e_1)(p_N-c_{2S})}{3b}+\frac{(e_2-2e_1)(p_N-c_{1N})}{3b}>0,$$

because we assume that $c_{2S}<c_{1N}$. Thus, for a small carbon tax and carbon tariff, the sum of the terms of trade effect of imports and the production efficiency effect of domestic sales is positive regardless of the gap in emissions intensities between the firms. Meanwhile, the terms of trade effect of exports and the production efficiency effect in export sales are the same as those in the case with the carbon tax regime without the carbon tariff and export rebate. Recall that the sum of these two terms is negative. The last term is the external cost effect that positively affects the welfare of the North. These results imply that a small carbon tax with a carbon tariff positively affects the welfare of the North

as long as the positive effect of the external costs outweighs the negative effect of the export production efficiency. The sufficient condition for this result is that the marginal damage, δ_N, is sufficiently large. We can also confirm that the second order derivative of the North's welfare with respect to its carbon tax under $\tau_N = t_N$ is negative,

$$\frac{\partial^2 w_N(c_{1N}, \tau_N, \tau_N, 0)}{\partial \tau_N^2} = -\frac{(e_1 - e_2)^2 + 2e_2^2}{3b} - \frac{4e_1^2}{9b} < 0.$$

In the carbon tax regime with the carbon tariff and export rebate, the change in the North's social welfare can de derived as

$$\begin{aligned}
&\frac{\partial w_N(c_{1N}, \tau_N, t_N, r_N)}{\partial \tau_N} + \frac{\partial w_N(c_{1N}, \tau_N, t_N, r_N)}{\partial t_N} + \frac{\partial w_N(c_{1N}, \tau_N, t_N, r_N)}{\partial r_N} \\
&= -q_{2N}\frac{\partial p_N}{\partial \tau_N} - q_{2N}\frac{\partial p_{2N}}{\partial t_N} + t_N e_2\left(\frac{\partial q_{2N}}{\partial \tau_N} + \frac{\partial q_{2N}}{\partial t_N}\right) + (p_N - c_{1N})\left(\frac{\partial q_{1N}}{\partial \tau_N} + \frac{\partial q_{1N}}{\partial t_N}\right) \\
&+ q_{1S}\left(\frac{\partial p_S}{\partial \tau_N} + \frac{\partial p_S}{\partial r_N}\right) + (p_S - c_{1N})\left(\frac{\partial q_{1S}}{\partial \tau_N} + \frac{\partial q_{1S}}{\partial r_N}\right) - \delta_N\left(\frac{\partial E_G}{\partial \tau_N} + \frac{\partial E_G}{\partial t_N} + \frac{\partial E_G}{\partial r_N}\right), \\
&= \frac{q_{2N}(2e_2 - e_1)}{3} - \frac{t_N e_2(2e_2 - e_1)}{3b} + \frac{(e_2 - 2e_1)(p_N - c_{1N})}{3b} \\
&- \left[\frac{e_1(e_2 - 2e_1)}{3b} + \frac{e_2(e_1 - 2e_2)}{3b}\right]\delta_N.
\end{aligned}$$

We will evaluate the welfare effects of the carbon tax under the constraint, $\tau_N = t_N = r_N$. On the RHS, the first three terms are the same as those in the case of the carbon tax regime with the carbon tariff. Due to the export rebate, the terms of trade effect of exports and the production efficiency effect of export sales disappear. The last term is the external cost effect that positively affects the welfare. These results imply that a small carbon tax with the carbon tariff and the export rebate increases the welfare of the North. We can also prove that the second order derivative of the North's welfare with respect to the carbon tax with $\tau_N = t_N = r_N$ is negative,

$$\frac{\partial^2 w_N(c_{1N}, \tau_N, \tau_N, \tau_N)}{\partial \tau_N^2} = -\frac{(e_1 - e_2)^2 + 2e_2^2}{3b_N} < 0.$$

In the equilibrium with northern firm's production in the South, the total demand and the price in the northern market can de derived, respectively, as

$$\begin{aligned}
q_N &= \frac{2a - c_{1S} - c_{2S} - (e_1 + e_2)t_N}{3b}, \\
p_N &= \frac{a + c_{1S} + c_{2S} + (e_1 + e_2)t_N}{3}.
\end{aligned}$$

In the southern market, the total demand and the price are, respectively,

$$q_S = \frac{2a - c_{1S} - c_{2S}}{3b},$$
$$p_S = \frac{a + c_{1S} + c_{2S}}{3}.$$

Under the northern firm's production in the South, the change in the North's welfare can be derived as

$$dw_N = -q_{2N}dp_N + e_2 q_{2N}dt_N + t_N e_2 dq_{2N} + (p_N - c_{1S})dq_{1N} - \delta_N dE_G.$$

In the carbon tax regime with the carbon tariff, the effects of the carbon tariff on the North's welfare can be derived as

$$\begin{aligned}\frac{\partial w_N(c_{1S}, t_N)}{\partial t_N} &= -q_{2N}\frac{\partial p_{2N}}{\partial t_N} + t_N e_2 \frac{\partial q_{2N}}{\partial t_N} + (p_N - c_{1S})\frac{\partial q_{1N}}{\partial t_N} - \delta_N \frac{\partial E_G}{\partial t_N}, \\ &= \frac{q_{2N}(2e_2 - e_1)}{3} - \frac{t_N e_2(2e_2 - e_1)}{3b} + \frac{(e_2 - 2e_1)(p_N - c_{1S})}{3b} \\ &\quad - \left[\frac{e_1(e_2 - 2e_1)}{3b} + \frac{e_2(e_1 - 2e_2)}{3b}\right]\delta_N.\end{aligned}$$

On the RHS, the first term is the terms of trade effect, the second term is the consumption distortionary effect, the third term is the production efficiency effect under the northern firm's production in the South, and the last term is the external cost effect. The first term can be written as

$$\frac{q_{2N}(2e_2 - e_1)}{3} = \frac{(p_N - c_{2S} - e_2 t_N)(2e_2 - e_1)}{3b},$$

by using

$$\frac{q_{2N}}{3} = \frac{(p_N - c_{2S} - e_2 t_N)}{3b}.$$

For a small carbon tariff, the consumption distortionary effect is negligible. Then, if the northern firm's emissions intensity exceeds fifty percent of that of the southern firm, $e_1 \in (e_2/2, e_2)$, then the positive effect of an improvement in the terms of trade could fall short of the negative effect of a decrease in the production efficiency. This can occur only if $c_{1S} < c_{2S}$, i.e., the northern firm's production in the South is more efficient than the southern firm's. These results imply that the sufficient condition for an increase in the North's welfare due to a small increase in the carbon tax is that the marginal damage is sufficiently large. Meanwhile, if the northern firm's emissions intensity is less than fifty percent of that of the southern firm, $e_1 \in (0, e_2/2)$, then a small carbon tariff improves the North's welfare. We can also prove that the second order derivative of the North's

welfare with respect to the carbon tariff is negative,

$$\frac{\partial^2 w_N(c_{1S}, \tau_N)}{\partial t_N^2} = -\frac{(e_1 - e_2)^2 + 2e_2^2}{3b_N} < 0.$$

If the northern firm produces in the South, then the effects of the carbon tariff on the North's welfare in the carbon tax regime with the carbon tariff and export rebate are the same as those in the case with the carbon tax regime with the carbon tariff.

Appendix D: Numerical Example

The numerical example uses the following values for parameters of the model.

$$a = 120,\ b = 1,\ c_{1N} = 20,\ c_{1S} = 3,\ c_{2S} = 6,\ e_2 = 6,\ f_1 = 1650,$$
$$\delta_N = 15,\ \delta_S = 5,\ L_N = \omega_S L_S = 3000.$$

We consider the case in which the marginal damage of the North is greater than that of the South because this implies that $\tau_N > \tau_S$.

If the northern firm's emissions intensity exceeds fifty percent of that of the southern firm, $e_1 \in (e_2/2, e_2)$, the emissions intensity of the northern firm is

$$e_1 = 4.$$

In this case, the optimal carbon tax rate is 98/11 when the northern firm stays in the North under the carbon tax regime with the carbon tariff and the export rebate. The prohibitive carbon tariff rate that eliminates the import from the southern firm is 96/5, which is greater than the optimal carbon tax rate. Similarly, the optimal carbon tax rate is 179/22 when the northern firm relocates to the South in the carbon tax regime with the carbon tariff. Then, the prohibitive carbon tariff rate, 35/2, is larger than the optimal carbon tax rate.

If the northern firm's emissions intensity is less than fifty percent of that of the southern firm, $e_1 \in (0, e_2/2)$, the emissions intensity of the northern firm is

$$e_1 = 2.$$

In this case, the optimal carbon tax rate is 2029/177 when the northern firm's relocation arises in the carbon tax regime with the carbon tariff or with the carbon tariff and the export rebate. Then, the prohibitive carbon tariff rate that eliminates the import from the southern firm is 35/3, which is greater than the optimal carbon tax rate.