Carbon-motivated Border Adjustment in Combating Carbon Leakage

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Abstract

This paper analyzes the potential effectiveness of carbon motivated border adjustments in addressing the issue of carbon leakage. I extend the Helpman-Krugman model of intra-industry trade to incorporate greenhouse gas emissions as a factor in production. Simulation exercises show that carbon motivated border adjustments alleviate carbon leakage, but are typically not environmentally effective with respect to global emissions under reasonable parameter specifications. Such measures benefit owners of domestic factors used intensively in emissions-intensive sectors, but reduce real income of other factors as well as the welfare of the foreign economy. It suggests that such border measures have limited impacts on the global environment, but may be useful as distributional instruments.

JEL Classification Codes: F18, Q54, Q58

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I. Introduction

Climate change, or anthropogenic global warming, has become one of the most important challenges facing the global society. Governments have agreed to the goal of holding the increase in global average temperature below 2 degrees Celsius above pre-industrial levels in the Copenhagen Accord (UN, 2009) and the Cancun Agreements (UN, 2010). In order to achieve this, global CO_2 emissions need to peak by as early as 2015 and be reduced by 50 to 85 percent by 2050 compared to 2000 levels (IPCC, 2007).

Meeting these targets is certainly difficult. The issue with greenhouse gas (GHG) involves a two-fold public good problem. The first level of externality is similar to any environmental problem, in that a clean environment is a public good. Private agents do not take into account the environmental damages of their GHG emissions when they optimize their economic activities and hence generate an excessive amount of emissions in the process. The second level comes from the nature of GHG emissions as a global bad, i.e., emissions anywhere in the world have the same impact on global climate, since most GHG emissions stay in the atmosphere for a long time and what ultimately matters is their concentration in the atmosphere. The issue then becomes a public good provision problem with national governments as agents. Self-interested governments may not internalize the potential damages of their domestic emissions on other countries, and elect to free-ride on other countries' efforts to reduce emissions.

The fact that GHG emissions are a global public bad dictates that efficient mitigation efforts entail global cooperation. However, international cooperation in the form of a global cap or a universal tax on emissions is hard to achieve. What exists today is a unilateral commitment to reduce GHG emissions by a group of industrialized countries under the Kyoto Protocol. Such a system invariably suffers from the free-rider problem and can lead to unwelcome side effects such as carbon leakage, i.e., emissions reduced by committed countries are offset by increases elsewhere resulting from linkages in global economic activities (Rutherford, 1992). The rate of carbon leakage is typically defined as the ratio of increased carbon emissions abroad over the reduced domestic emissions as a result of unilateral climate change policies. A large amount of research has attempted to assess the magnitude of potential leakage and suggest possible solutions. Since the channels of the leakage mainly work through international trade linkages, one possible policy option to address the issue is to use trade measures. Carbon-motivated border adjustment on domestic emissions taxes or permits applied to imports from countries with lax climate policies have become increasingly popular in the past few years and are being considered by several governments, including the European Union and the United States, to complement regulations on domestic emissions. Such border measures are often referred to as "carbon tariffs," indicating that they are meant to address issues related to carbon emissions.

In the meantime, another driver for border adjustment policies is the concern about the competitiveness of domestic companies in emissions-intensive and trade-exposed (EITE) industries. In fact, such motives have been very strong in practice. A World Bank (2008) study suggests that when designing emissions abatement policies, countries often offer exemptions or subsidies to EITE industries, sometimes resulting in the opposite effects on trade patterns from what is normally expected. While addressing concerns for carbon leakage aims at the environmental impacts, resolving the competitiveness concerns focuses on the economic effects. It is therefore important to distinguish the two motives behind border adjustment policies.

In this paper, I analyze the potential effects of a carbon tariff on the environment as well as economic welfare, using a simple model of international trade. Based on the Helpman-Krugman (1985) model of intra-industry trade, I incorporate GHG emissions as a factor in production. I then simulate the model to evaluate the potential impact of a carbon tariff on emissions and real compensation. The results suggest that such a border adjustment policy does reduce the leakage rate, but is not so effective in reducing overall global emissions. In the meantime, this policy negatively affects the economic welfare of a country's trading partners as well as the domestic owners of the productive factor used more intensively in the clean sectors. On the other hand, domestic owners of the factor that is used more intensively in emissions-intensive sectors stand to gain. Therefore, a carbon tariff acts more like a typical "beggar thy neighbor" tariff than a viable alternative for environmental purposes.

The rest of the paper is organized as follows. The next section briefly reviews the relevant theoretical and empirical literature on carbon leakage and border adjustment. Section III describes the economic model used for the analysis, characterizes the equilibrium, and discusses the key economic intuition behind the potential effects of the policies. Section IV reports simulation results of various policy scenarios with a few sets of parameter values and investigates the sensitivity of the results to key parameters. The last section concludes.

II. Related Literature

The role of trade. The theoretical literature on carbon leakage centers on the role of international trade. Trade alone is not to be blamed for the problem here. As shown by previous research (Copeland and Taylor, 2005), trade in virtual carbon, i.e., carbon emissions incurred in the production process of traded goods, need not imply inefficiency. If all countries have binding emissions targets and there is national and international trade of emissions permits, trade in embodied carbon will reflect patterns of comparative advantage. When the global supply of emissions permits is fixed, international trade is efficient and environmentally neutral. Theoretically, trade in goods alone suffices to equalize the price of emissions permits across the world when there are no trade costs; technologies are identical across countries; every country has a cap-and-trade system for GHG emissions; and emissions targets relative to endowments of production factors are not too different across countries.[1] In this case, emissions abatement costs are equalized across countries as a result of factor price equalization (FPE). In practice, however, the aforementioned conditions for FPE are far from satisfied. There are sizable costs for international trade, including transportation, time, tariffs and non-tariff barriers; technological differences are substantial across countries with varying levels of development; and a universal mitigation commitment is unlikely to be achieved.

Carbon leakage. Currently, there is not sufficient cooperation from the international community for a global commitment, necessitating unilateral

[1] Treating emissions as a factor in production, as I do in this paper, this condition means that the countries relative endowments must lie within the factor price equalization set of the model.

schemes, such as the Kyoto Protocol. These unilateral policies can lead to carbon leakage, through three main channels. The first channel is production relocation. Countries committed to reduce emissions may resort to importing more emissions-intensive goods to meet domestic demand, resulting in the production of these goods being relocated to countries with little or weak emissions regulations. This is also referred to as the "scale effect," when it pertains to the increased size of emissions-intensive industries in the non-abating economies. The second channel is through technological differences, and is called the "technology effect." Countries with lax climate change policies experience expansions of emissions-intensive sectors. At the same time, they also tend to employ more emissions-intensive production technologies, or may lack access to the latest abatement technologies. Hence the resulting increase in emissions as a result of relocation of production can sometimes exceed the emissions reductions in the mitigating country. The last channel is through increased demand for energy from non-abating countries. Lower energy prices as a result of reduced demand from participating countries may induce more consumption in non-participating countries. In addition, some economists believe that there is also a supply-side channel, with the announcement of green policies generating more supply of fossil fuels for current periods and thereby increasing carbon consumption and GHG emissions, which constitutes a "Green Paradox" (Sinn, 2008).

Assessing leakage. The carbon leakage rate is typically measured as the number of units of increased carbon emissions in non-regulating countries, per unit of decreased emissions in the regulating countries, usually reported in percentage terms. Studies with simulations of integrated assessment models (IAM) or computable general equilibrium (CGE) models have found a wide range of estimates for potential carbon leakage as a result of Kyoto-style policies, from 5-15% (Paltsev, 2001) to 130% (Babiker, 2005). A leakage rate of over 100% means that the policy actually increases overall emissions. Results of these simulated models are often sensitive to parameterization and modeling assumptions (Karp, 2010; Melo and Mathys, 2010). Some scholars claim that, in practice, carbon leakage is unlikely to be substantial because transport costs, local market conditions, product variety and incomplete information all favor local production (Sijm, et al., 2004).

Aichele and Felbermayr (2010) provides one of the few empirical studies that have attempted to find evidence for carbon leakage. At the sectoral level, they find that imports of virtual carbon by a country committed to limit GHG emissions from an uncommitted exporter are about 10% higher than if the country had no commitments. On average, they find a carbon leakage rate of about 44%. Wang (2012) analyzes U.S. imports from 1990 to 2010 and finds that committing to a quantified emissions target under the Kyoto Protocol is associated with a country exporting less to the United States in emissions-intensive industries. Other empirical studies suggest that, in reality, actions by Annex I governments have generally exempted or provided special treatments for energy-intensive industries (IPCC, 2007). The subsidies and exemptions for some EITE industries are so generous that their exports, instead of imports, increased after the introduction of emissions regulations (World Bank, 2008).

Pollution Haven Hypothesis. The issue of carbon leakage is closely related to that of the Pollution Haven Hypothesis, the idea that pollution-intensive industries will relocate to jurisdictions with less stringent environmental regulations. The early literature in this area (see Jaffe et al., 1995 for a summary) only finds small, insignificant or non-robust effects of environmental regulation on trade or foreign direct investment (FDI) flows in cross-sectional data. By employing panel methods to control for unobserved heterogeneities and instrumenting for environmental regulations, more studies find significant pollution haven effects for trade flows (see e.g. Ederington et al., 2005; Levinson and Taylor, 2008) as well as FDI flows (see e.g. Keller and Levinson, 2002; List et al., 2003; Dean et al., 2009). On the other hand, there is little evidence of a "race to the bottom," i.e., freer international trade makes a government choose weaker environmental regulations so as to attract or retain economic activity. Frankel and Rose (2005) analyze data on a cross-section of countries and find little evidence that trade openness leads poor, i.e., unregulated, countries to become pollution havens. In the meantime, decomposition studies have suggested that most of the clean-up of local pollution in developed countries were not due to production relocation through international trade. For instance, Levinson (2009) shows that most of the decline in U.S. manufacturing pollution since the 1970s has resulted from technological improvements, rather than changes in the mix of goods produced, and increased net imports of polluting goods accounts for only a small portion of the pollution reductions resulting from compositional changes.

Carbon tariff. In recent years, carbon tariffs have been considered by policy makers as a popular option to counter carbon leakage. Such border adjustment measures have been suggested in proposals in various jurisdictions including the European Union and the United States, though there has yet to be an actual implementation anywhere. A large number of studies have been conducted to assess the potential usefulness of these policies in addressing carbon leakage. Simulation studies generally find that carbon tariffs have small effects on the environment, but potentially large costs on economic welfare. Most scholars agree that they will alleviate leakage, reduce imports of the countries administering the policies, and increase imports by other countries. Such policies have protectionist potential, as they have the capacity to support domestic production in EITE sectors, but are not necessarily effective at reducing the global emissions (Fischer and Fox, 2011; Dong and Whalley, 2012). The environmental benefits are often too small to justify their administrative complexity or the deleterious effects on international trade (McKibbin and Wilcoxen, 2009). There could also be negative implications for domestic production due to abatement shifting if the border adjustment is implemented only for selected EITE industries, i.e., the burden of mitigation would fall on less emissions-intensive industries further distorting the market (Alexeeva-Talebi, et al., 2008). A closely related literature looks at the practical implementation of carbon tariffs and its compatibility with WTO rules. Over the years, this literature has become more optimistic that carbon tariffs may be acceptable under the WTO subject to certain administrative issues.

This paper analyzes the effects of a unilateral abatement policy and an accompanying carbon-motivated border adjustment using a simple theoretical framework and attempts to use sensitivity analysis to identify the parameters that are important determinants of the magnitude of carbon leakage and the effectiveness of the border adjustment measures. Rather than providing a realistic estimate of the environmental and economic outcomes of the border measures, the analysis sheds light on the important factors to consider in the debate on carbon tariffs.

III. Model

I use a static model of international trade to analyze the role of a carbon tariff in addressing carbon leakage and its potential economic consequences. The model features intra-industry trade, which allows for imports of emissions-intensive goods even if a country is a net exporter in these sectors. This is important since according to World Bank's (2008) estimates, the developed economies (which are considering imposing a carbon tariff) are still net exporters of energy-intensive, therefore emissions-intensive, goods to the developing economies. Hence I incorporate intra-industry trade to generate exports in emissions-intensive industries from developing countries to developed countries, despite developing countries being net importers in these industries. In a model with only homogenous goods, a carbon tariff would not have an impact if it is administered by a country that is a net exporter of these goods, because there would be no imports.

The setup of the model follows Markusen and Venables's (2000) extension of the Helpman-Krugman model (1985), which incorporates trade costs. The modelling of emissions and the abatement technology is based on Copeland and Taylor's (2001; 2005) framework for analyzing trade and the environment. It is a typical $2 \times 2 \times 2$ Heckscher–Ohlin model with two main extensions, the inclusion of emissions and the modeling of one sector as imperfectly competitive.

There are two economies, the North and the South (i = N, S). Each economy is endowed with quantities K_i and L_i of two primary productive factors, capital and labor, the prices of which are denoted w_i and r_i.

GHG emissions, or carbon emissions, Z_i, are modeled as a third factor of production. Under certain conditions on the form of the abatement function, this formulation is equivalent to modelling the emissions as a by-product of production (see Appendix A for details). Consequently, an implied assumption is that the emissions are supplied perfectly elastically at a binding emissions price absent any regulations. Emissions can be used to substitute for other productive factors. However, the underlying production and abatement structure does impose a cap on emissions at the level of output,[2] and the economies cannot "pollute to prosperity."

There are two sectors, a "clean" sector producing an emissions-free homogenous good and a "dirty" sector producing a differentiated emissions-intensive good. The clean sector Y is perfectly competitive and is relatively labor intensive. The good is freely traded and used as a numeraire. Its constant-returns-to-scale production technology is specified by a unit cost function $c^Y(w_i, r_i)$. The dirty sector X is imperfectly competitive, with product differentiation of the Dixit-Stiglitz form and free entry and exit. The differentiated products are traded with an iceberg trade cost $\gamma > 1$, i.e., γ units of the good need to be transported in order to deliver one unit. Production of X employs, or generates, emissions. It features internal increasing returns to scale. A cost function $c^X(w_i, r_i, \tau_i)$ specifies the marginal production cost with τ_i being the price of emissions. A cost function $c^F(w_i, r_i)$ gives the marginal cost associated with capital and labor only, when no emissions abatement is performed. Hence, when the emissions price is not binding, i.e., regulations

[2] In the model to be specified, this limit for each variety of X is the total quantity $x_{ii} + x_{ij}$plus the fixed input requirement f.

on emissions are lax or absent,

$$c^X(w_i, r_i, \tau_i) = c^F(w_i, r_i) + \tau_i \tag{1}$$

Production of each variety of good X also requires a fixed input requirement, f, which is assumed to use the inputs in the same fashion as variable production. Hence, $c^X(w_i, r_i, \tau_i)f$ is the fixed cost.

The preferences over the differentiated products of the X sector take the standard constant-elasticity-of-substitution (CES) form.

$$X_i^C \equiv \left[n_i (x_{ii})^{\frac{\sigma-1}{\sigma}} + n_j (x_{ji}/\gamma)^{\frac{\sigma-1}{\sigma}} \right]^{\frac{\sigma}{\sigma-1}} \tag{2}$$

where $\sigma > 1$ is the elasticity of substitution between the differentiated varieties of X; n_i and n_j are the measures of the varieties of good X produced by the respective economies, endogenously determined in the equilibrium; x_{ij} is the quantity of one variety of X produced in country i and shipped to country j; x_{ii} and x_{ji}/γ are therefore the quantities of a domestic variety and an imported variety consumed in economy i. The utility from consuming the dirty good, X_i^C, can also be viewed as a composite X good for consumption in economy i produced with intermediate goods x_{ii} and x_{ji} according to a CES production technology specified in equation (2). The price index for the composite X_i^C in country i is then given by

$$\begin{aligned} P_i &= \left[n_i p_i^{1-\sigma} + n_j p_{ij}^{1-\sigma} \right]^{\frac{1}{1-\sigma}} \\ &= \left[n_i p_i^{1-\sigma} + n_j (p_i \gamma)^{1-\sigma} \right]^{\frac{1}{1-\sigma}} \end{aligned} \tag{3}$$

where p_i and p_j are the prices for each variety of good X in the respective economies where they are produced, and $p_{ij} = p_i\gamma$ denotes the price of the dirty good produced in economy i and exported to economy j. The presence of the trade cost γ scales up the price of an imported variety proportionally. Note that all the varieties of X in one economy have the same quantities and prices. This is an equilibrium property as the varieties are assumed to be symmetric.

Preferences over the private goods X and Y are assumed to be quasi-concave and homothetic. It is further assumed that the preferences can be represented by a linear homogeneous utility function $u()$. Then the utility can be expressed in the form of an expenditure function.

$$u(X_i^C, y_i^C) = e(1, P_i)v_i \tag{4}$$

where X_i^C and y_i^C are the composite dirty good and the quantity of the clean good consumed in economy i; v_i is the level of utility and $e(1, P_i)$ is the minimum expenditure to obtain one unit of utility.

Finally, preferences over the private goods and the environment are assumed to be weakly separable across the set of private goods and the public bad of emissions. Overall utility is decreasing in the level of overall emissions, $Z = \sum_{i=N,S} Z_i$ since GHG emissions are a global bad.

The exact form of the preferences over goods consumption and the emissions is not specified in the current analysis. Any realistic specification of the utility function for overall preference will necessarily involve dealing with the inherent uncertainties of the potential damages of climate change as a result of current emissions levels as well as appropriately discounting future (dis)utilities, both of which are beyond the scope of the current paper. Without a specific overall utility function, the welfare discussions that follow are limited to either the economic well-being based on the consumption of private goods or the environmental consequences related to the level of emissions, but not a proper aggregation of the two. As a consequence of this incompleteness of the model, optimal policies, either for the individual governments or collectively, are not well defined. Therefore, I will not solve the policy choice endogenously as in an optimal policy problem. Rather, I adopt the common practice in the literature on carbon tariffs of setting the target of emissions reduction against a baseline scenario.

Equilibrium

I now describe the equilibrium conditions of the baseline model. Cost minimization and zero profits in the Y sector yield

$$c^Y(w_i, r_i) \geq 1 \quad \perp \quad y_i \geq 0 \tag{5}$$

where y_i is the quantity of good Y produced in economy i. The symbol $\perp$ denotes complementary slackness, i.e., the two inequalities cannot both be slack.

The profit of a single firm in the X sector in country i is expressed by

$$\pi_i = p_i(x_{ii} + x_{ij}) - c^X(w_i, r_i, \tau_i)(f + x_{ii} + x_{ij}) \tag{6}$$

In each economy, profit maximization in the X sector, taking the price index P_i as given, yields

$$p_i\left(1-1/\sigma\right)=c^X\left(w_i,r_i,\tau_i\right) \tag{7}$$

i.e., domestic price of a variety is a constant mark up over the marginal cost of production.

It follows that, in equilibrium, free entry and exit requires

$$f\left(\sigma-1\right)\geq x_{ii}+x_{ij}, \quad \perp \;\; n_i\geq 0 \tag{8}$$

which means that all firms in the X sector in both economies must have the same size. This stems from the specification of a CES utility functions, as a constant elasticity implies a constant markup and hence a constant firm size.

Meanwhile, consumer optimization, taking all prices as given, must satisfy the budget constraints,

$$E_i=e(1,P_i)v_i=w_iL_i+r_iK_i+\tau_iZ_i \tag{9}$$

Note that the budget, or national income, includes the revenue of the emissions tax, as it is assumed to be returned to domestic consumers in lump sum.

The demand for each variety of X are then given by

$$\begin{aligned} x_{ii} &= p_i^{-\sigma}P_i^{\sigma-1}E_iP_ie_P(1,P_i)/e(1,P_i) && (10)\\ x_{ij} &= \gamma p_{ij}^{-\sigma}P_j^{\sigma-1}E_jP_je_P(1,P_j)/e(1,P_j) && (11)\\ &= p_i^{-\sigma}\gamma^{1-\sigma}P_j^{\sigma-1}E_jP_je_P(1,P_j)/e(1,P_j) \end{aligned}$$

where e_P, the derivative of the unit expenditure function with respect to the price index, gives the demand for the composite good X_i^C to obtain unit utility. Let $\xi(P_i) \equiv P_i e_P(1, P_i)/e(1, P_i)$. Then $\xi(P_i)$ is the fraction of expenditure spent on the good X by economy i, which will be a constant if the utility function $u()$ is assumed to take a Cobb-Douglas form.

It follows that the demand for the clean good is

$$y_i^C = (1 - \xi(P_i))E_i \tag{12}$$

Lastly, factor market clearing yields,

$$L_i = y_i c_w^Y(w_i, r_i) + n_i(x_{ii} + x_{ij} + f)c_w^X(w_i, r_i, \tau_i) \tag{13}$$

$$K_i = y_i c_r^Y(w_i, r_i) + n_i(x_{ii} + x_{ij} + f)c_r^X(w_i, r_i, \tau_i) \tag{14}$$

$$Z_i = \begin{cases} n_i(x_{ii} + x_{ij} + f)c_\tau^X(w_i, r_i, \tau_i) & \text{if } \tau_i \text{ is binding} \\ n_i(x_{ii} + x_{ij} + f) & \text{otherwise} \end{cases} \tag{15}$$

where $c_w^Y()$, $c_r^Y()$, $c_w^X()$, $c_r^X()$ and $c_\tau^X()$ are the derivatives of the unit cost functions of the two sectors with respect to the price each factor. Equations (13) and (14) will allow us to pin down the sizes of the two sectors, y_i, n_i, in the respective economies.

A set of 20 equations characterize an equilibrium of the model. These include two of equations (3), (5), (7), (8), (10), (11), (12), (13), (14) and (15), for the North and the South.[3] These equations pin down the following variables: w_N, w_S, r_N, r_S, p_N, p_S, P_N, P_S, x_{NN}, x_{NS}, x_{SS}, x_{SN}, n_N, n_S, y_N^C, y_S^C, y_N, y_S, Z_N, Z_S, taking as given factor endowments K_N, K_S, L_N, L_S, emissions prices τ_N, τ_S, and parameters γ, σ, f. The open-economy equilibrium features both inter-industry and intra-industry trade. The pattern of trade is in part

[3] The one redundant market clearing condition that is not included is the one for the clean good, $y_N^C + y_S^C = y_N + y_S$.

shaped by the Heckscher–Ohlin forces of factor endowment ratios relative to the factor intensity difference in the production of the two goods. They are also affected by the absolute levels of endowments, which determine the market sizes and exert their influence through the product market. A wide range of outcomes in production and trade are possible (see Markusen and Venables (2000) for more details). Nonetheless, the current paper will focus on the case in which the endowments of the two economies are in the diversification set, i.e., neither of the economies is completely specialized in only one sector. This is because I would like to utilize the model to depict the interaction between the developed and the developing countries in reality as two blocs. Empirically we do not observe complete specialization by either of the two groups of countries in more or less emissions-intensive industries. Further, the differences in capital and labor endowment across the two blocs are not too extreme in either relative or absolute levels. In terms of the characterizing equations, the first of the two inequalities in equations (5) and (8) hold with equality, and the equilibrium is an interior one.[4]

The equilibrium conditions can be reduced to a set of equations in only endogenous prices and the model's parameters. Assuming an interior solution, the size of the two sectors can be derived from the factor market clearing conditions (13) and (14), substituting out $x_{ii}+x_{ij}$ using the free entry condition

[4]There are possibilities that conditions (5) and (8) bind with equality in an equilbrium at a corner solution (i.e. with complete specialization), which are limit cases of the interior solutions.

(8).

$$
\begin{aligned}
y_i &= \frac{c_r^X(w_i, r_i, \tau_i)L_i - c_w^X(w_i, r_i, \tau_i)K_i}{c_w^Y(w_i, r_i)c_r^X(w_i, r_i, \tau_i) - c_r^Y(w_i, r_i)c_w^X(w_i, r_i, \tau_i)} & (16) \\
n_i &= n_i(w_i, r_i) = \frac{1}{\sigma f} \frac{c_w^Y(w_i, r_i)K_i - c_r^Y(w_i, r_i)L_i}{c_w^Y(w_i, r_i)c_r^X(w_i, r_i, \tau_i) - c_r^Y(w_i, r_i)c_w^X(w_i, r_i, \tau_i)} & (17)
\end{aligned}
$$

Treating τ_i as an exogenous parameter of the model, these results are exactly the same as those for a Helpman-Krugman model with one differentiated sector. They are similar to those in a standard Heckscher–Ohlin model, except that n_i is scaled by a constant $1/\sigma f$ since it is the measure of firms in the imperfectly competitive X sector and not the quantity of goods in a perfectly competitive sector.

I then use equation (17) to substitute out n_i and n_j in the price indices (3), and use the variety demand equations (10) and (11) to substitute out x_{ii} and x_{ij} in the free entry condition (8). Together with equations (5) and (7) from the optimization in production, there are eight equations (four for each economy) to pin down the endogenous prices. The goods prices p_i and p_j (using equation (7)) and the price indices P_i and P_j (using equation (3)) can be further substituted out of equation (8) to obtain, after simplification,

$$
\begin{aligned}
1 &= \frac{c^X(w_i, r_i, \tau_i)^{-\sigma} E_i \xi(P_i(w_i, r_i, w_j, r_j))}{\sigma f n_i(w_i, r_i) c^X(w_i, r_i, \tau_i)^{1-\sigma} + o f n_j(w_j, r_j) c^X(w_j, r_j, \tau_j)^{1-\sigma}\gamma^{1-\sigma}} & (18) \\
&+ \frac{c^X(w_i, r_i, \tau_i)^{-\sigma} E_j \xi(P_j(w_i, r_i, w_j, r_j))}{\sigma f n_i(w_i, r_i) c^X(w_i, r_i, \tau_i)^{1-\sigma} + o f n_j(w_j, r_j) c^X(w_j, r_j, \tau_j)^{1-\sigma}\gamma^{\sigma-1}}
\end{aligned}
$$

The two terms on the right hand side give the fraction of production for domestic consumption versus that for export (including the lost quantity in transport because of the iceberg trade cost). The four equations, (18) and (5) for each economy, determine the equilibrium factor prices w_N, w_S, r_N and r_S taking as given K_N, K_S, L_N, L_S, τ_N, τ_S, and parameters γ, σ, f.

Policy Scenarios

Using the specified model, I study the equilibrium of the world economy, given the policy choice of the North. The South is assumed to not implement any emissions regulations, i.e., $\tau_S = 0$.[5] In this case, the marginal cost of good X production in the South is

$$c^X(w_S, r_S, 0) = c^F(w_S, r_S) \tag{19}$$

and there is no abatement of potential emissions. Therefore, the amount of emissions in the South is given by

$$Z_S = n_S(x_{SS} + x_{SN} + f) = \sigma f n_S \tag{20}$$

which increases linearly with the size of the X sector in the South. The emissions intensity, i.e., the amount of emissions per unit of production (or provision of the fixed cost) is 1.

The North sets an emissions tax, $\tau_N > 0$, on domestic emissions, Z_N, with the objective of achieving a target level of its domestic emissions or achieving a global emissions reduction against a certain baseline, for instance, the case with no regulations. Available accompanying border measures for the North include a carbon tariff in the form of an ad valorem tariff, t, on the overall value

[5] Presumably, the Southern government may be unwilling to commit to emissions abatement because of political economy concerns or development needs, or it may lack the administrative capacity to effectively pursue any active mitigation policy. The analysis remains essentially the same if a non-binding $\tau_S > 0$ is assumed instead. When a binding $\tau_S > 0$ is assumed, the calculations are slightly more complicated, but results remain similar.

of the imported dirty goods, and a rebate on emissions charges or an export subsidy, s, on the exported dirty goods, also in the ad valorem form.[6] The rates of the tariff and the subsidy are calculated based on the emissions tax τ_N and the emissions content of the dirty good. Once set, they are taken as given by the private firms in the X sector of the two economies, and therefore do not alter the cost functions, except through changes in factor prices in general equilibrium. The tariff has a similar effect on the price of imported goods to the trade cost, while the subsidy's impact is in the other direction, as shown below

$$p_{SN} = p_S\gamma(1+t) \tag{21}$$

$$p_{NS} = p_N\gamma(1-s) \tag{22}$$

which in turn affects the price indices (equation (3)) and the variety demand (equations (10) and (11)). The key difference between implementing the border measures and a change in the trade cost is that the tariff raises government revenue and the subsidy imposes a cost. It is assumed that the tax base of the tariff (and the subsidy) is on the value of the traded goods in the home markets, i.e., $p_S x_{SN}$ for the tariff and $p_N x_{NS}$ for the subsidy. More specifically, this is assuming that the tariff is assessed on the value of delivered imports $p_S\gamma(x_{SN}/\gamma)$ after accounting for the loss due to the iceberg trade cost, while the subsidy is on the value of potential exports $p_N x_{NS}$ prior to the loss of the trade cost. This formulation allows the profit function (6) to remain unchanged.

[6] Since there is no uncertainty, In equilibrium, the ad volerm tariff and subsidy are equivalent to some specific tariff and subsidy.

The North's tariff revenue is

$$T = tn_S p_S x_{SN} \tag{23}$$

which is assumed to be transferred to the South, and further distributed to the Southern consumers. This seems to be an atypical assumption, but it allows the interpretation that the border measures are environmentally motivated, at least at face value, since they are meant to address carbon leakage rather than to accrue tariff revenue for the home economy. In practice, the returned funds may take the form of financial assistance for the South in its adaptation to climate change, which is indeed an integral part of the intended global mechanism to tackle the problem. Hence the South's budget constraint is now

$$E_S = w_S L_S + r_S K_S + tn_S p_S x_{SN} \tag{24}$$

The North's subsidy cost is

$$S = sn_N p_N x_{NS} \tag{25}$$

which is assumed to be financed by the emissions tax revenue collected on domestic firms, which is otherwise returned to the consumers. Nominal income of the North becomes

$$E_N = w_N L_N + r_N K_N + \tau_N Z_N - sn_N p_N x_{NS} \tag{26}$$

Because there is no uncertainty in the model, this set of policy options is equivalent to having a domestic cap-and-trade system on GHG emissions, setting Z_N rather than τ_N, with corresponding border adjustments. Conceptually, requiring imports from non-mitigating countries to have offsetting permits for the embodied emissions is equivalent to a border tariff tied to the level of emissions permit price, which will be endogenously determined by demand from both domestic production and imports. Relieving exports of emissions permits at the border is equivalent to a rebate of emissions tax or an export subsidy. The carbon tax formulation allows the emissions price to remain unchanged with different border measures. It also allows more options in setting the tariff rate. In particular, it may be set by pricing emissions embodied in goods imported at the domestic emissions price, or it may be calculated by pricing carbon using the importer's emissions intensity rather than that of the exporter. The resulting rates may be of similar magnitudes, but the approaches can have different implications on WTO compatibility with respect to the "product" versus "process" issue. Specifically, the North may not be able to levy a different charge on the imported dirty goods simply because they embody more virtual carbon. Therefore, in the simulation exercise, I focus on the case where the carbon tariff is calculated based on the carbon content of the domestically produced dirty good in the North.

To calculate this tariff rate, I equate the ad valorem tariff rate to the ratio of the emissions charge over the marginal cost of the domestically produced dirty good net of the emissions charges. Assuming τ_N is binding,

$$t = \frac{\tau_N c^X_\tau(w_N, r_N, \tau_N)}{c^X(w_N, r_N, \tau_N) - \tau_N c^X_\tau(w_N, r_N, \tau_N)} = \frac{\alpha_X}{1 - \alpha_X} \tag{27}$$

where $\alpha_X = \tau_N c^X_\tau(w_N, r_N, \tau_N)/c^X(w_N, r_N, \tau_N)$ is the cost share of emissions in the dirty good production, which will be a constant when the cost function

$c^X()$ takes a Cobb-Douglas form. Since we have assumed that the fixed cost is associated with the same technology as the variable cost, the tariff rate is equal to the total emissions charges over the total revenue of the domestic dirty good sector. Similarly, the subsidy rate based on domestic emissions intensity will be the same as the cost share of emissions, i.e., $s = \alpha_X$.

If the carbon tariff were set based on the emissions content of the delivered imported dirty good, taking into account the emissions associated with transportation (the iceberg cost) and the fixed cost of production, then the tariff rate would become

$$t' = \frac{\tau_N}{c^X(w_S, r_S, \tau_S)} = \frac{\tau_N}{c^F(w_S, r_S)} \tag{28}$$

as the emissions intensity of the North is 1. Using this configuration will be closer to the cap-and-trade scheme with border adjustment for emissions embodied in imports. When the emissions tax is small to moderate, the carbon tariff rates calculated using importer and exporter emissions intensities are similar in magnitude. When the emissions tax gets large, the difference becomes more pronounced, as the difference in emissions intensity widens.

Another key assumption in the model is that the North cannot directly tax the emissions content of imports, rather it can only do so indirectly through a tariff on the total value of the imported dirty good. The Southern firms view the tariff as based on the value of shipments and not on the emissions content, and therefore do not have any incentive to internalized the cost of emissions in their production process. This is consistent with the idea that, in practice, it is difficult to measure or verify the embodied carbon in imports or distinguish the emissions intensities from different producers. This provides another reason why it is administratively easier to base the carbon tariff on domestic emissions intensity. Given this assumption, the carbon tariff acts like a regular tariff in the eyes of the private sector. The tariff rate is set based on the emissions tax and the carbon content of the dirty good, but the tariff is still a second-best policy to address environmental problems. Therefore, it is not surprising to find that the border measures possess similar properties as other trade policies used to address other issues.

Decomposing Emissions Mitigation and Carbon Leakage

A unilateral initiative to strengthen its climate change policy by the North leads to changes in emissions levels in both economies. These changes resulting from a larger τ_N, with or without accompanying border measures, can be decomposed into two sources: a scale effect, which is tied to the decreased (increased) production of the dirty good in the North (South); and a technology effect, which stems from the fact that the emissions intensity in the Northern dirty sector will drop in response to a high enough emissions tax. These effect are endogenously determined in the equilibrium after the policy change.

When τ_N is small, the emissions tax only works through pecuniary effects. It raises the relative price of the dirty good produced in the North, resulting in lower quantities consumed by both economies. Both the clean good and the dirty good produced in the South are substitutes for the Northern dirty good, and the demand for them will be higher. Hence, while the dirty good production in the North goes down, that in the South increases, leading to carbon leakage. Note that, because of the CES preferences for the varieties of the dirty good and the free entry assumption, in neither the North nor the South do the firm sizes in the dirty sector change. Therefore the adjustment is only on the extensive margin, through changes in the measures of firms, $\Delta n_N < 0$ and $\Delta n_S > 0$. Hence, this is consistent with a story of firms relocating from the North to the South, but the Southern firms do not grow and the remaining Northern firms do not shrink.

The technology channel is only present when the emissions price τ_N is sufficiently large so that it is binding in the firms' optimization problem. In this case, firms are incentivized to use more productive factors to substitute for the emissions in production. In other words, there is indeed abatement of potential emissions. The technology effect can be represented by $1 - c_\tau^X(w_N, r_N, \tau_N)$ where 1 is the emissions intensity without abatement and that with active abatement is given by the partial derivative of the marginal cost function for the dirty good with respect to the emissions price. Both the scale and the technology effects become stronger as the size of the emissions tax increases, as shown by the simulation analysis.

The decrease in emissions in the North, $-\Delta Z_N$ can be decomposed into the two aforementioned effects. An additive decomposition, similar to the Paasche or Laspeyres indices, yields

$$-\Delta Z_N = \sigma f(-\Delta n_N) + \sigma f n'_N(1 - c_\tau^X(w_N, r_N, \tau_N)) \tag{29}$$

where n'_N is the measure of the Northern dirty good varieties after the policy change. The first term is the change due to the scale effect, holding emissions intensity constant at 1, and the second term is the additional change due to the technology effect.[7] Dividing equation (29) by $-\Delta Z_N$ will give the effect in

[7] Note that the weight on the scale effect, 1, is the emissions intensity in the pre-period, while the weight on the technology effect, $\sigma f n'_N$, is the size of the dirty good sector in the post-period. Therefore, in this formulation, the term for the scale effect will include the residual term in the Paasche index decomposition, while the term for the technology effect

fractions, which are reported in the simulation analysis.

The size of the carbon leakage in the model is simply $\Delta Z_S = \sigma f \Delta n_S$, which varies proportionally with the change in the size of the dirty good sector in the South. To the extent that a larger emissions tax shifts demand to the Southern dirty goods through a substitution effect, it increases the level of carbon leakage. However, raising emissions tax is equivalent to reducing the emissions endowment and therefore lowers the national income of the North, lowering its demand for imported Southern goods. This income effect may potentially reduce carbon leakage. Additionally, there is a terms of trade effect that will depend on the patterns of trade. In particular, if the North is a net exporter of the dirty good, a small increase in τ_N will improve its terms of trade by making its exports, the Northern dirty good, relatively more expensive than its imports, the Southern dirty good as well as the clean good, increasing the export demand for the Southern dirty good. With higher and higher emissions tax, the North will eventually become a net importer of the dirty good, and the terms of trade effect will turn to the opposite direction. Though not shown analytically, the simulation analysis suggests that the first effect dominates and the higher the emissions tax, the larger the size of carbon leakage.

An accompanying carbon tariff to the emissions tax lowers the export demand for the dirty good produced in the South, resulting in a lower pre-tariff price and a smaller size of the sector, thereby reversing some of the

will include the residual term following a Laspeyres index decomposition. Either way, this decomposition tends to understate the contribution of the technology effect as both weights, the emissions intensity and the size of the dirty good sector, are smaller in the post-period. There are many decomposition methods available (see Wang (2015) for a brief discussion of the various methods). This particular decomposition method chosen here gives natural meanings for the decomposed terms.

carbon leakage. The tariff also generates the income effect and the terms of trade effect considered above. Further the transfer of the tariff revenue alters the demand structure as well. Since there are only a few meaningful ways of setting the tariff rate given the emissions tax, I will not explore the effect of varying levels of carbon tariff on carbon leakage. However, as shown in the next section, the effect of an increase in carbon tariff is qualitatively similar to that of an increase in trade cost.

In line with the scale and technology effects discussed above, total carbon leakage can be decomposed into two parts,

$$\sigma f \Delta n_S = \sigma f \Delta n_S c_\tau^X(w_N, r_N, \tau_N) + \sigma f \Delta n_S (1 - c_\tau^X(w_N, r_N, \tau_N)) \tag{30}$$

where the first term represents the scale effect, i.e., the emissions that would have happened in the North if the dirty good production relocated to the South had stayed in the North with the new less emissions-intensive technology, and the second term is the technology effect, i.e., the further increased emissions as a result of relocation due to the South employing a more emissions-intensive technology. Dividing the equation by the level of leakage, a decomposition in the scale and technology effects is obtained.

$$1 = c_\tau^X(w_N, r_N, \tau_N) + (1 - c_\tau^X(w_N, r_N, \tau_N)) \tag{31}$$

The scale effect is simply the emissions intensity in the North after the policy change, and the technology effect is the difference in emissions intensities across the two economies.

The two decompositions of the Northern emissions change and the carbon leakage, or the Southern emissions change, are not directly comparable. This is because there is inherently no technology change in the South and the decomposition of the leakage level essentially investigates the changes in the North's emissions intensity. Nonetheless, the respective decompositions can be compared across different scenarios to review the relative importance of the scale and technology effects.

The rate of carbon leakage is defined as the increase in the Southern emissions, ΔZ_S, as a fraction of the decrease in the Northern emissions, $-\Delta Z_N$, as a result of the North strengthening its climate change policy. The rate of leakage does not vary proportionally with the magnitude of the emissions tax. As explained previously, with a small τ_N, all adjustment of the economy is through reallocation and no abatement occurs, therefore the leakage rate is fairly high. The rate goes down as the Northern dirty sector starts to adjust more through technological adaptation rather than relocation. Eventually, the technological difference between the two economies is so high that any relocation means disproportionally high leakage, and the leakage rate will level off and begin to increase with higher emissions tax.

Since carbon leakage is a central concern with unilateral mitigation policies, I will explore a number of key factors that may affect the level and the rate of leakage. The next section provides a brief theoretical discussion and the simulation analysis that follows will report the calculated values in various scenarios.

Home Bias and Carbon Leakage

The reason for using a simulation analysis is that an analytical solution of the model cannot be derived due to the presence of the trade cost. It is nonetheless important to include the trade cost in the model for policy analysis, as the carbon tariff and the export subsidy both enter the model in a similar fashion as the trade cost, affecting prices in equilibrium. The additional impact is the change in income due to the tariff revenue or subsidy cost shown in equations (24) and (26).

Since trade is costly, diversification does not necessarily imply FPE. The positive trade cost creates a trade-off for the firms in the X sector between locating in the economy with a higher demand versus locating in the economy with a lower cost of production, as a firm's sales are skewed towards the market where it is located in. This can be seen in the following derivation from equations (10), (11) and (3),[8]

$$\begin{aligned} \frac{x_{ii}}{x_{ij}} &= \frac{E_i \xi(P_i)}{E_j \xi(P_j)} \frac{P_i^{\sigma-1}}{\gamma^{1-\sigma} P_j^{\sigma-1}} \\ &= \frac{E_i \xi(P_i)}{E_j \xi(P_j)} \left(\frac{1 + (n_j/n_i)(p_j/p_i)^{1-\sigma} \gamma^{\sigma-1}}{1 + (n_j/n_i)(p_j/p_i)^{1-\sigma} \gamma^{1-\sigma}} \right) \end{aligned} \tag{32}$$

which is greater than $E_i \xi(P_i) / (E_j \xi(P_j))$, the relative market size of the home versus the foreign economies, as long as $\gamma > 1$. If the economies are symmetric, then absent regulations, $x_{ii}/x_{ij} > 1$ whenever there is a positive trade cost. Therefore relocating an X-sector firm affects both the factor demand and the supply of output in each economy. This is the home market effect shown by Krugman (1980) and others, but from the perspective of the firms with respect to home and export demands. Equation (32) shows that the magnitude of the trade cost is an important factor that helps determine the size of the carbon leakage. To the extent that a higher trade cost biases the firms' sales more

[8] Alternatively, a similar expression with marginal costs rather than prices can be derived taking the ratio of the two terms on the right hand side of equation (18).

toward the home market, it also dampens the incentive for them to relocate in the event of a strengthening of the climate policy in the home economy. Since a carbon tariff takes a form similar to an increase in trade cost, albeit for only the Southern firms, it strengthens the home market bias and reverses some of the carbon leakage from the initial unilateral policy change. On the other hand, the export subsidy works differently by increasing export demand for the Northern dirty good.

Apparent from equation (32), a second factor that affects the leakage is the relative size of the two economies. If the North is larger than the South, i.e., it has more endowment of the productive factors, then it will have a higher income, i.e., E_N/E_S is larger. Therefore the potential market for the dirty good varieties will be larger in the North, contributing to stronger home bias for the Northern firms. In equilibrium, a larger economy tends to have a larger dirty good sector, provided that the relative endowment is not too skewed. It can be seen from equation (17) that a proportionally larger endowment in both capital and labor will likely result in the economy expanding in both sectors.

In addition to the level of the endowments, the relative endowment ratios of the two economies also play an important role in shaping the production arrangements of the dirty good. If the two sectors have different factor intensities as in a typical Heckscher-Ohlin model, then the varying endowment ratios will drive comparative advantage. The model has assumed that the dirty good X is relatively more capital intensive than the clean good Y,

$$\frac{c_r^Y(w_i, r_i)}{c_w^Y(w_i, r_i)} < \frac{c_r^X(w_i, r_i, \tau_i)}{c_w^X(w_i, r_i, \tau_i)} = \frac{c_r^F(w_i, r_i)}{c_w^F(w_i, r_i)} \tag{33}$$

for any set of factor prices. Therefore if the North is relatively abundant in capital, i.e.,

$$\frac{K_N}{L_N} > \frac{K_S}{L_S} \tag{34}$$

then the Heckscher-Ohlin forces of its comparative advantage in the dirty good sector will offset its comparative disadvantage generated by a higher cost of emissions.

Another parameter that appears in equation (32) is σ, the elasticity of substitution between the different varieties of the differentiated dirty good. A larger σ implies that the varieties are closer substitutes to each other, therefore lowers the gains from consuming more varieties. Hence a large σ magnifies the effect of the trade cost. Lastly, the weights in the CES preferences can also make a difference. If the utility function specifically includes a larger weight on the consumption of the domestic varieties, then it strengthens the home bias.

Note that equation (32) contains various endogenous variables on the right hand side. Therefore the discussion above is not based on robust comparative static analysis. Rather, it provides some conjectures based on intuition, which are illustrated in the simulation exercise that follows.

Limitations of the Model

It is worth clarifying a few issues before proceeding with the analysis. First, the model does not address any dynamic issues with respect to climate change or economic growth. Since it is a static model, the equilibrium result is best viewed as a projection of a long-term equilibrium after new regulations are introduced. It takes time for the private economy to adjust to any new policy, and the transition period is certainly important for the climate change problem, which is time sensitive. Nonetheless, the results in this paper do not address the transition path. Meanwhile, growth of the economies is also not modelled. In reality, differing growth rates of the respective economies can have important implications for the results in the long run. The results can be viewed as assuming that the two economies, and their respective productive factors, grow at the same rate.

Further, there are two important omissions in the model, the supply-side channels of carbon leakage illustrated in Sinn (2008) and technological advances studied by Acemoglu and coauthors (2012). The emissions in the model are supplied elastically at a certain price at τ_i. In reality, most of the carbon emissions are from the use of fossil fuel energy, the supply of which can be quite inelastic. Therefore, the lower demand for fossil fuels by the economy that implements a more stringent climate policy can lower their prices, encouraging the non-mitigating economy to consume more fossil fuels, leading to even higher emissions. In the extreme case of perfectly inelastic supply, the carbon leakage rate will be above 100% as there is no reduction in consumption of fossil fuels and the economies that use more are likely those with more emissions-intensive technologies. Speaking of technologies, the technological differences discussed in the model of this paper only refers to the different factor mixes in production in response to changes in factor prices. The underlying production and abatement functions are the same for each economy. In general, there are also other sources of technology differences.

Lastly, the policy options discussed here certainly are not exhaustive. There are many potentially fruitful alternative policies, including consumption based caps, directed or assisted technological diffusion, carbon labeling as well as helping developing countries strengthen their domestic institutions to achieve the maximum potential of existing policies. These are all worth studying in future research.

IV. Simulation

Since the model cannot be solved analytically, I simulate the model with simple functional forms and canonical parameters to analyze potential effects of an emissions tax with accompanying carbon-motivated border adjustment under certain scenarios. The numerically solved results are not meant to be a characterization or prediction of reality. Rather, it is the qualitative features of the results that may shed light on practical issues.

Functional Forms and Parameters

For simplicity, I use a Cobb-Douglas specification of the utility and production functions for the current simulation,

$$e(1,P) = P^{\xi} \tag{35}$$

$$C^Y(w,r) = (r/\alpha_Y)^{\alpha_Y}(w/(1-\alpha_Y))^{1-\alpha_Y} \tag{36}$$

$$C^F(w,r) = (r/\alpha_F)^{\alpha_F}(w/(1-\alpha_F))^{1-\alpha_F} \tag{37}$$

$$C^X(w,r,\tau) = (\tau/\alpha_X)^{\alpha_X}(c^F(w,r)/(1-\alpha_X))^{1-\alpha_X} \tag{38}$$

The Cobb-Douglas form allows an easy interpretation of the choice of modelling emissions as an input. As shown in Appendix A, it is equivalent to modelling emissions as a by-product which can then be abated using a particular technology. However, it is noted that the Cobb-Douglas formulation limits the elasticities of substitution between the productive factors to 1. The cost share on each factor is fixed, leading to corresponding changes in factor mix when relative factor prices change. If the factors are more substitutable in production, for instance with a CES technology with an elasticity larger than 1, then the effect of a higher emissions tax on emissions intensity or factor mix will be magnified as production shifts more toward using other factors. A larger emissions tax will lead to more abatement, i.e., a smaller emissions intensity in production, compared to the case with unit elasticity. On the other hand, a smaller elasticity of substitution in production will result in smaller abatement for a given emissions tax. In the extreme case of Leontief technology, there is no room for abatement.

I use the following set of parameters for the simulation:

$$\xi = 1/2; \ \ \sigma = 5; \ \ \ f = 1/4; \ \ \gamma = 1.2;$$

$$\alpha_Y = 1/3; \ \ \ \alpha_F = 2/3; \ \ \ \alpha_X = 1/10.$$

The expenditure share, ξ, on emission-intensive goods is assumed to be a half, representing an equal importance of the dirty good and the clean good in private consumption. Using a different value for ξ will scale the size of the dirty good sector relative to the overall economy, but will not alter results qualitatively. The CES elasticity of substitution $\sigma = 5$ is within the reasonable range suggested by Broda and Weistein (2006), and is often used in the literature. This implies that markup will be constant at $\sigma/(\sigma - 1) = 1.25$. The effect of different values of σ will be explored in the sensitivity analysis. The fixed cost f, is then chosen such that the output of each variety $(x_{ii} + x_{ij}) = f(\sigma - 1)$ is equal to 1, and therefore x_{ii} and x_{ij} can be interpreted as the share of the firm's output for domestic consumption and export respectively. A larger fixed cost will increase the size of the X sector firms and reduce the measure of varieties in equilibrium, leading to higher price indices. Again, it will not change the results qualitatively. The iceberg trade cost $\gamma = 1.2$, meaning that 20% more needs to be shipped in order to deliver one unit across borders. This value is larger than the transportation cost reported by Hummels (2007), but in line with the estimates of these costs given by Anderson and van Wincoop (2004)[9] after factoring in the time value of goods in transit. The 20% number is used as a benchmark in the analysis and the sensitivity analysis will explore the impact of changes in γ. The coefficients in the Cobb-Douglas production technology are chosen so that the dirty good sector is relatively capital intensive than the clean good sector. Emissions abatement costs or the emissions tax charges are assumed to account for 10 percent of the total production cost when the emissions tax is binding.

Symmetric Economies

I first present the simulation results with ex ante symmetric economies. The factor endowments are set as

$$K_S = L_S = K_N = L_N = 1.$$

Without any regulations, the model is equivalent to a Helpman-Krugman model with trade costs. In this case, there is a symmetric equilibrium with FPE. All trade that takes place in the equilibrium is intra-industry in the

[9] For the overall trade cost, the estimate by Anderson and van Wincoop (2004) is much higher. The "representative" trade costs for industrialized countries is 170%, with 21% transportation costs, 44% border-related trade barriers, and 55% retail and wholesale distribution costs.

X sector. Given the particular set of parameters and endowments, the ratio of production for domestic consumption to export is $\gamma^{\sigma-1}$, reaffirming the previous discussion that higher trade cost leads to more pronounced home bias. Other variables can be obtained using the equilibrium equations. This symmetric equilibrium will be used as the benchmark for comparison for the following set of simulations with the same parameters and endowments, but varying policy arrangements. The results of various numerical solutions are presented as changes against the baseline variables.

Low Carbon Tax.—The first set of results, shown in Table 1 and in Figure 1, reflect a series of scenarios starting with the North setting a domestic emissions tax, τ_N, aimed at reducing its national emissions by 30% against the baseline level. The specific tax is solved to be 0.1148, which is equivalent to 11.48% of the marginal cost of producing the dirty good prior to the policy change. Since this is larger than $\alpha_X/(1-\alpha_X)$, the emissions tax will be binding in equilibrium. On the other hand, it represents only a small increase in the effective price of GHG emissions,[10] i.e., to achieve the 30% reduction in domestic emissions, only a small carbon tax is needed. By specification of the production technology, the emissions charges represent 10% of the domestic production cost of the dirty good X in equilibrium.

Columns (a) and (b) in the table give the changes of various regional and global variables from the baseline case when only the emissions tax is implemented, with no border adjustment. These changes are represented by the blue bars in the figure. Compared to the equilibrium without government interventions, the overall environmental effect is fairly small at just below a

[10] Without emissions charges, the marginal product of GHG emissions is still positive given the particular set-up. See Appendix A for more detail.

6% reduction of emissions globally, considering that the domestic mitigation is targeted at 30%. This is a result of substantial carbon leakage, at a rate of about 60%. The decomposition of carbon leakage following equation (31) shows that it is mostly attributed to the scale effect, i.e., due to a shift of dirty good production from the North to the South. The emissions tax gives the North a comparative advantage in the clean good and the South a comparative advantage in the dirty good. Hence the economies move away from the symmetric equilibrium toward specialization in the respective sectors. Since the economies are ex ante the same and the emissions tax is not high, the specialization is moderate. The North produces just below 40% of the world's dirty good and about 60% of the clean good. This also means that the Northern emissions intensity only goes down by a small amount.

As expected, the policy raises the relative price of the dirty good in both regions, raises the wage and reduces the rental rate domestically and has the opposite effect in the South. Because of the increase in prices, the changes in the real wage and the real rental rate are more negative (or less positive) than those in the nominal ones. The policy has significant distribution effects, reducing the real compensation for capital in the North by more than 14%, while the impact on the Northern real wage is relatively small and positive. The changes in the real compensation in the South are less dramatic, but the gap between the two factors is of about the same size. This pattern of welfare implications can be understood in the context of the classic Heckscher-Ohlin framework. The higher price for the Southern dirty good benefits the owners of capital in the South as dirty good production is relatively capital intensive. In the North, however, the situation is the opposite as the price of the dirty good that the firms receive net of the emissions charge is actually lower than before. To see this, note that the price of each variety of the dirty good goes up by less than 8%, the ratio of emissions charges to price in equilibrium.[11] Alternatively, the emissions tax reduces the supply of emissions in the North, which hurts the dirty sector that uses it as a factor. Since capital is used relatively more in this sector, it loses as a result. The overall welfare in the North, not including any environmental benefits, represented by its real income, is down by 2.4%, while that in the South is up by about 0.7%. These numbers are smaller in magnitude than those for the individual factors. Beside the effect of aggregation, another reason is that the North also has additional income in the form of the emissions tax revenue.

Columns (c) and (d) give the results if the same domestic carbon tax is accompanied by a carbon tariff based on importer emissions intensity. The changes are illustrated with the red bars in the chart. This border adjustment takes the form of an ad valorem tariff on imported dirty goods. The rate of 11.11% is calculated following equation (27). As discussed before, because the tariff is imposed on units or values of imported goods rather than on the embodied emissions directly, it acts like a regular tariff. The main effect is through an increase in the dirty good price in the North and a decrease of that in the South. The change in relative prices dampens some of the welfare effects of the emissions tax, so that real compensation adjusts partially to the opposite direction. At the same time, the tariff limits trade, leading the dirty-sector firms in both economies to shift sales from export to domestic markets. This illustrates the strengthening of home bias similar to that brought by an increase in the trade cost. The real wage in the North falls below the baseline

[11] In equilibrium, when the emissions tax is binding, the ratio of the marginal emissions cost to the price of the dirty good is $\tau_N c_\tau^X/(\sigma/(\sigma-1)c^X) = a_X(\sigma-1)/\sigma$, which is 8% with the current set of parameters.

level due to higher prices. The overall welfare in the North is down slightly, by just above 0.2 percentage point. On the other hand, the South's real income goes up by about 0.4%. The South loses as its terms of trade worsens but is compensated by the returned tariff revenue from the North. The overall environmental effect is about the same as the case with no adjustment, while the carbon leakage rate is down by about a third to around 40%. Hence, even though the leakage situation is modestly improved, the net environmental result is no more desirable. The leakage is still predominantly attributed to the scale effect, but less so because the tariff discourages the relocation of dirty good production and consequently there is a rebound in emissions intensity in the North. For completeness, I report the results when the carbon tariff is based on exporter emissions intensity in columns (e) and (f). Following equation (28), the ad valorem rate is 11.26%, which is very close to that based on importer intensities. Not surprisingly, all effects are similar to the previous case. This configuration is omitted from the comparison chart in Figure 1.

Columns (g) and (h) report the case with an export subsidy, the results of which are shown as green bars in the chart. The ad valorem subsidy rate is 10%, equal to the emissions cost share of domestic dirty good production. The individual factor welfare implications are similar to those in the case with a tariff, as the subsidy results in a similar increase in the dirty good price in the North and a decrease of that in the South. However, instead of limiting trade, the subsidy encourages trade, making firms in both economies sell more in the export market compared to the baseline as well as to the case with only emissions tax. Rather than collecting the returned tariff revenue, the South benefits as the Northern subsidy lowers the price of its imports which lowers the price index in the South. In this case, the emissions reduction is even less at about 4%, as the subsidy does not limit the dirty good production in the South as much as the tariff while it encourages Northern production even more. Consequently, the leakage rate, at 54%, is only down by about one tenth relative to the case with no border adjustment. Note that the real incomes in both economies are higher than the no adjustment case, but at the cost of a worse environmental outcome.

The last two columns (i) and (j) show the results for a full border adjustment with a carbon tariff and an export subsidy, both based on Northern intensities. The changes in variables are illustrated by the purple bars in Figure 1. The diverging effect on the dirty good prices is even stronger as the tariff and the subsidy combine to exert influence. The impact on the real compensation in the South due to the emissions tax is almost offset entirely as the price and the price index of the dirty good in the South return to about the baseline level. The South's real income is higher than the baseline due in part to the returned tariff revenue. In the North, both the wage and the rental rate get back closer to the baseline levels, as the border measures help revert the unequal impacts on the returns to capital and labor. Both factors nonetheless lose because of the higher price of the domestically produced dirty good. Both border measures reduce carbon leakage by themselves. It is therefore not surprising that when combined, they deliver an even smaller carbon leakage rate. In fact, there is actually negative carbon leakage in this case as the Southern dirty good sector shrinks slightly, resulting in lower emissions in the South relative to the baseline. However, the arrangement is far from being environmentally friendly, as there is only about 4% overall emissions reduction, similar to that with the subsidy only. Therefore, focusing exclusively on emissions leakage rates might be misleading.

To summarize, in the case of a small carbon tax with symmetric economies, border measures do not seem appealing from the perspectives of the environment or the overall welfare. Both the tariff and the subsidy reduce the rate of carbon leakage, but also lead to higher world emissions. The tariff further reduces the North's real income. While the subsidy improves the North's real income (by about 0.13%), it reverts about a quarter of the emissions reduction due to the emissions tax. On the other hand, these border measures can be used as redistribution policies, aiming at reverting the differential welfare impact of the emissions tax across the owners of different productive factors.

High Carbon Tax.—The next set of simulations, presented in Table 2 and Figure 2, assume that the Northern government initially implements a policy that attempts to reduce the global emissions by 15% against its baseline level. If there were no leakage possibilities, this would be equivalent to reducing its domestic emissions by 30%. As it turns out, achieving this global target requires the North to remove almost all of its emissions after factoring in the resulting leakage. The corresponding emissions tax level is $\tau = 2.4187$, or over 240% of the marginal cost of the dirty good production prior the emissions tax, more than 20 times higher than in the previous set of simulations.

As before, columns (a) and (b) give the changes of various regional and global variables from the same baseline case as a result of the emissions tax. Because of the much more stringent policy, the environmental and economic impacts are of much larger magnitudes, though qualitatively they are in the same direction as in the previous case. Note that the comparison chart now has a much wider range on the axes. The overall environmental impact is by design a 15% reduction in the global emissions, over 150% more than that in the previous case. The North's emissions are down by 99.8% from the symmetric equilibrium without an emissions tax, while there is about a 70% increase in the South, resulting in a carbon leakage rate of about 70%. Both the level and the rate of leakage are higher than those in the case with a low emissions tax. The large environmental impact comes with significant adjustment in the private sector. The North's dirty good sector is shell of its former self, accounting for only about 2% of the world's dirty good production compared to 50% prior the emissions tax, while its clean good production represents about 89% of the world total. In addition to the dramatic decrease in scale, the Northern dirty good sector operates with an emissions intensity that is about 5% of its pre-policy levels, meaning that most of the potential emissions are abated. The very high carbon tax has shifted the comparative advantage structure of the two economies from the ex ante symmetric situation to one where the South possesses a very strong comparative advantage in the dirty good production, so that the economies move to a high degree of specialization, though both are still incompletely specialized. World trade moves from all intra-industry to about 50-50 with respect to intra- versus inter-industry trade. The sales of the traded dirty good represent just above 50% of the total value of all traded goods. Similarly, the effects on prices for factors and goods are large, creating a large disparity between the real returns to different factors. The real national income of the North is more than 19% lower than the baseline level, largely due to the increase in prices. The South's real income, on the other hand, experiences a sizable increase.

A review of the information presented in the rest of Table 2 and Figure 2 suggests that the effects of border measures based on importer emissions intensity on prices and nominal and real factor compensation are in the same direction as in the case with a low emissions tax. They raise the real rental rate and lower the real wage in the North and have the opposite effects in the South, partially offsetting the diverging effects on real factor compensation of the emissions tax. The sizes of these effects are also similar to those presented before in terms of percentage changes relative to the case with only an emissions tax. As for overall economic welfare, the carbon tariff still lowers the real income of the North and increases that of the South. The export subsidy, contrary to the previous case, raises the real income in the North and lowers that in the South. This is because the Northern dirty sector, and hence its exports, are so small that the benefit the South accrues through the export subsidy does not offset the adverse effects due to changes in prices. These effects are still small in magnitude, with the changes relative to the case with no border adjustment less than 2%.

Unlike the case with a low carbon tax, the environmental outcome is better with the adoption of a carbon tariff or export subsidy. This is because the border measures encourage production of the dirty good in the North and discourage its production in the South. With a high emissions tax, the production technology of the dirty good in the North is substantially cleaner, or less emissions intensive, than that in the South. Therefore the increase in the Northern emissions is more than offset by the reduction in the North's emissions, resulting in lower world emissions. All these border measures also lower the carbon leakage rate, with the carbon tariff more effective than the export subsidy in this regard.

The case with a carbon tariff based on exporter intensity is again included in the table. This time, with the large emissions tax, the corresponding ad valorem tariff rate is 244.45%, much larger than the rate based on importer intensity. This tariff limits the Southern exports so much that it leads to a shrinking of the South's dirty good sector, resulting in negative carbon leakage. The real income in the South also becomes smaller than the baseline no-regulation case and the real income in the North goes down further. In return, this delivers the best environmental outcome, with the global emissions down by almost a half relative to the baseline.

In summary, this set of simulations show that, with a sufficiently large carbon tax, an accompanying carbon tariff or export subsidy can reduce the rate of carbon leakage as well as the global emissions, thanks to the substantial difference in the emissions intensities of the dirty good production between the two economies. The positive environmental impact can be sizable while the negative effects on domestic and foreign welfare are relatively small. The border measures do help alleviate the changes in factor compensation, which could be important for distribution and political economy considerations. This suggests that border measures are justifiable with a very high emissions tax. However, the extremely high emissions tax makes this an unlikely scenario in the real world.

Asymmetric Economies

In the initial simulations, the North and the South are assumed to be ex ante identical and only differ in policy choices. In reality, if we consider the developed economies versus the developing ones, they are obviously vastly different in many aspects, including in absolute and relative endowments. Here I consider two asymmetric cases that explore these respective dimensions.

The first asymmetric case involves the North being proportionally larger than the South. According to the national accounts data from the World Bank (2015), the share of the developed countries' GDP (in current dollars) as a fraction of the world total ranges between 60% to two thirds in 2013, depending on the exact classification of countries. For simplicity, I assume that the North is twice as large as the South in terms of endowments,

$$K_S = 1; L_S = 1; \;\; K_N = 2; L_N = 2.$$

The relative factor endowment ratio is the same across the two economies. In the baseline equilibrium without an emissions tax, the North's nominal income is about 67% of the world's total, matching empirical data fairly closely.

The second asymmetric case focuses on the relative endowment ratio. Using data from the most recent Penn World Table (Feenstra, et. al., 2015), I find that the relative ratio of the capital stock per capita in the developed countries to that in the developing countries is about 6. In the simulations, I use the following endowment structure,

$$K_S = 1; L_S = 2; \;\; K_N = 2; L_N = 1,$$

which yields a relative endowment ratio of 4.[12] In equilibrium, the North's nominal income is 98% of the South's, so the economies are of about the same size.

In both of these cases, the endowments are outside of the FPE set. The model without regulations (and ignoring the emissions) is a Helpman-Krugman model with trade costs. Markusen and Venables (2000) show that with $\gamma > 1$, the FPE set is one dimensional. Given total endowments of the world, the FPE

[12] In order to match the ratio of 6 exactly, I could have used $L_S = K_N = \sqrt{6}$. However, it turns out that the endowment ratios would be so different that it would lead to complete specialization in the baseline no-regulation equilibrium in the model. The simulation results would remain qualitatively similar.

line goes through the midpoint of the endowment box and has a slope dL/dK smaller than the ratio of world endowment in the two factors. When the trade cost becomes large, i.e., $\gamma \to \infty$, the FPE set approaches the diagonal of the endowment box, as in autarky, FPE only occurs with the economies having the same endowment ratio. Therefore, the first set of asymmetric endowments is only compatible with FPE if the trade cost is prohibitive. As the trade cost decreases, i.e., $\gamma \to 1$, the slope of the FPE line decreases and eventually becomes negative. With a smaller trade cost, it is easier for the dirty good sector to be drawn into the larger economy, so FPE is possible only if the two markets are of very similar size. It can be verified that the second set of asymmetric endowments is only compatible with FPE if there is free trade in the dirty good.

With proportionally larger factor endowments, the North will have a larger market for the dirty good. With a relatively abundant endowment of capital, the North will have a comparative advantage in producing the dirty good. Therefore in both of these asymmetric cases, the North attracts a larger dirty good sector in equilibrium. Prior to the policy change, it hosts about 70% of the world's dirty good production in the first case and 95% in the second case. The larger market size and the comparative advantage based on differential factor endowment ratios will help offset the cost disadvantage created by the emissions tax, thereby alleviating the problem of carbon leakage and resulting in a larger global reduction in emissions. Intuitively, since the majority of the initial emissions occur within its boundaries, it is easier for the North to achieve global emissions targets using unilateral policies as these policies will cover a larger portion of all the emissions directly.

Tables 3 and 4 and Figures 3 and 4 present the simulation results for the two asymmetric cases respectively, following the same scheme as the previous cases. The initial policy scenario is that the North sets a domestic carbon tax aiming to reduce its national emissions by 30% against the baseline level. The specific emissions tax is 0.1269 in the first case and 0.1263 in the second. These are higher than the low emissions tax in the symmetric simulations but still quite modest. Now that the North is more attractive to the dirty sector, it takes a higher level of carbon tax to achieve the same national emissions target, because it requires a larger incentive to drive any dirty good production away from the North. The moderate emissions tax leads to greater changes in factor intensity in the dirty good production compared to the low-tax symmetric case, resulting in a more prominent role for the scale effect in determining changes in the emissions levels. The reduction in the global emissions is more than that in the symmetric case, and the carbon leakage rate is significantly lower.

Economically, the effects of the emissions tax remain similar in both direction and magnitude to the symmetric case with a low emissions tax. There are only two exceptions. With asymmetric sizes, the impact on the Northern real wage is negative; and with asymmetric endowment ratios, the impact on the South's real income is negative. Both are likely due to the North hosting a majority of the world's dirty good production, allowing the increase in the Northern price to lead to a large increase in the Southern price index of the dirty good.

When border measures are implemented together with the emissions tax, they bring similar distributional effects, raising the real rental rate and lowering the real wage in the North while having the opposite effects in the South, relative to the case with the emissions tax only. With respect to the environmental outcomes, they all reduce the rate of carbon leakage at all times.

In the case of asymmetric sizes, a carbon tariff actually reduces world emissions relative to that with no border adjustment. In the case of asymmetric endowment ratios, the tariff increases the global emissions slightly. An export subsidy leads to a rebound of world emissions by a larger margin in both cases.

These simulations results suggest that in these particular asymmetric situations, it may be worthwhile for the North to adopt a carbon tariff. It either reduces the global emissions slightly more with a small additional cost in terms of the North's real income (with asymmetric sizes), or raises the North's real income with a slight increase in world emissions (with asymmetric endowment ratios). This is likely due to the fact that the North still hosts the majority of the world's dirty good production even with the emissions tax. The damage of the high prices is offset by the benefit to the domestic dirty good sector, or the improvement in its terms of trade. Meanwhile, since the North is employing appreciably cleaner technology in its dirty good production, with emissions intensity at about 80% to 90% of that in the South, the increase in emissions due to a rebound of the Northern dirty sector is likely to be offset by the corresponding decrease in the South, leaving the global emissions levels little changed. An export subsidy, on the hand, worsens the environmental outcome and lowers the real income of the North.

Sensitivity Analysis

The four set of simulations suggest that the economic and environmental impacts of the emissions tax and the accompanying border adjustment could potentially vary in different situations. The unilateral emissions tax tends to be more effective in reducing emissions when the dirty good sector is predominantly located in the mitigating economy. The border measures, particularly the carbon tariff, make sense environmentally and economically for the North either when the emissions tax is very high or when it hosts the majority of the world's dirty good production.

Like other simulation exercises, the results, even qualitative ones, often depend on model selection and parameter choices. To further explore the determinants of the economic and environmental effects in the current model, I explore different choices of a number of parameters. As discussed previously, a key consideration with respect to the carbon leakage is the home bias in the dirty good provision, as illustrated in equation (32). The key variables or parameters to consider include the emissions tax, τ_N, the trade cost, γ, the elasticity of substitution between varieties of the dirty good, σ, and the relative size and the relative endowment ratio of the economies.

Emissions tax.—The stringency of the carbon tax has important impacts on the size and rate of carbon leakage. Figure 5 summarizes the changes in key variables of interest when τ_N varies, holding the other parameters and the endowments constant at the values used in the previous simulations. The first column of graphs corresponds to the case with symmetric economies and the other two columns present the asymmetric cases.

Note that initially, the very low emissions tax is not binding and only affects the economy through changes in prices, while the technology effect kicks in when the tax is higher. Therefore there exists a kink at just above $\tau_N = 0.1$ for all the series. I first look at the effect of the stand-alone emissions tax, represented by the blue line in the graphs. In all three configurations of the factor endowments, an increase in the size of the carbon tax lowers the global emissions when the tax is low; however, when the tax is sufficiently high, a further increase will lead to less mitigation. An increase in the tax has two opposing effects. It lowers the domestic emissions by reducing the dirty good production and inducing a cleaner factor mix; meanwhile it raises the foreign emissions as the dirty good production relocates across borders. Initially, the first effect dominates because the impact on domestic sector size tends to be larger than that on foreign sector size and the emissions intensities are similar. Eventually, the gap in emissions intensities in the two economies is so wide that an increase in sector size in the South will result in a much larger movement in the emissions level than a similar-sized change in the North. Therefore the second effect dominates. For the same reason, an increase in the magnitude of the emissions tax initially lowers the carbon leakage ratio but eventually the effect turns in the other direction. This inflection happens earlier than that for the global emissions levels, as it measures the ratio, rather than the sum, of the two effects.

With respect to welfare, a larger emissions tax tends to reduce the real income of the home country in most situations. When the emissions tax is binding, an increase in the tax is equivalent to a decrease in the endowment of emissions for production, and therefore lowers national welfare. The exception is in the case of asymmetric endowment ratios, before the emissions tax binds. A non-binding emissions tax changes relative prices, but does not alter production optimization directly. As previously mentioned, with the particular specification with a relative endowment ratio of 4, the economies are very close to complete specialization. In this situation, the change in relative prices creates an improvement in the terms of trade for the North, which more than offsets any negative effect on welfare through higher prices. As for the South, its real income increases with an increase in the Northern emissions tax when the economies are moderately specialized. With the North producing most of the dirty good, an increase in the Northern emissions tax will lower the real income of the South. Its gain from less competition in the Northern dirty good market will be outweighed by the welfare loss from the increase in dirty good prices since the majority of its consumption of this good is imported from the North.

I then analyze the effects of the border measures relative to the scenario of a standalone emissions tax. These measures are all based on importer emissions intensity and therefore do not vary with the level of the emissions tax. The ad valorem carbon tariff, t is 11.11%, and the ad valorem export subsidy, s is 10%, when the emissions tax is binding. They are smaller when the emissions tax is not large enough to affect the factor mix in production. The graphs in Figure 5 present changes of the key variables with respect to the no-tax baseline. The position of the curve for a particular border measure relative to that for the tax indicates its effect at varying levels of emissions tax.

The border measures change the relative prices of the goods, and raise domestic emissions while lowering foreign emissions. In all three cases, a carbon tariff tends to lower the global emissions relative to the case with only an emissions tax, except for a small window when the emissions taxes are around the kink, i.e., the level when it starts to bind. This is because the presence of a carbon tariff raises the price of the dirty good and therefore causes the binding level of the emissions tax to be slightly higher, delaying the technology effect. An export subsidy tends to increase the global emissions with low levels of emissions tax but with higher levels of taxes, it lowers emissions. Both measures reduce the rate of carbon leakage at all parameter values. When combined, the effects of the two are aggregated and result in the largest deviation from the case with emissions tax only if they work in the same direction. With a small emissions tax, the tariff and the subsidy will combine to generate negative carbon leakage. These qualitative results of border measures are generally encouraging, particularly for the carbon tariff, however, the effects on emissions are typically limited to a few percentage points for moderate levels of the emissions tax.

The welfare effects of the border measures seem less consistent across the three scenarios. However, a closer look at the patterns suggests that when the dirty good production is highly concentrated in the North, as in the case with asymmetric endowment ratio, a carbon tariff tends to increase the North's real income and lower that of the South. In this situation, the North's gain from the terms of trade improvement overweighs its loss from higher prices. For the South, its loss from the price changes is not fully compensated by the transfer of the tariff revenue, which is small since the South only has a very small dirty good sector. When the economies move away from the extreme specialization by the North in the dirty good sector, a carbon tariff tends to lower the North's real income while improving that for the South. For the same reason, the pattern is the opposite for an export subsidy. The North tends to lose and the South tends to gain when the dirty good industry is concentrated in the North. This echoes the standard neoclassical result of the Lerner symmetry theorem, which state that, under balanced trade, an ad valorem import tariff will have the same effects as an export tax. Since an export subsidy is a negative export tax, it tends to have an opposite effect to an import tariff. However, the two border measures do not necessarily have to work in the opposite directions. For instance, in the symmetric case and the case with asymmetric endowment sizes, both measures increase the South's real income. This is in part due to the assumption that the tariff revenue is transferred to the exporter and the magnitudes of the tariff and the subsidy are not the same.

Trade cost.—Figure 6 presents the results when varying γ, the trade cost, holding the other parameters and the endowments constant. The emissions tax τ_N is set to be 0.2 in the rest of the simulations. The impact of a higher trade cost on equilibrium outcomes depends again on the pattern of specialization. This time, what matters is how the relative size of the dirty good sector in the two economies compares to the relative size of the overall economy. When the trade cost is zero, the location of the dirty-sector firms is not important. When the trade cost is small, the firms are attracted to where the market is large and where the production cost is small. As the trade cost becomes larger, the economies move closer to autarky, and the relative size of the dirty good sector in the two economies gets closer to that of their market size or national income. In the symmetric case and the case with asymmetric endowment sizes, the North's dirty good sector is relatively small compared to its relative income with the South. An increase in the trade cost will therefore increase the share of dirty good production happening in the North, making the emissions tax more effective in reducing the global emissions. In the case of asymmetric endowment ratios, the North's share of dirty good production is much larger than its share of the world income. Therefore an increase in trade cost will lower the share of dirty good production located in the North, making the emissions tax less effective. Meanwhile, a higher trade cost always lowers the rate of carbon leakage, as it strengthens the home bias in production.

With respect to welfare, there is only a very small influence of the size of the trade cost on the magnitude of the impacts of the policies on the real income of both economies. It is noted that when the trade cost is small, an increase in the trade cost tends to magnify the welfare impacts, as a higher trade cost makes it more costly for the economies to adjust to policy changes. On the other hand, a higher trade cost also limits the pattern of production of the dirty good, leaving less room for the policy to make an impact. Therefore, when trade cost is sufficiently high, a further increase will reduce the impact of the policies.

The border measures always tend to reduce the global emissions and the carbon leakage rate given the current parameters. Their effects on national welfare are similarly largely dictated by the pattern of dirty good production. When a change in the trade cost attracts dirty good production to the North, it tends to make the welfare effect of a carbon tariff more favorable for the North and less so for the South, and the effect of an export subsidy will move in the opposite direction. Another observation is that, as the trade cost becomes larger, the border measures make smaller differences. This is because the large trade cost makes it less likely for the economies to adjust to the policy measures.

Elasticity of substitution.—Figure 7 presents the results of varying the elasticity of substitution, σ, in the range from 2 to 10. A higher σ means that the different varieties of the dirty good are more substitutable. Given the set of parameters and endowment values, varying σ seems to have similar effects to varying γ. This is not very surprising. As can be seen in equation (32), increasing σ exerts a similar effect as increasing γ if the prices are not too different between the economies. In the symmetric case and the case with asymmetric endowment sizes, a higher σ leads to lower global emissions with the same emissions tax. In the case of asymmetric endowment ratios, this leads to higher emissions. In all three cases, a higher σ is associated with a lower rate of carbon leakage. In terms of welfare, a higher σ tends to lower the loss in the real income as a result of the emissions tax. This is possibly due to the smaller loss because of fewer varieties of the dirty good when they are more substitutable for each other. In the symmetric case and the case with asymmetric endowment sizes, the emissions tax leads to a gain in the real income in the South with low to moderate σ. Increasing σ initially raises the South's real income but turns to a negative effect with higher σ levels.

Similar to the case with the trade cost, with varying levels of elasticity of substitution, the border measures always reduce the global emissions and the rate of carbon leakage, given the parameters chosen. Effects on real national incomes again follow the general pattern related to production allocation of the dirty good. The magnitude of the welfare effects shrinks as σ becomes large. However, unlike the case with varying trade cost, the sizes of the environmental effects do not become smaller.

Endowment.—As can be seen from the different sets of simulations conducted before, the endowments of the two economies play an important role in determining the environmental and economic effects of the emissions tax and the accompanying border measures. Following the previous set-up, I analyze the effects of varying the relative size of the economies as well as varying the relative endowment ratio. The graphs in the two columns of Figure 8 present the results for the respective exercises. The first set of simulations hold $K_S = L_S = 1$, and allow $K_N = L_N$ to change from 1 to 2. As the North becomes larger, it attracts the dirty good sector because of product market considerations. The second set of simulations hold $K_S = L_N = 1$, and allow $K_N = L_S$ to take values from 1 to 2. The relative endowment ratio

$(K_N/L_N)/(K_S/L_S)$ is therefore the square of this quantity. As it increases, the North attracts the dirty good sector because it possesses a stronger comparative advantage. Both effects are evident looking at the shares of the North in dirty good production in the respective cases.

As the North gets bigger or more capital abundant, its emissions tax brings about more emissions reduction and the carbon leakage rate gets smaller. In either case, the advantage for the dirty good industry offered by the endowment structure offsets the disadvantage created by the emissions tax, resulting in less reallocation. Alternatively, it can be reasoned that the larger share of dirty good production in the North means that the North's emissions policy covers more of the world's potential emissions and will therefore be more effective. Meanwhile, these changes tend to lower the welfare loss of the North and have little or negative effects on the South's real income.

The border measures once again always reduce global emissions and lower the rate of carbon leakage given the current parameters. The patterns of the welfare effects are also consistent with the description before.

Discussion

The simulation results presented above demonstrate the effects of a unilateral emissions tax and the accompanying carbon-motivated border adjustment in a number of different specifications of parameter values and endowment structure. A common theme that emerges is that the environmental and economic impacts of the various policies depend largely on the stringency of the policies and the pattern of specialization of the two economies, namely, the relative location of the dirty good sector. The impacts are typically of a larger magnitude with a higher emissions tax. Many factors, including the trade cost, the elasticity of substitution and the endowment structure, can affect the economies' production patterns. In general, when the home economy hosts a large portion of the world's dirty good production, the emissions tax leads to a better environmental outcome with lower rate of carbon leakage. Based on these observations, a moderately restrictive unilateral emissions tax adopted by an economy that hosts a majority of the emissions-intensive industries will have less concern on carbon leakage.

A carbon tariff or an export subsidy may have qualitatively different effects on overall emissions and real income of the two economies in patterns explained earlier. Nonetheless, these effects are quite small, usually within a few percentage points of change relative to the no-adjustment case. On the other hand, these border measures can significantly reduce the rate of carbon leakage and ameliorate the differential effects of the emissions tax on real compensation of the different factors. However, focusing exclusively on the leakage rate is misleading as it is not indicative of the overall environmental effect. In addition, the border measures are not the most direct distribution policies. Hence, there is not a very strong case for carbon-motivated border adjustment with unilateral emissions mitigation.

Before ending the analysis, it is worth pointing out that the previous discussion on the potential effects of the emissions tax and the carbon border adjustment are based on the particular model constructed in this paper, which has a number of limitations that has been mentioned earlier. The choices of the particular functional forms and parameter values for simulation also have an influence on the exact results. Hence, these simulations best serve to illustrate key insights rather than to offer precise predictions.

V. Conclusion

In this paper, I construct a classical international trade model with intra-industry trade, augmented to include trade cost and emission, to analyze the potential effects of unilateral GHG emissions abatement policies and the accompanying border adjustment. Comparison of the simulated equilibria of the model under various policy choices offers a few key ideas on the potential long run effects. The border adjustment measures, when used in conjunction with a unilateral emissions regulation, can almost always lower the rate of carbon leakage. However, the effects on the global emissions and national incomes are typically small and ambiguous in direction. Therefore it is hard to explain the motive for policies such as carbon tariffs in terms of large effects on the global emissions. Other potential explanations for the adoption of such policies include political economy issues related to domestic interest groups, as these border measures benefit the owners of the domestic factors used intensively in the emissions-intensive sectors.

The results also shed some light on the current discussion regarding carbon leakage. The focal concern of the debate is on the leakage from the industrialized countries to the developing countries. This paper suggests that as long as the existing comparative advantage structure and the world's income distribution favor emissions-intensive production in countries that commit to reduce emissions, carbon leakage will be less of a problem even if a global agreement cannot be reached. The real question will be which countries will it be enough to include in the international mechanism. If the large emitters in the world, namely the industrialized economies and the large emerging economies, agree to a collective mitigation scheme, it will likely be successful regardless of whether the remaining smaller economies are on board.

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Appendix A: Modelling Emissions and Abatement

Following Copeland and Taylor (2001, 2005), the GHG emissions are modelled as a factor of production. It is nonetheless equivalent to modelling the emissions as a by-product of production together with a special form of abatement technology which uses the good produced.

Production of potential output, X^P, generates potential emissions, Z^P, equal to the level of output.

$$Z^P = X^P = F(K_X, L_X)$$

A fraction θ of the potential output, denoted X^A, is used for abatement.

$$X^A = \theta F(K_X, L_X)$$

The amount of abated emissions Z^A is given by the constant-returns-to-scale function

$$\begin{aligned} Z^A &= A(Z^P, X^A) \\ &= Z^P A(1, X^A/Z^P) \\ &= Z^P A(1, \theta) \\ &= a(\theta) Z^P \end{aligned}$$

where $a(\theta) \equiv A(1, \theta)$ specified the abatement technology.

The net output X and emissions Z can then be expressed by

$$\begin{aligned} X &= X^P - X^A \\ &= (1-\theta)F(K_X, L_X) \\ Z &= Z^P - Z^A \\ &= (1-a(\theta))F(K_X, L_X) \\ &= \phi(\theta)F(K_X, L_X) \end{aligned}$$

where $\phi(\theta) \equiv 1 - a(\theta)$.

Take $\phi(\theta) = (1-\theta)^{1/\alpha}$ to obtain the following Cobb-Douglas production function

$$X = Z^{\alpha} \left[F(K_X, L_X)\right]^{1-\alpha} \tag{39}$$

With this formulation, emissions are treated as a production factor.

Given the production and abatement technology, the ratio of emissions to final output is

$$\frac{Z}{X} = \frac{\phi(\theta)}{1-\theta} = (1-\theta)^{\frac{1-\alpha}{\alpha}} \leq 1$$

since $0 \leq \theta \leq 1$. This ratio is the largest when $\theta = 0$, i.e., no abatement is done, which case,

$$X = Z = F(K_X, L_X)$$

In equilibrium, this happens as long as the price for emissions, τ, is less than or equal to the marginal revenue product of emissions according to the production function (39)

Appendix B: Equations for Simulation

With the use of Cobb-Douglas expenditure (utility) and cost (production) functions (equations (35) through (38)), the following set of equations characterize an interior equilibrium for the model.

Clean sector Y profit maximization, for $i = N, S$, (2 equations)

$$(\frac{r_i}{\alpha_Y})^{\alpha_Y}(\frac{w_i}{1-\alpha_Y})^{1-\alpha_Y} = 1$$

Price indices (2 equations)

$$\begin{aligned} P_N &= \left[n_N p_N^{1-\sigma} + n_S(p_S\gamma(1+t))^{1-\sigma}\right]^{\frac{1}{1-\sigma}} \\ P_S &= \left[n_S p_S^{1-\sigma} + n_N(p_N\gamma(1-s))^{1-\sigma}\right]^{\frac{1}{1-\sigma}} \end{aligned}$$

Demand for each variety of X (shipment), for $i, j = N, S$, (4 equations)

$$\begin{aligned} x_{NN} &= p_N^{-\sigma} P_N^{\sigma-1}\xi(w_N L_N + r_N K_N + \tau_N Z_N - s n_N p_N x_{NS}) \\ x_{NS} &= (p_N(1-s))^{-\sigma}\gamma^{1-\sigma} P_S^{\sigma-1}\xi(w_S L_S + r_S K_S + t n_S p_S x_{SN}) \\ x_{SS} &= p_S^{-\sigma} P_S^{\sigma-1}\xi(w_S L_S + r_S K_S + t n_S p_S x_{SN}) \\ x_{SN} &= (p_S(1+t))^{-\sigma}\gamma^{1-\sigma} P_N^{\sigma-1}\xi(w_N L_N + r_N K_N + \tau_N Z_N - s n_N p_N x_{NS}) \end{aligned}$$

Dirty sector X in the South, without regulation

$$p_S(1-1/\sigma) = (\frac{r_S}{\alpha_F})^{\alpha_F}(\frac{w_S}{1-\alpha_F})^{1-\alpha_F}$$

Dirty sector X in the North, with regulation

$$p_N(1-1/\sigma) = \begin{cases} (\frac{\tau_N}{\alpha_X})^{\alpha_X}(\frac{1}{1-\alpha_X}(\frac{r_N}{\alpha_F})^{\alpha_F}(\frac{w_N}{1-\alpha_F})^{1-\alpha_F})^{1-\alpha_X} & \text{if } \tau_N \text{ is binding} \\ (\frac{r_N}{\alpha_F})^{\alpha_F}(\frac{w_N}{1-\alpha_F})^{1-\alpha_F} + \tau_N & \text{otherwise} \end{cases}$$

Free entry conditions in dirty sector X, for $i, j = N, S$, (2 equations)

$$f(\sigma - 1) = x_{ii} + x_{ij}$$

Factor market clearing conditions in the South

$$\begin{aligned} L_S &= y_S(\frac{r_S}{\alpha_Y})^{\alpha_Y}(\frac{w_S}{1-\alpha_Y})^{-\alpha_Y} + n_S\sigma f(\frac{r_S}{\alpha_F})^{\alpha_F}(\frac{w_S}{1-\alpha_F})^{-\alpha_F} \\ K_S &= y_S(\frac{r_S}{\alpha_Y})^{\alpha_Y-1}(\frac{w_S}{1-\alpha_Y})^{1-\alpha_Y} + n_S\sigma f(\frac{r_S}{\alpha_F})^{\alpha_F-1}(\frac{w_S}{1-\alpha_F})^{1-\alpha_F} \\ Z_S &= n_S\sigma f \end{aligned}$$

Factor market clearing conditions in the North if τ_N is binding

$$\begin{aligned} L_N &= y_N(\frac{r_N}{\alpha_Y})^{\alpha_Y}(\frac{w_N}{1-\alpha_Y})^{-\alpha_Y} \\ &\quad + n_N\sigma f(\frac{\tau_N}{\alpha_N})^{\alpha_X}(\frac{(r_N/\alpha_F)^{\alpha_F}}{1-\alpha_X})^{1-\alpha_X}(1-\alpha_F)(1-\alpha_X)(\frac{w_N}{1-\alpha_F})^{(1-\alpha_F)(1-\alpha_X)-1} \\ K_N &= y_N(\frac{r_N}{\alpha_Y})^{\alpha_Y-1}(\frac{w_N}{1-\alpha_Y})^{1-\alpha_Y} \\ &\quad + n_N\sigma f(\frac{\tau_N}{\alpha_N})^{\alpha_X}(\frac{(w_N/(1-\alpha_F))^{1-\alpha_F}}{1-\alpha_X})^{1-\alpha_X}\alpha_F(1-\alpha_X)(\frac{r_N}{\alpha_F})^{\alpha_F(1-\alpha_X)-1} \\ Z_N &= n_N\sigma f(\frac{\tau_N}{\alpha_N})^{\alpha_X-1}(\frac{1}{1-\alpha_X}(\frac{r_N}{\alpha_F})^{\alpha_F}(\frac{w_N}{1-\alpha_F})^{1-\alpha_F})^{1-\alpha_X} \end{aligned}$$

otherwise

$$
\begin{aligned}
L_N &= y_N(\frac{r_N}{\alpha_Y})^{\alpha_Y}(\frac{w_N}{1-\alpha_Y})^{-\alpha_Y} + n_N\sigma f(\frac{r_N}{\alpha_F})^{\alpha_F}(\frac{w_N}{1-\alpha_F})^{-\alpha_F} \\
K_S &= y_N(\frac{r_N}{\alpha_Y})^{\alpha_Y-1}(\frac{w_N}{1-\alpha_Y})^{1-\alpha_Y} + n_N\sigma f(\frac{r_N}{\alpha_F})^{\alpha_F-1}(\frac{w_N}{1-\alpha_F})^{1-\alpha_F} \\
Z_S &= n_N\sigma f
\end{aligned}
$$

Table 1: Simulation Results: Symmetric Economies with Low Carbon Tax

	carbon tax		tariff (importer)		tariff (exporter)		subsidy		tariff + subsidy[&]	
	(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)	(i)	(j)
Changes	North	South	North	South	North	South	North	South	North	South
Regional Variables										
Emissions (Z_i)	-0.3000	0.1818	-0.1947	0.0776	-0.1934	0.0763	-0.1886	0.1025	-0.0848	-0.0023
scale effect$^{\wedge\#}$	0.8022	0.9218	0.7419	0.9413	0.7409	0.9415	0.7370	0.9424	0.5657	-
technology effect$^{\wedge\#}$	0.1978	0.0782	0.2581	0.0587	0.2591	0.0585	0.2630	0.0576	0.4343	-
Wage (w_i)	0.0592	-0.0449	0.0349	-0.0193	0.0347	-0.0190	0.0336	-0.0255	0.0110	-0.0006
Rental Rate (r_i)	-0.1087	0.0962	-0.0664	0.0397	-0.0659	0.0391	-0.0639	0.0529	-0.0216	-0.0012
Price of X^* (p_i)	0.0585	0.0470	0.0808	0.0197	0.0811	0.0194	0.0821	0.0261	0.1039	0.0006
Price Index of X (P_i)	0.0826	0.0383	0.1199	0.0335	0.1203	0.0335	0.0756	0.0045	0.1154	0.0019
Real Wage (w_i/P_i^{ξ})	0.0180	-0.0627	-0.0220	-0.0353	-0.0225	-0.0350	-0.0034	-0.0276	-0.0428	-0.0003
Real Rental Rate (r_i/P_i^{ξ})	-0.1434	0.0758	-0.1178	0.0227	-0.1175	0.0221	-0.0974	0.0506	-0.0736	-0.0021
Regional Y output (y_i)	0.2271	-0.1860	0.1363	-0.0783	0.1352	-0.0770	0.1311	-0.1038	0.0435	0.0023
Regional X output (n_i)	-0.2406	0.1818	-0.1444	0.0776	-0.1433	0.0763	-0.1390	0.1025	-0.0479	-0.0023
domestic* (x_{ii})	0.0496	-0.0524	0.0990	0.0635	0.0995	0.0650	-0.0858	-0.0928	0.0583	0.0273
export* (x_{ij})	-0.1028	0.1086	-0.2052	-0.1317	-0.2064	-0.1348	0.1779	0.1924	0.1274	-0.0566
Real Income (E_i/P_i^{ξ})	-0.0240	0.0065	-0.0262	0.0107	-0.0262	0.0107	-0.0227	0.0115	-0.0256	0.0158
World Variables										
Emissions ($Z_N + Z_S$)	-0.0591		-0.0586		-0.0585		-0.0431		-0.0435	
Y output ($y_N + y_S$)	0.0206		0.0290		0.0291		0.0136		0.0229	
X output ($n_N + n_S$)	-0.0294		-0.0334		-0.0335		-0.0182		-0.0251	
Leakage[#] ($-\Delta Z_S/\Delta Z_N$)	0.6059		0.3984		0.3946		0.5434		-0.0275	

^ See equations (29) and (31). [#] After-policy value. * Value is for each variety. [&] Both are based on importer intensity.

Parameter values: $\xi = 1/2$; $\sigma = 5$; $f = 1/4$; $\gamma = 1.2$; $\alpha_Y = 1/3$; $\alpha_F = 2/3$; $\alpha_X = 1/10$; $K_S = L_S = K_N = L_N = 1$, $\tau_N = 0.1148$.

Table 2: Simulation Results: Symmetric Economies with High Carbon Tax

	carbon tax		tariff (importer)		tariff (exporter)		subsidy		tariff + subsidy[&]	
	(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)	(i)	(j)
Changes	North	South	North	South	North	South	North	South	North	South
Regional Variables										
Emissions (Z_i)	-0.9980	0.6980	-0.9915	0.5680	-0.9549	-0.0426	-0.9949	0.6508	-0.9889	0.5291
scale effect$^{\wedge\#}$	0.9628	0.0513	0.8473	0.0530	0.2888	-	0.9066	0.0521	0.8021	0.0537
technology effect$^{\wedge\#}$	0.0372	0.9487	0.1527	0.9470	0.7112	-	0.0934	0.9479	0.1979	0.9463
Wage (w_i)	0.2455	-0.1650	0.2013	-0.1359	0.0036	0.0107	0.2239	-0.1546	0.1843	-0.1271
Rental Rate (r_i)	-0.3554	0.4343	-0.3071	0.3394	-0.0071	-0.0210	-0.3324	0.3990	-0.2870	0.3123
Price of X^* (p_i)	0.2409	0.1976	0.2819	0.1573	0.5071	-0.0106	0.2606	0.1828	0.2985	0.1456
Price Index of X (P_i)	0.3751	0.1548	0.4495	0.1320	0.7919	0.0857	0.3505	0.1418	0.4308	0.1202
Real Wage (w_i/P_i^{ξ})	0.0621	-0.2230	-0.0022	-0.1879	-0.2503	-0.0301	0.0532	-0.2088	-0.0099	-0.1752
Real Rental Rate (r_i/P_i^{ξ})	-0.4503	0.3347	-0.4245	0.2589	-0.2582	-0.0605	-0.4256	0.3093	-0.4039	0.2399
Regional Y output (y_i)	0.8464	-0.7643	0.7098	-0.6113	0.0142	0.0424	0.7803	-0.7081	0.6556	-0.5664
Regional X output (n_i)	-0.9608	0.6980	-0.8401	0.5680	-0.2758	-0.0426	-0.9020	0.6508	-0.7932	0.5291
domestic* (x_{ii})	0.1515	-0.1809	0.2211	-0.0974	0.3958	0.4709	-0.0072	-0.1760	0.0883	-0.0976
export* (x_{ij})	-0.3141	0.3750	-0.4585	0.2020	-0.8206	-0.9764	0.0150	0.3649	-0.1831	0.2023
Real Income (E_i/P_i^{ξ})	-0.1920	0.0558	-0.2048	0.0726	-0.2135	-0.0367	-0.1826	0.0502	-0.1987	0.0683
World Variables										
Emissions ($Z_N + Z_S$)	-0.1500		-0.2117		-0.4987		-0.1720		-0.2299	
Y output ($y_N + y_S$)	0.0411		0.0493		0.0283		0.0361		0.0446	
X output ($n_N + n_S$)	-0.1314		-0.1360		-0.1592		-0.1256		-0.1321	
Leakage[#] ($-\Delta Z_S/\Delta Z_N$)	0.6994		0.5729		-0.0446		0.6542		0.5350	

$^{\wedge}$ See equations (29) and (31). [#] After-policy value. * Value is for each variety. [&] Both are based on importer intensity.

Parameter values: $\xi = 1/2$; $\sigma = 5$; $f = 1/4$; $\gamma = 1.2$; $\alpha_Y = 1/3$; $\alpha_F = 2/3$; $\alpha_X = 1/10$; $K_S = L_S = K_N = L_N = 1$; $\tau_N = 2.4187$.

Table 3: Simulation Results: Economies with Asymmetric Sizes but Same Endowment Ratio

	carbon tax		tariff (importer)		tariff (exporter)		subsidy		tariff + subsidy[&]	
	(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)	(i)	(j)
Changes	North	South	North	South	North	South	North	South	North	South
Regional Variables										
Emissions (Z_i)	-0.3000	0.2925	-0.2322	0.1263	-0.2241	0.1067	-0.2438	0.1974	-0.1735	0.0209
scale effect^#	0.6213	0.8603	0.5208	0.8734	0.5053	0.8750	0.5414	0.8712	0.3787	0.8846
technology effect^#	0.3787	0.1397	0.4792	0.1266	0.4947	0.1250	0.4586	0.1288	0.6213	0.1154
Wage (w_i)	0.0458	-0.0649	0.0284	-0.0283	0.0264	-0.0239	0.0313	-0.0440	0.0139	-0.0047
Rental Rate (r_i)	-0.0856	0.1435	-0.0545	0.0590	-0.0507	0.0496	-0.0598	0.0942	-0.0272	0.0095
Price of X^* (p_i)	0.0804	0.0693	0.0968	0.0291	0.0987	0.0245	0.0940	0.0460	0.1109	0.0047
Price Index of X (P_i)	0.1041	0.0587	0.1281	0.0544	0.1309	0.0542	0.1003	0.0096	0.1261	0.0079
Real Wage (w_i/P_i^{ξ})	-0.0048	-0.0911	-0.0317	-0.0537	-0.0348	-0.0493	-0.0168	-0.0486	-0.0445	-0.0086
Real Rental Rate (r_i/P_i^{ξ})	-0.1298	0.1114	-0.1098	0.0314	-0.1074	0.0223	-0.1037	0.0890	-0.0833	0.0055
Regional Y output (y_i)	0.1860	-0.2484	0.1169	-0.1052	0.1087	-0.0887	0.1286	-0.1657	0.0579	-0.0172
Regional X output (n_i)	-0.1864	0.2925	-0.1210	0.1263	-0.1133	0.1067	-0.1320	0.1974	-0.0657	0.0209
domestic* (x_{ii})	0.0348	-0.0693	0.0581	0.1091	0.0606	0.1325	-0.0446	-0.1514	-0.0173	0.0318
export* (x_{ij})	-0.1159	0.0894	-0.1934	-0.1409	-0.2017	-0.1711	0.1485	0.1955	0.0575	-0.0411
Real Income (E_i/P_i^{ξ})	-0.0244	0.0068	-0.0238	0.0087	-0.0237	0.0081	-0.0261	0.0180	-0.0255	0.0196
World Variables										
Emissions ($Z_N + Z_S$)	-0.1197		-0.1232		-0.1235		-0.1096		-0.1143	
Y output ($y_N + y_S$)	0.0287		0.0365		0.0372		0.0220		0.0307	
X output ($n_N + n_S$)	-0.0407		-0.0457		-0.0463		-0.0318		-0.0393	
Leakage[#] ($-\Delta Z_S/\Delta Z_N$)	0.4264		0.2378		0.2083		0.3540		0.0527	

^ See equations (29) and (31). [#] After-policy value. * Value is for each variety. [&] Both are based on importer intensity.

Parameter values: $\xi = 1/2$; $\sigma = 5$; $f = 1/4$; $\gamma = 1.2$; $\alpha_Y = 1/3$; $\alpha_F = 2/3$; $\alpha_X = 1/10$; $K_S = L_S = 1$, $K_N = L_N = 2$; $\tau_N = 0.1269$.

Table 4: Simulation Results: Economies with Similar Sizes but Asymmetric Endowment Ratios

	carbon tax		tariff (importer)		tariff (exporter)		subsidy		tariff + subsidy[&]	
	(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)	(i)	(j)
Changes	North	South	North	South	North	South	North	South	North	South
Regional Variables										
Emissions (Z_i)	-0.3000	1.9604	-0.2765	1.5248	-0.2753	1.5036	-0.2072	0.7388	-0.1775	0.1964
scale effect$^{\wedge\#}$	0.5070	0.8256	0.4747	0.8328	0.4730	0.8332	0.3454	0.8539	0.2634	0.8628
technology effect$^{\wedge\#}$	0.4930	0.1744	0.5253	0.1672	0.5270	0.1668	0.6546	0.1461	0.7366	0.1372
Wage (w_i)	0.0660	-0.0504	0.0557	-0.0392	0.0552	-0.0387	0.0267	-0.0190	0.0150	-0.0051
Rental Rate (r_i)	-0.1200	0.1090	-0.1027	0.0833	-0.1019	0.0821	-0.0514	0.0392	-0.0293	0.0102
Price of X^* (p_i)	0.0647	0.0531	0.0741	0.0408	0.0746	0.0402	0.1013	0.0194	0.1128	0.0051
Price Index of X (P_i)	0.0949	0.0559	0.1060	0.0651	0.1065	0.0656	0.1132	-0.0039	0.1249	0.0087
Real Wage (w_i/P_i^{ξ})	0.0188	-0.0759	0.0038	-0.0691	0.0031	-0.0687	-0.0269	-0.0171	-0.0430	-0.0094
Real Rental Rate (r_i/P_i^{ξ})	-0.1590	0.0792	-0.1468	0.0497	-0.1462	0.0482	-0.1009	0.0412	-0.0847	0.0058
Regional Y output (y_i)	2.9563	-0.1093	2.5171	-0.0845	2.4955	-0.0833	1.2409	-0.0405	0.7017	-0.0107
Regional X output (n_i)	-0.1521	1.9604	-0.1312	1.5248	-0.1302	1.5036	-0.0716	0.7388	-0.0468	0.1964
domestic* (x_{ii})	0.0830	-0.0351	0.0902	0.0600	0.0905	0.0649	-0.0292	-0.1043	-0.0276	0.0108
export* (x_{ij})	-0.0868	0.1443	-0.0944	-0.2465	-0.0947	-0.2669	0.0306	0.4289	0.0288	-0.0445
Real Income (E_i/P_i^{ξ})	-0.0146	-0.0215	-0.0095	-0.0253	-0.0092	-0.0255	-0.0291	0.0033	-0.0226	-0.0027
World Variables										
Emissions ($Z_N + Z_S$)	-0.1873		-0.1867		-0.1867		-0.1600		-0.1589	
Y output ($y_N + y_S$)	0.0181		0.0236		0.0239		0.0127		0.0189	
X output ($n_N + n_S$)	-0.0468		-0.0487		-0.0488		-0.0312		-0.0346	
Leakage[#] ($-\Delta Z_S/\Delta Z_N$)	0.3428		0.2893		0.2864		0.1870		0.0581	

$^\wedge$ See equations (29) and (31). [#] After-policy value. * Value is for each variety. [&] Both are based on importer intensity.

Parameter values: $\xi = 1/2$; $\sigma = 5$; $f = 1/4$; $\gamma = 1.2$; $\alpha_Y = 1/3$; $\alpha_F = 2/3$; $\alpha_X = 1/10$; $K_S = L_N = 1$, $L_S = K_N = 2$; $\tau_N = 0.1263$.

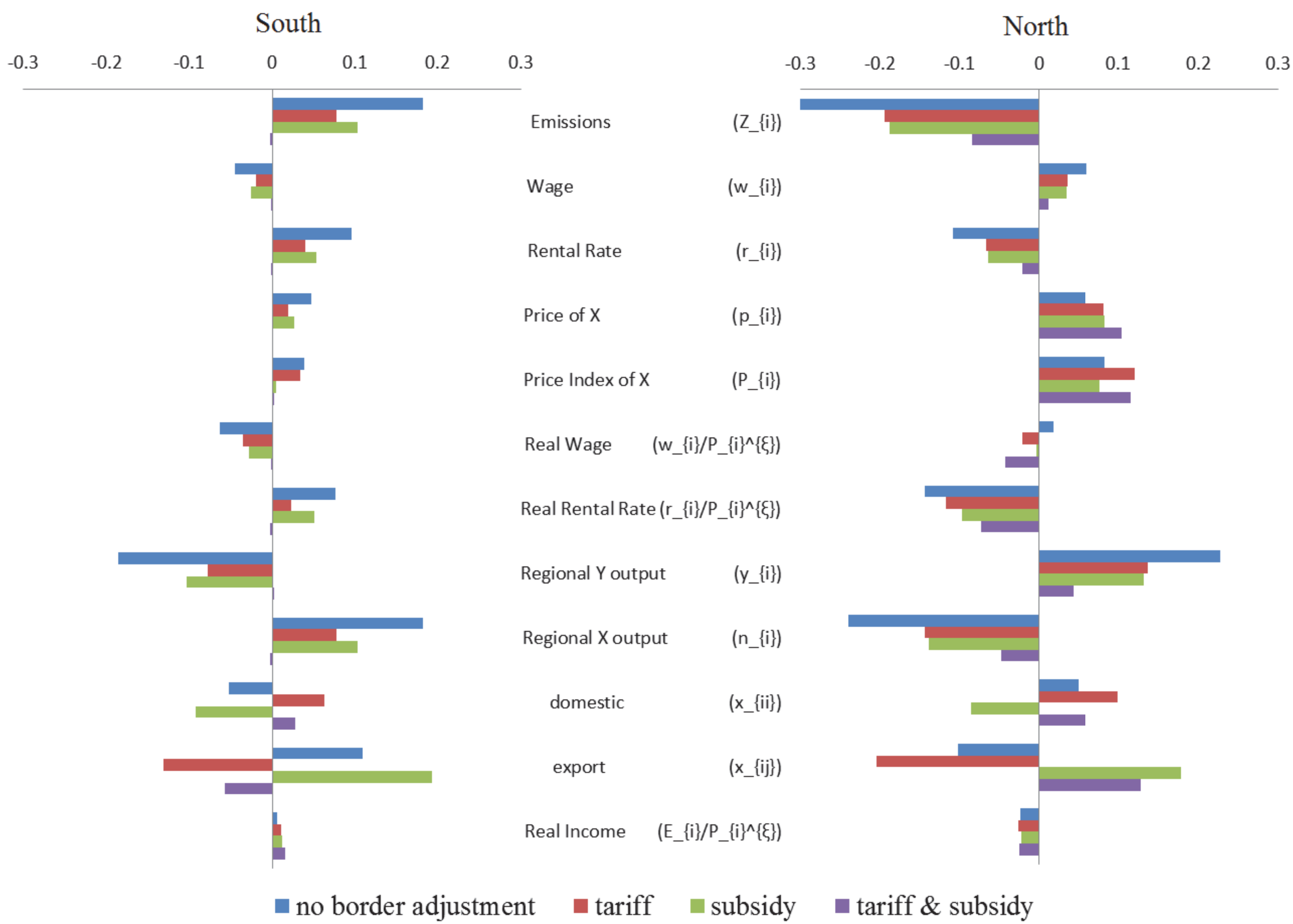

Figure 1: Simulation Results: Symmetric Economies with a Low Emisisions Tax

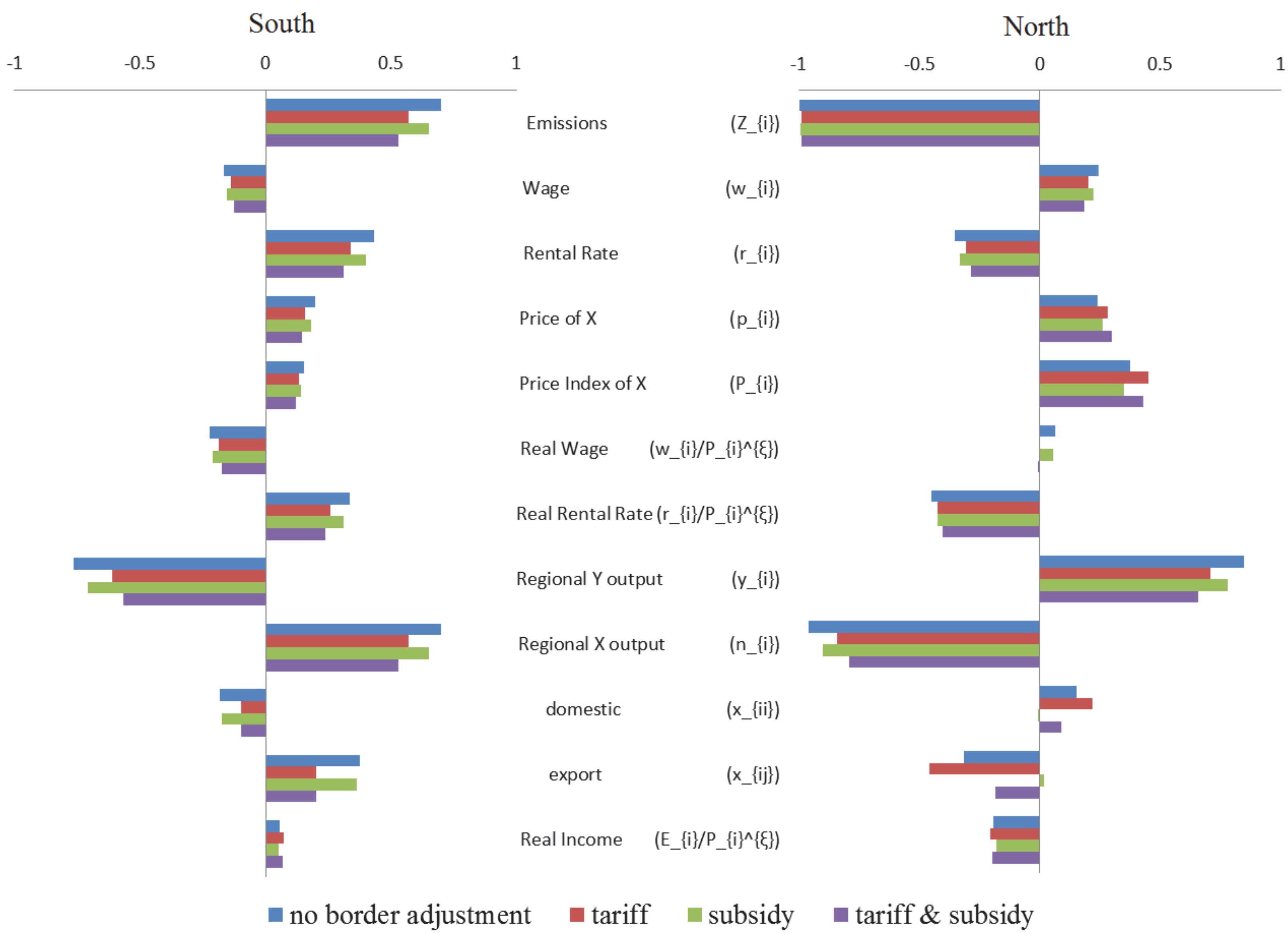

Figure 2: Simulation Results: Symmetric Economies with a High Emissions Tax

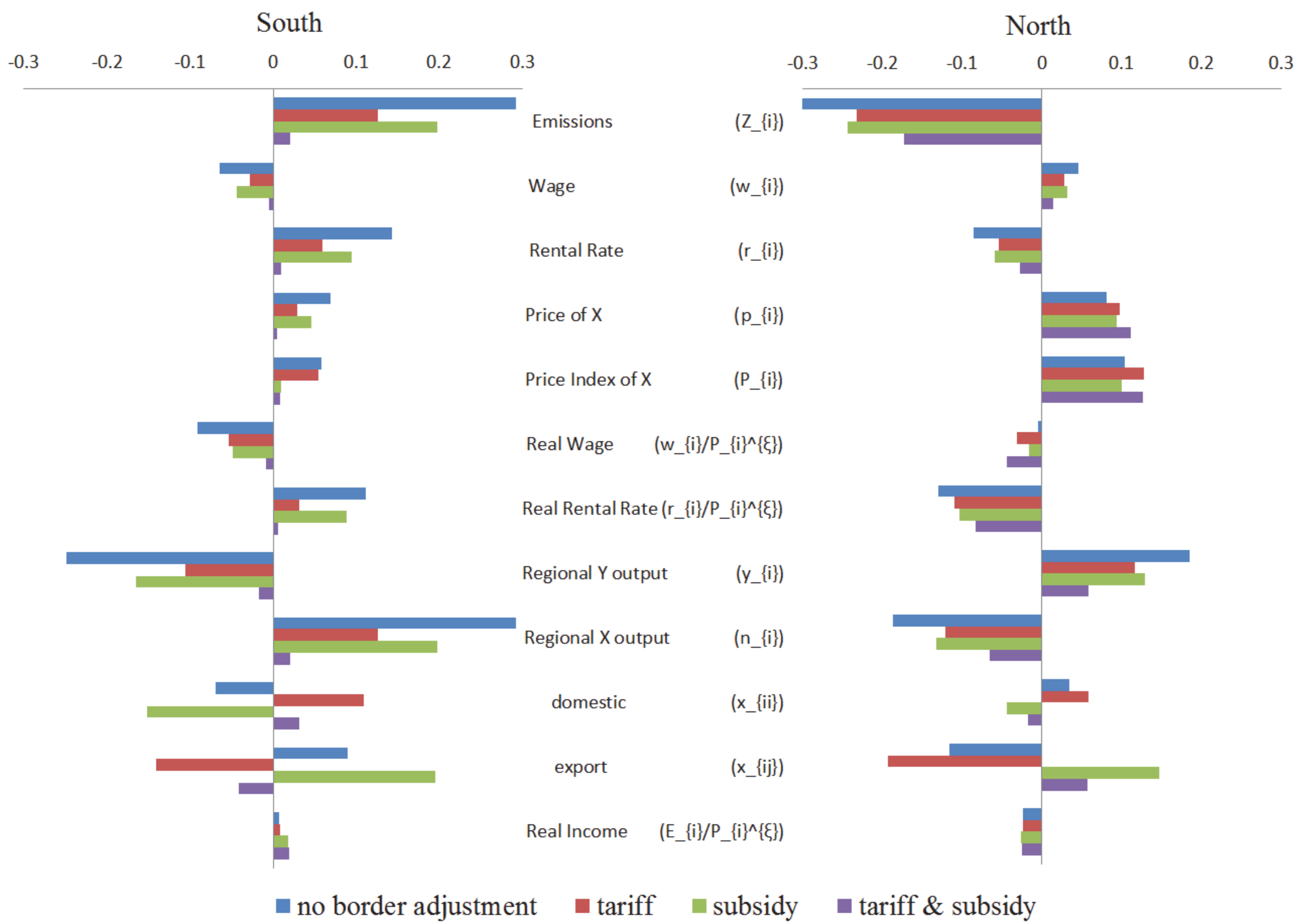

Figure 3: Simulation Results: Economies with Asymmetric Sizes but Same Endowment Ratio

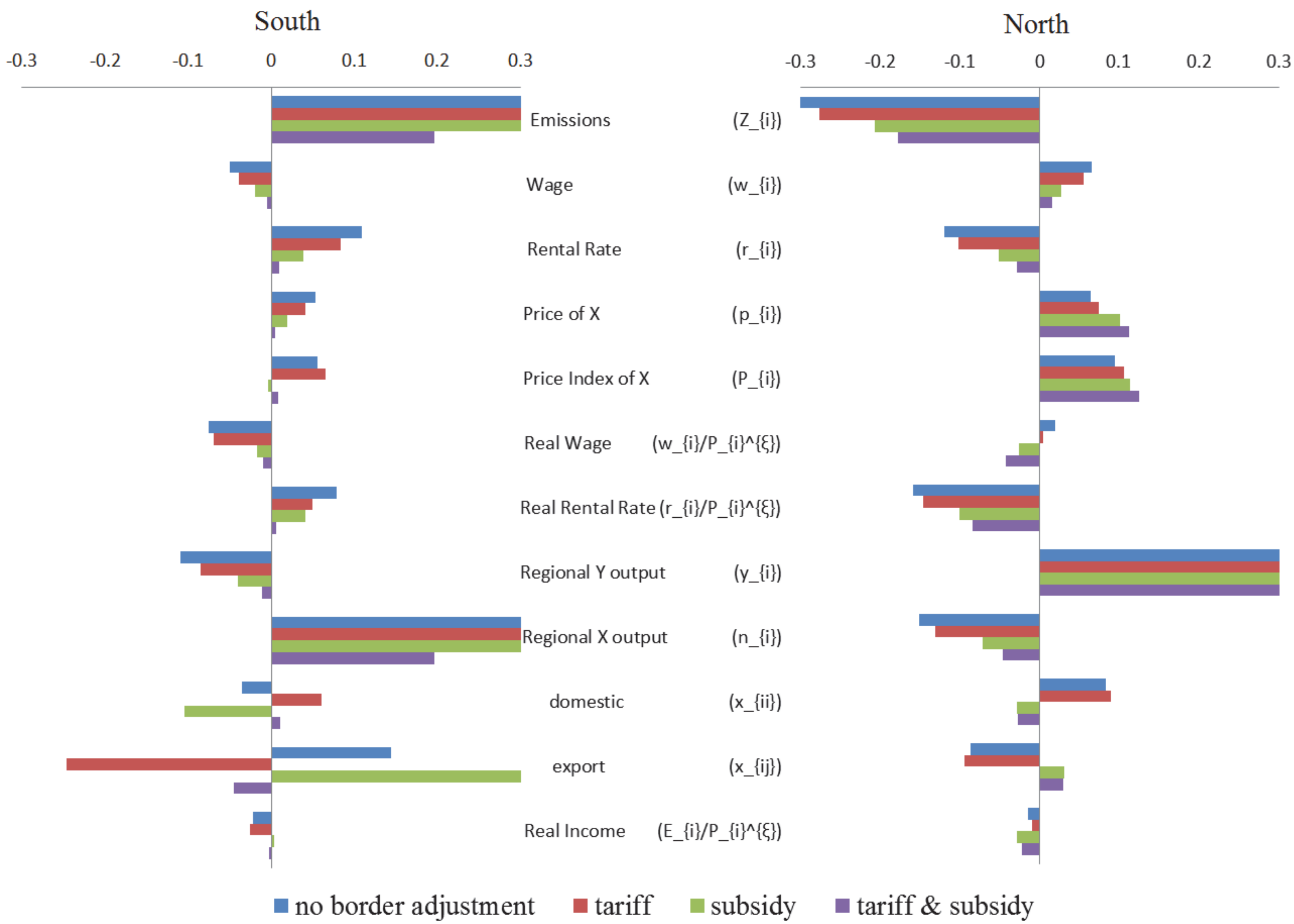

Figure 4: Simulation Results: Economies of Similar Size but with Asymmetric Endowment Ratios

The changes in the South's emissions, X output and export ratios, and the North's Y output are outside of the range shown on the axes. Please check Table 4 for exact values.

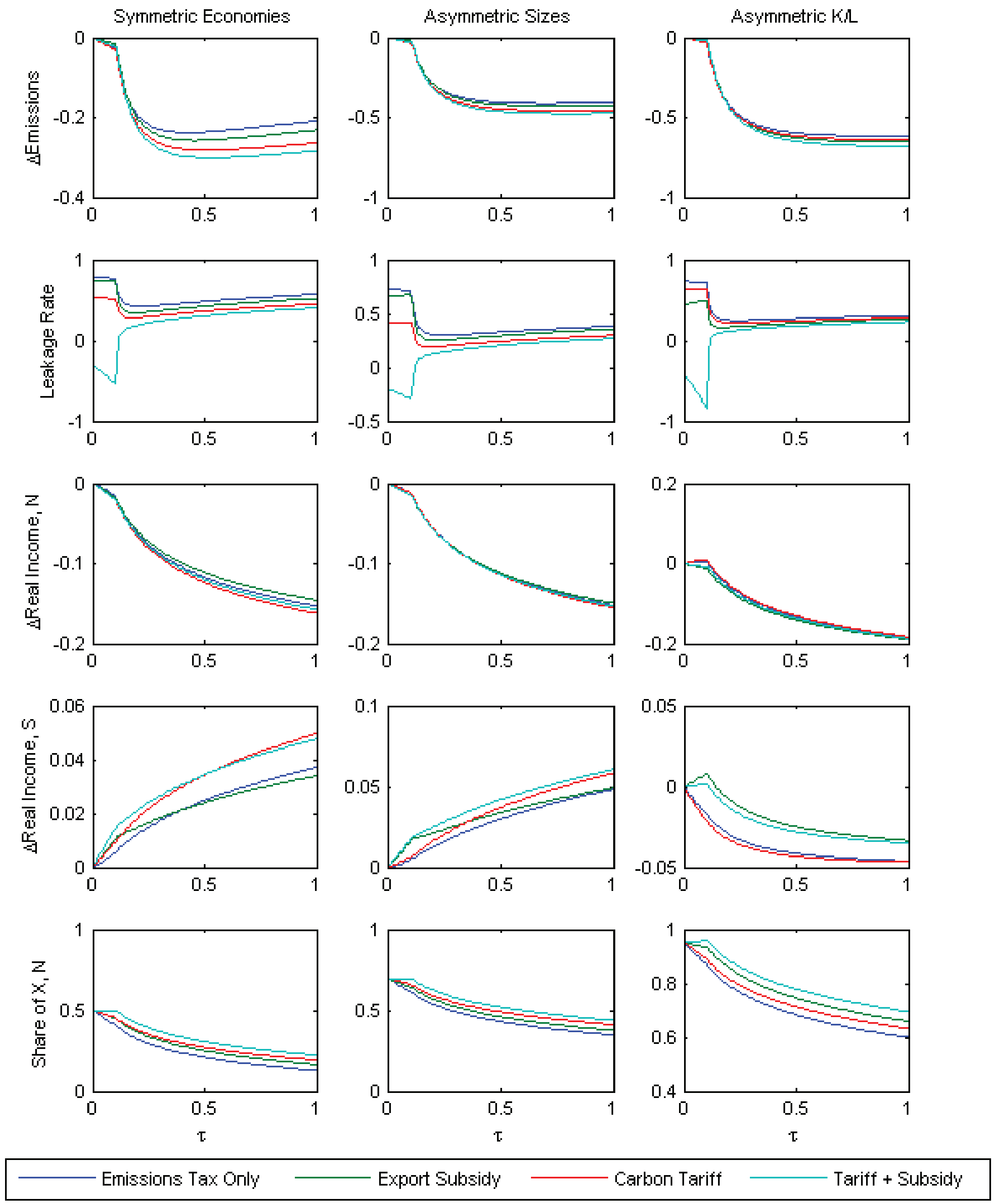

Figure 5: Sensitivity Analysis: τ_N

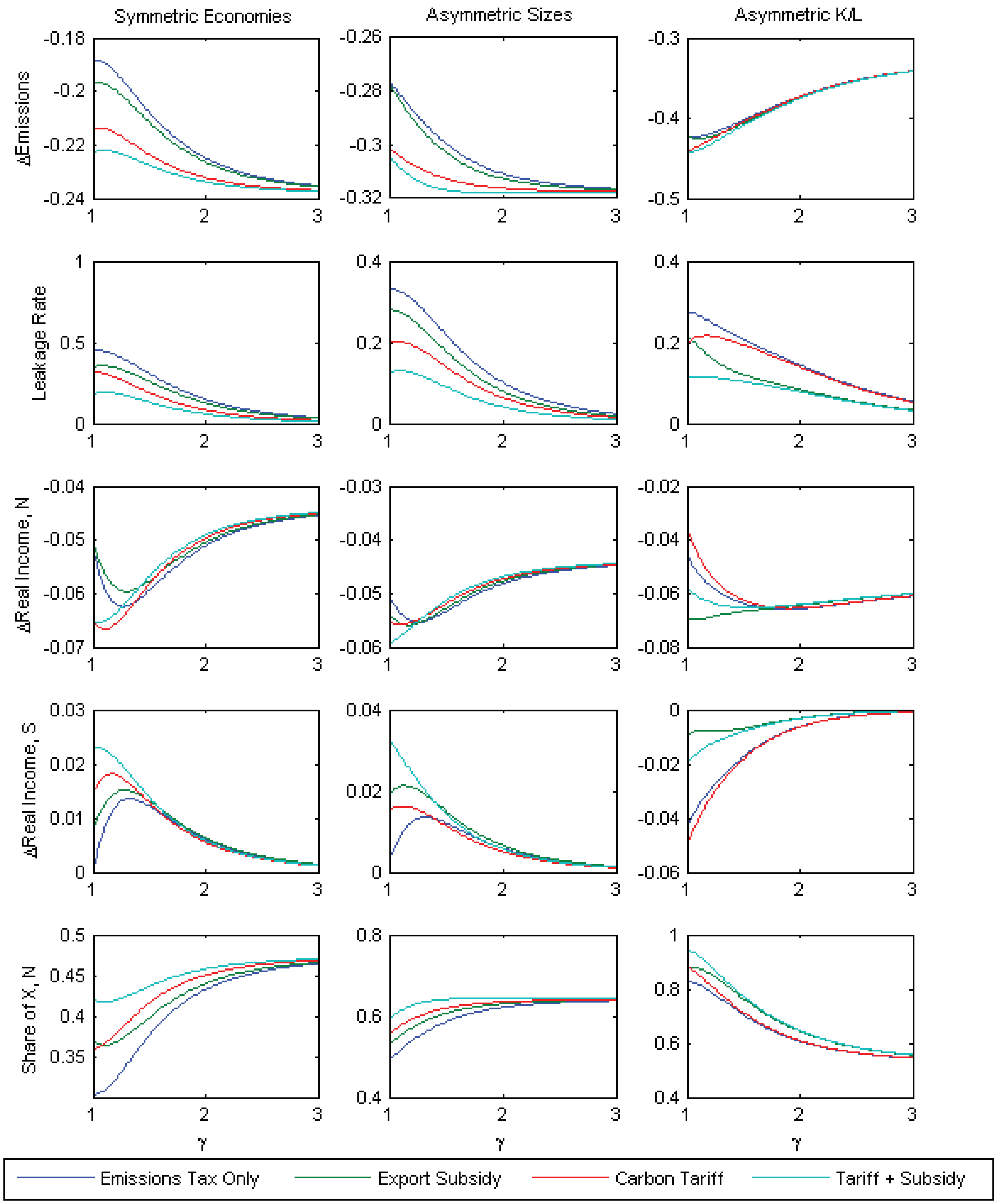

Figure 6: Sensitivity Analysis: γ

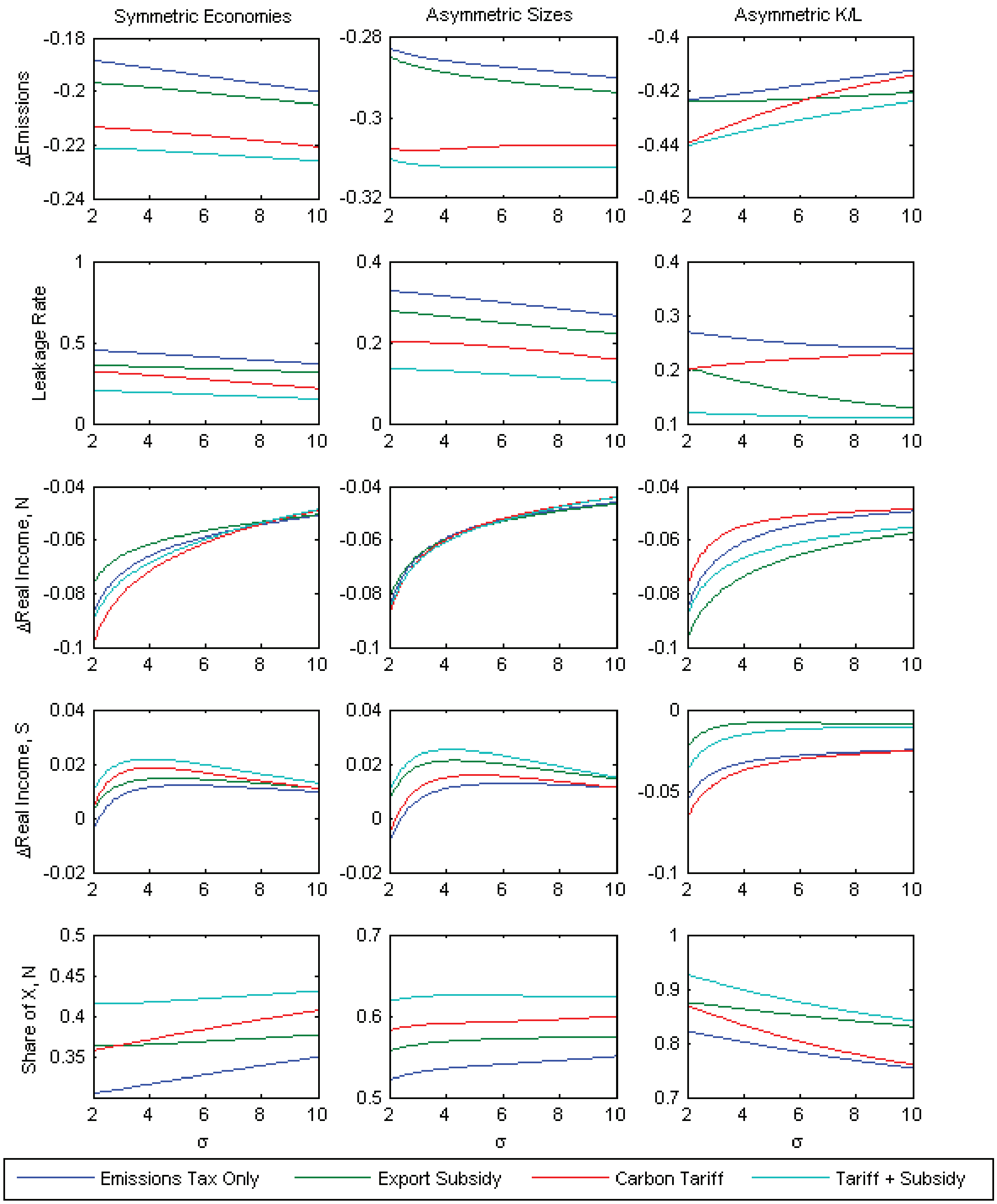

Figure 7: Sensitivity Analysis: σ

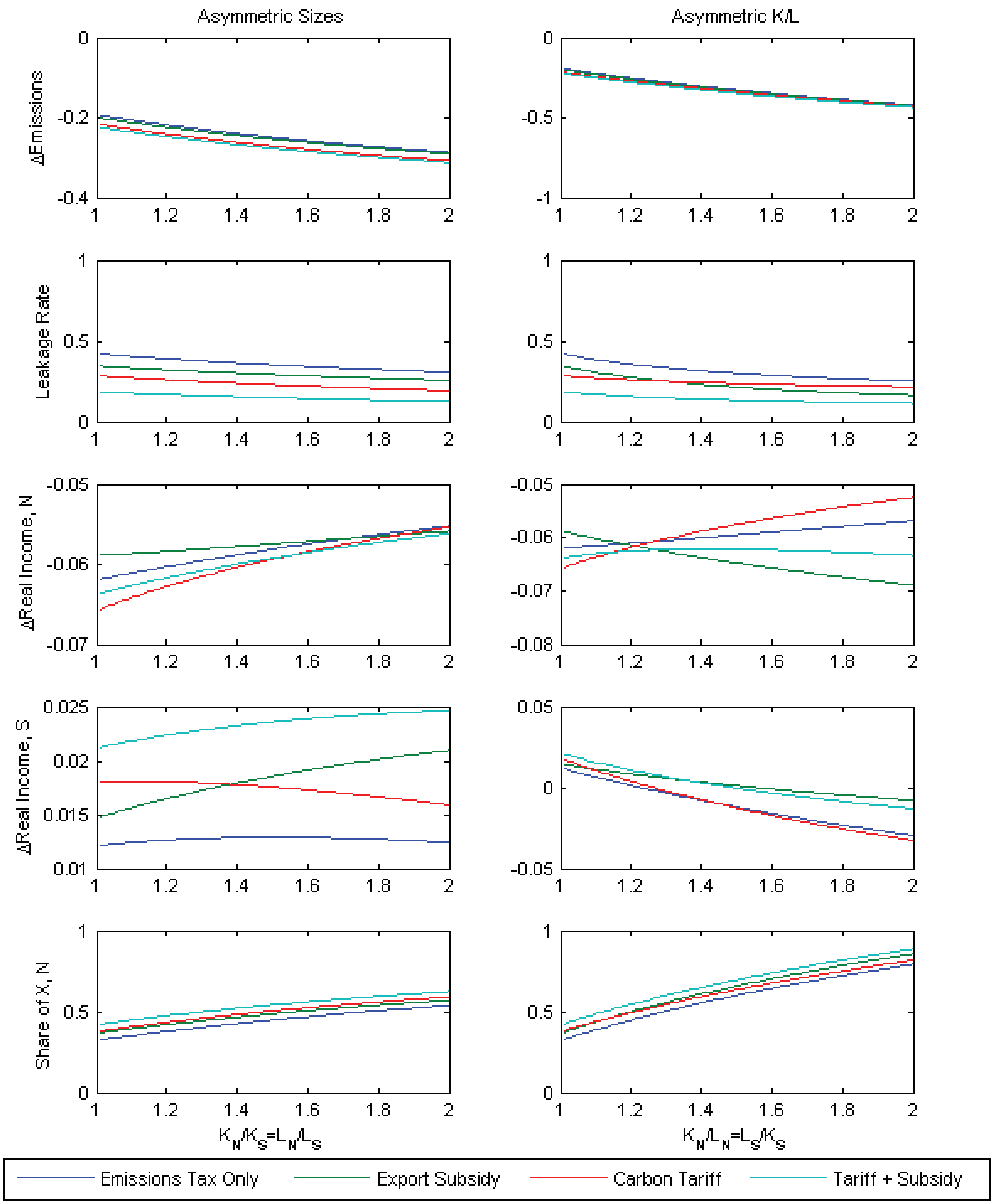

Figure 8: Sensitivity Analysis: Endowment Values