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Essays on International Trade and Climate Change

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Essays on International Trade and Climate Change

Tao Wang

A Dissertation
Presented to the Faculty
of Princeton University
in Candidacy for the Degree
of Doctor of Philosophy

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Abstract

This collection of essays investigates the interaction between policies and outcomes related to international trade and climate change. Chapter 1 analyzes the relationship between climate change policies and international trade flows. Using data on carbon dioxide (CO_2) emissions intensities for disaggregated industries and U.S. imports from 1990 to 2010, I find that committing to a quantified emissions target under the Kyoto Protocol is associated with a country exporting less to the U.S. in emissions-intensive industries. This effect is quantitatively important and is comparable to that of relative factor endowments on comparative advantage. Moreover this pattern was not present prior to the adoption of the Kyoto Protocol, but only emerged as it went into effect. Chapter 2 analyzes the potential effectiveness of using trade policy to address the issue of carbon leakage with unilateral emissions mitigation. 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 reducing global emissions. Such measures benefit owners of domestic factors used intensively in emissions-intensive sectors, but reduce real income of owners of other factors as well as the welfare of the foreign economy. These results suggest that such border measures have limited impacts on the global environment, but may be used as second-best redistribution policies. Chapter 3 investigates the driving forces behind the decreasing trend of CO_2 emissions from the U.S. industrial sector. From 1998 to 2007, real gross output grew by 7.9%, while CO_2 emissions decreased by 4.6%. Using CO_2 emissions intensities data compiled for year 1998 and subsequent emissions and production data, I decompose the changes in emissions into technology, composition and scale effects. The technology effect, i.e., the decrease in emissions intensities, accounted for almost all of the reduction in industrial emissions. Increasing net imports, on the other hand, amounted to about one third of the size

of the technology effect. These essays suggest that there is considerable interaction between patterns of international trade and trade policy and CO_2 emissions and climate change policy.

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To Weining.

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Chapter 1

Climate Change Policy and Patterns of International Trade

1.1 Introduction

Climate change is one of the greatest challenges of our time. Deep and rapid cuts in global greenhouse gas (GHG) emissions are required to prevent dangerous anthropogenic interference with the climate system.[1] Since the GHG emissions are a global public bad, efficient mitigation efforts must entail international coordination. 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 emissions by a group of industrialized countries under the Kyoto Protocol. Such a system invariably suffers from free rider problems 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. Policy

[1]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 in 2009 and the Cancun Agreements in 2010. In order to achieve this target, global CO_2 emissions need to peak by as early as 2015 and be reduced by 50% to 85% by 2050 compared to 2000 levels (Intergovernmental Panel on Climate Change (IPCC), 2007).

makers have also been worried about potential negative effects on the competitiveness of domestic companies in emissions-intensive industries exposed to international trade. On the other hand, there is wide-spread skepticism on the effectiveness of the Kyoto Protocol in reducing emissions. It is therefore useful to assess whether the carbon leakage and competitiveness concerns are supported by data.

In this paper I analyze empirically whether climate change policies have had an effect on the organization of economic activities. In particular, I explore whether the stringency of a country's climate change policies is an important determinant of comparative advantage in international trade. The channel that I consider builds on the well-established insight that differences in the stringency of environmental regulations across countries may result in pollution havens. Since countries with less stringent climate change policies have a lower implied price of GHG emissions, they will have a comparative advantage in producing goods that are more emissions intensive. Thus, the variation in the composition of production and trade associated with the tightening of climate change policies constitutes an important channel for carbon leakage and reflects competitiveness effects.

I examine the aforementioned hypothesis by testing whether countries that commit to a quantified emissions target under the Kyoto Protocol export relatively less in industries that are more emissions intensive. I use detailed data on U.S. imports from 1990 to 2010 and carbon dioxide (CO_2) emissions intensity data for over 200 disaggregated industries for the analysis.[2] In cross-sectional specifications for years after the Kyoto Protocol went into effect, I find that countries with emissions targets under the Protocol export less to the U.S. in more emissions-intensive industries compared to those without commitment. The magnitude of this relationship is comparable to that of traditional determinants of comparative advantage, namely the relative factor

[2] CO_2 is the most important type of greenhouse gases. It represents 77% of total anthropogenic GHG emission in 2004 measured in CO_2-equivalent in terms of global warming potential (IPCC, 2007).

endowments. One potential concern for such an analysis is that the countries that commit to emissions abatement could have already been specializing in cleaner industries prior to the Kyoto Protocol for reasons other than climate change policies. The panel structure of the trade data allows me to analyze data from the years preceding and after the introduction of the Kyoto Protocol. I find little evidence that the committed countries specialized in less emissions-intensive industries prior to the adoption of the Kyoto Protocol. Rather, this pattern emerged as countries signed and ratified the Protocol. This is consistent with the view that the commitment have entailed more stringent domestic climate change policies and the resulting higher implied price for GHG emissions have made the countries' comparative advantage shift away from emissions-intensive industries. Contrary to the belief that it is a failed treaty, the Kyoto Protocol is associated with a sizable shift in the composition of trade of the committed countries. On the other hand, there is little evidence that uncommitted countries have moved toward specializing in emissions-intensive industries, suggesting that the forces of production relocation might not have been fully at work.

The rest of the paper is organized as follows. The next section provides some background information on the Kyoto Protocol and briefly reviews relevant theoretical and empirical literature on international trade and the environment. Section 1.3 discusses the empirical strategies and the estimation equations. Section 1.4 describes the data used in the analysis. Section 1.5 reports the cross-sectional estimation while Section 1.6 tackles the issue of endogeneity. The last section concludes.

1.2 Background and Related Literature

The Kyoto Protocol is an international agreement linked to the United Nations Framework Convention on Climate Change (UNFCCC). It was adopted at the third session of the Conference of Parties (COP3) of the UNFCCC in December 1997. Cur-

rently, there are 193 Parties to the Protocol, including 192 States and the European Union (E.U.). The major feature of the Protocol is that it sets quantified emissions targets for the Annex I Parties to the UNFCCC, which include 40 industrialized countries and the E.U. Table 1.1 lists the countries that are Annex I Parties and reports the targets specified in the Kyoto Protocol.[3] They have committed themselves to national or joint reduction targets, that range from a joint reduction of eight percent for the E.U., seven percent for the U.S.,[4] six percent for Japan and zero percent for Russia. These targets amount to a reduction of total emissions from the Annex I countries of about five percent against 1990 levels over the five-year period 2008-2012. The Protocol adopts the principle of "common but differentiated responsibilities,"[5] so that developing countries, including major emitters like China or India, do not face any binding emissions limits.

The Kyoto Protocol has been criticized for its lack of credible punishment. Like most international treaties, the explicit consequences for noncompliance are weak compared to domestic law (Grubb, 2003) and many have worried that it wold not be successful in delivering the promised reduction in emissions, especially without the participation of the U.S. Nonetheless, a quick look at the total fossil-fuel related CO_2 emissions data in the past 20 years (Boden, Marland, & Andres, 2011) suggest that the

[3]Since these targets are specified in the Annex B to the Kyoto Protocol, the committed countries are sometimes referred to as the Annex B parties. I will use the term Annex I throughout this paper to denote committed countries unless otherwise specified. The Annex I countries in this paper refers to the Annex I Parties that are committed to a quantified emissions target under the Kyoto Protocol. It differs from the list of current Annex I members to the UNFCCC as it does not include the U.S., Malta and Turkey. The U.S. is not a Party to the Kyoto Protocol. Malta was not an Annex I party when it ratified the Protocol and Turkey is recognized as in a situation different from that of other Annex I Parties. They are not committed to emissions targets under the Protocol.

[4]The U.S. originally signed the Kyoto Protocol in 1998, however, it did not ratify the protocol after a non-binding senate resolution (the Byrd-Hagel resolution) urged the Clinton administration to not accept any treaty that did not include "meaningful" participation of all developing as well as industrialized countries, arguing that to do so would unfairly put the U.S. at a competitive disadvantage.

[5]Article 3.1 of the UNFCCC states, "(t)he Parties should protect the climate system for the benefit of present and future generations of humankind, on the basis of equity and in accordance with their common but differentiated responsibilities and respective capabilities." Accordingly, the developed country Parties should take the lead in combating climate change and the adverse effects thereof.

UNFCCC and the Kyoto Protocol may have had some effect on overall emissions after all. Figure 1.1 shows that the total emissions from the Annex I countries (including the U.S.) have experienced much slower increase in the last two decades compared to that from the non-Annex I countries and it seemed to have peaked in 2005, when the Kyoto Protocol went into force. In 1990, total emissions from the non-Annex I countries were about half of the Annex I emissions; by 2006, the non-Annex I countries were emitting more than the Annex I countries, and their emissions have continued to grow. Figure 1.2 offers a closer look at the emissions from different groups of countries. The Annex I countries with economies in transition (EIT) experienced a large decrease in emissions in the 1990s due to the decline of their economy, which also explains the decrease in total Annex I emissions in that period. Nonetheless, emissions from other Annex I countries with Kyoto commitment, as well as that from the U.S., have increased much more slowly than the non-Annex I countries. The increase became even slower in the early 2000s and eventually the emissions level peaked in 2005 or 2006. On the other hand, emissions from the non-Annex I countries have increased dramatically, with China soaring to overtake the U.S. to become the largest emitter in the world by 2006. The increase in emissions from other non-Annex I countries seems to have sped up in the 2000s as well. This observed difference in the evolution of emissions from different groups of countries and the peaking of the Annex I emissions are consistent with the idea that commitments made by the Annex I countries under the Kyoto Protocol and in the UNFCCC process in general are indeed associated with efforts to mitigate GHG emissions and helped slow down and eventually revert the growth of emissions in these countries. Meanwhile, these unilateral policies may have contributed to speeding up the growth of the non-Annex I emissions through carbon leakage. There are many possible interpretations, such as the faster integration of the global economy in the past two decades or the natural

outcome of the stages of development for the countries. Nonetheless, it at least offered hope for finding an effect of the climate change policies.

In recent years, there has been increased interest from policy makers on the interaction of international trade and the global GHG mitigation effort, since trade can have potentially large yet ambiguous effects on the effectiveness of domestic and global climate change policies. Carbon leakage through "dirty" industry relocation to and lower energy prices in non-participating countries has been an important concern for the committed Parties to the Kyoto Protocol. If the climate change policy in a country raises local costs associated with emissions, then another country with a more relaxed policy may have a comparative advantage in industries where such costs are substantial. If demand for these goods remains the same, production may move offshore to the cheaper country with lower standards, and global emissions will not be reduced. This constitutes a composition effect, and is the channel that I will focus on in the current study. Closely related is the technology effect stemming from the large differences in emissions intensities of the production process across countries.[6] The countries with less stringent policies are usually less developed and may employ out-dated and more emissions-intensive technologies, generating more emissions for the same amount of good produced and further contributing to leakage. Lastly, on the supply side, if environmental policies in one country add a premium to certain fuels or commodities, then the demand may decline and their prices may fall. Countries that do not place a premium on those items may then pick up the demand and use the same supply, negating any benefit (Sinn, 2008).

[6]The differences may arise because of the varying access to clean technologies among countries. Chua (1999) surveys the literature and summarizes evidence that there are technological innovations that greatly reduce emissions intensities for a wide range of pollutants including CO_2. The differences may also be a reflection of the different composition of a country's energy sources, ranging from the different types of fossil fuels to renewable sources or nuclear power (Douglas & Nishioka, 2009). Another source of difference for empirically measured sectoral emissions intensities across countries is the different within-sector composition of sub-industries or goods with varying emissions intensities.

On the other hand, despite all these concerns, various studies have suggested that the presence of international trade provides more benefit than harm for combating climate change. In theory, in an environment with global commitment, international trade in goods may substitute for trade in emissions permits and facilitate more efficient emissions reduction by aligning abatement costs across countries (Copeland & Taylor, 2001; 2005). With the tradable nature of environmental technologies, international trade and foreign direct investment (FDI) serve as conduits of technology diffusion to developing countries (Chua, 1999). In addition, pressure from enhanced environmental regulations and product standards from developed-world importers encourages more stringent environmental policy enforcement and compliance and induces technological upgrading and innovation by the developing-world producers (Zeng & Eastin, 2007; Frankel, 2009).

With both sides seemingly plausible, it will be useful to empirically estimate the actual effect of existing climate change policies in relation to international trade. So far, there has been little empirical evidence for the pollution haven hypothesis with respect to GHG emissions, yet the potential for carbon leakage under deepening regulations cannot be ruled out. With the first and only agreed-upon commitment period of the Kyoto Protocol coming to an end in 2012, it is important to understand the impacts of the Protocol so as to shed light on the design and implementation of a successor to the current system. This paper therefore complements the existing literature on climate change and international trade by providing empirical evidence for the effects of climate change policies on international merchandise trade. By assessing whether the Kyoto Protocol is associated with a shift in the patterns of international trade flows, the paper sheds light on the important industry relocation channel of potential carbon leakage.

There are three main lines of literature that are related to the current study. The first is the thriving literature on carbon accounting. Most of these studies employ

input-output analysis to quantify CO_2 emissions embodied in international trade flows (see Minx et al., 2009 for an overview of such applications), similar to the literature on factor content of trade. Developed economies such as the E.U. and the U.S. tend to be net importers of embodied carbon, while emerging economies such as China and Russia are often net exporters (Peters & Hertwich, 2008; Atkinson, Hamilton, Ruta, & van der Mensbrugghe, 2010). This paper utilizes similar data on international trade, and the data on CO_2 emissions intensities are derived from an input-output analysis. However, rather than focusing on the overall carbon content of trade, it examines the patterns of trade in goods across disaggregated industries. An advantage of carrying out the analysis at a finer level than typical carbon accounting studies is that it limits issues related to sector aggregation stemming from within sector heterogeneity in trade exposure and emissions intensities as discussed in Wiedmann, Lenzen, Turner and Barrett (2007) and Su, Huang, Ang and Zhou (2010).

The second line of literature concerns the pollution haven hypothesis. These studies build on the intuition that everything else equal, countries or regions with weaker environmental regulations tend to have a comparative advantage in polluting industries and these places become pollution havens as they open up to trade. Early studies, mostly utilizing cross-sectional data across countries or industries, do not find significant evidence for the hypothesis (see Chua, 1999 for a survey), partly hampered by the fact that the industries with the largest abatement costs tend to be the least geographically mobile (Ederington, Levinson & Minier, 2005). Later analyses, taking advantage of newly available panel data and using more advanced econometric techniques, have found support for the hypothesis for new plant locations (List, Millimet, Fredriksson, & McHone, 2003), FDI (Keller & Levinson, 2002; Dean, Lovely & Wang, 2009) as well as trade flows (Levinson & Taylor, 2008; Broner, Bustos, & Carvalho, 2011). This paper draws on the empirical tradition in this literature and attempts identify the potential sources of comparative advantage in CO_2 emissions-

intensive industries. The baseline estimation equations are particularly similar to the study by Broner et al. (2011) on comparative advantage in industries intensive in local air pollutants. Apart from the focus on a global bad in CO_2 emissions, this paper also differs in the following ways. While Broner et al. (2011) have relied mostly on a cross-sectional specification, I also exploit the panel structure of available trade data to analyze patterns of trade before and after significant developments in climate change policies. In addition, while they use a survey based measure on stringency of environmental regulation to proxy for cross-country differences in relative pollution costs, I use a direct measure based on actual climate change policies, namely the commitment to emissions targets under the Kyoto Protocol.

The last set of studies look at the economic impacts of existing and potential climate change policies, driven by carbon leakage or competitiveness concerns resulting from unilateral abatement policies like the Kyoto Protocol or the E.U. Emissions Trading System (ETS).[7] A myriad of papers have reported simulation results of various policy scenarios, based on computable general equilibrium (CGE) models or integrated assessment models (IAM) which combine the scientific and economic aspects of climate change (see Karp, 2010 and Zhou, Kojima & Yano, 2010 for recent reviews). These models generally have strong parametric assumptions, while the parameters are not typically estimated using actual data. Therefore the results are very sensitive to assumptions of specific models and the reported measures of carbon leakage vary wildly.[8] Partial equilibrium models have also been used, primarily for studies of specific sectors, such as the cement or iron and steel industries under the E.U. ETS (Demailly & Quirion, 2006; 2008). Only a handful of studies have attempted to empirically assess the impacts of specific policies. A World Bank

[7]E.U. ETS is a cornerstone of the E.U.'s policy to combat climate change and its key tool for meeting its emissions target under the Kyoto Protocol. Launched in 2005, it was the world's first large-scale emissions trading scheme.

[8]The reported figures range from single digits to over 100, measured in terms of the increase in emissions in non-participating economies resulted directly from unilateral abatement policies as a percentage of mitigated emissions in the participating countries.

(2008) study concludes that both carbon taxes and energy efficiency standards have a negative effect on competitiveness for industries that are energy intensive or subject to higher energy efficiency standards. It also reports a gradual increase in the import-export ratio of energy intensive goods in developed countries, and a gradual decline in the ratio in some developing regions, suggesting potential leakage. Reinaud (2008), however, finds no evidence for carbon leakage in the aluminum sector as a result of the E.U. ETS. While industry-specific analyses offer insights on potential impacts of climate change policies, other studies have taken a broader perspective to assess economy-wide effects. Grunewald and Martínez-Zarzoso (2011) finds that an obligation from the Kyoto Protocol has a measurable reducing effect on a country's overall CO_2 emissions. Aichele and Felbermayr (2010) finds evidence that Kyoto commitments affect trade in embedded carbon and suggests substantial carbon leakage. Douglas and Nishioka (2009) pays special attention to the international differences in sectoral emissions intensities, and finds no evidence that developing countries specialize in emissions-intensive sectors. Using richer data, this paper adds to the empirical literature by analyzing the effect on the composition of industry trade flows. The findings echo those from the aforementioned studies in that climate change policies do appear to have an impact on production and trade, however, countries without quantified emissions targets under the Kyoto Protocol do not seem to specialize in emissions-intensive industries.

In sum, this paper contributes to the existing literature by empirically assessing the impacts of climate change policies on the patterns of international trade across industries using detailed trade and CO_2 emissions data. Specifically, I examine whether committing to a quantified emissions target under the Kyoto Protocol is associated with a shift in the patterns of trade in industries with high versus low emissions intensities. The study uses the U.S. imports data which cover a large number of developed and developing countries and the level of analysis is much more disaggregated than

similar studies with the newly available U.S. industry emissions intensity data. I also take advantage of the panel data structure to examine patterns of trade before and after the adoption of the Kyoto Protocol.

1.3 Empirical Strategy and Estimation Equations

1.3.1 Cross-sectional Specification

In this section, I describe in detail my empirical strategy and the main estimation equations to assess the effectiveness of climate change policies and identify potential carbon leakage. I analyze the relationship between such policies and patterns of international trade in industries with varying levels of CO_2 emissions intensities. The empirical analysis is informed by recent developments in quantitative general equilibrium models of trade. Eaton and Kortum (2002) develops a multi-country model of international trade with a continuum of industries that captures the Ricardian forces of comparative advantage, based on technological differences, as well as geographical barriers. Their probabilistic formulation of technological heterogeneity allows a tractable framework for general equilibrium analysis and results in a gravity equation for bilateral trade flows. Chor (2010) extends the Eaton-Kortum model beyond aggregate trade volumes and incorporates both Ricardian and Heckscher-Ohlin (H-O) forces, based on relative factor endowments, in order to quantify the importance of various sources of comparative advantage within a common framework. Chor's model explains cross-country patterns of specialization based on the intuition that industries vary in factor input requirements and institutional support needed for production, and countries differ in their abilities to meet these industry-specific requirements. Comparative advantage therefore arises from these country-industry matches. By unpacking the technological parameter in the Eaton-Kortum model, Chor derives the following estimation equation (equation (18) in Chor, 2010) to assess the various

determinants of comparative advantage,

$$\ln(X_{ni}^k) = \sum_{f=1}^{F} \beta_f \left(\ln \frac{\omega_{if}}{\omega_{i0}} \right) s_f^k + \sum_{\{l,m\}} \beta_{lm} L_{il} M_m^k + \beta_d D_{ni} + \alpha_i + \alpha_{nk} + \upsilon_{ni}^k \qquad (1.1)$$

where X_{ni}^k denotes the trade flow from exporter i to importer n in industry k, ω_{if} the price for factor f in country i, s_f^k the share of factor f in production for industry k, L_{il} an institutional measure l for country i, M_m^k the dependency of industry k on institution component m, D_{ni} the bilateral general distance variables, α's the fixed effects, β's the regression coefficients and υ the error terms. In this cross-sectional specification, log bilateral industry trade flows are regressed on the following determinants of comparative advantage: (i) H-O forces, through the interaction of exporter's relative factor prices, $\ln \frac{\omega_{if}}{\omega_{i0}}$, and industry factor shares, s_f^k; (ii) institutional forces, captured by the interaction between the exporter institutional measures, L_{il}, and industry dependency measures, M_m^k; (iii) bilateral distance variables, D_{ni}, that impose an iceberg cost on trade, including physical distance, linguistic ties, colonial links, border relationships, and trade agreements; (iv) an exporter fixed effect, α_i, which absorbs any exporters' country-specific characteristics that have common effects on trade flows across industries and importers; and (v) an importer-industry fixed effect, α_{nk}, which collects such factors as specific industry demand by an importing country or an industry specific tariff rate of an importer, provided it does not vary across exporters. This estimation equation embeds the empirical specification of recent studies on sources of comparative advantage ranging from factor endowments (Romalis, 2004) and energy abundance (Gerlagh & Mathys, 2011), to institutional sources such as financial development (Beck, 2003) and legal institutions (Levchenko, 2007; Nunn, 2007). Using this specification, Chor (2010) finds that factor endowments and legal institutions appear to have the largest influence on industry trade specialization. In the specification in this paper, I will control for the factor endowments in my esti-

mation, since emissions intensities are more likely to be correlated with factor shares than dependency on legal institutions.

To use equation (1.1) for the analysis of comparative advantage in emissions-intensive industries, I can treat the stringency of climate change policies as an institutional measure and use CO_2 emissions intensities as the dependency score of each industry on a country's climate change institutions. Alternatively, I can model CO_2 emissions as a factor of production, a common practice in the theoretical literature on trade and the environment. I then view emissions intensity as analogous to factor shares and use the stringency of climate change policies to approximate for the relative emissions prices. Copeland and Taylor (2001) provides a particular functional form of emissions abatement technology so that emissions modeled as a joint output in production can be equivalently expressed as an input factor. Drawing on that work, Broner, et al. (2011) explicitly extends Chor's model to include pollution as an additional factor for production and derives an estimation equation to analyze comparative advantage in polluting industries. Adding to equation (1.1) the emissions related interaction and leaving out other institutional terms, I have,

$$\ln(X_{ni}^k) = \beta_E \left(\ln \frac{\tau_i}{\omega_{i0}} \right) s_E^k + \sum_{f=1}^{F} \beta_f \left(\ln \frac{\omega_{if}}{\omega_{i0}} \right) s_f^k + \beta_d D_{ni} + \alpha_i + \alpha_{nk} + \upsilon_{ni}^k \qquad (1.2)$$

where τ_i is the price of emissions in country i, in the form of an emissions tax or implicitly embodied in the cost of energy use. The additional term is the interaction of the industry emissions share in production, s_E^k, and the relative price of emissions in the exporting country, $\ln \frac{\tau_i}{\omega_{i0}}$. As Copeland and Taylor (2001) pointed out, their model does not allow "polluting to prosperity," i.e., there is an upper bound of emissions per physical unit of output. Only when τ_i is high enough will emissions prices factor into the firms' decisions, and induce active emissions abatement which can be viewed as substitution between emissions and other factors of production. In a world

where emissions are not regulated anywhere, β_E is zero and equation (1.2) reduces to equation (1.1). When the emissions prices are high enough in a group of countries, β_E is expected to be negative, through both the direct channel of cost of production in countries with high enough emissions prices and the indirect general equilibrium production relocation effect that countries with non-binding emissions prices are also affected.

I estimate equation (1.2) in the current study using the stringency of climate change policies in a country, CP_i, to proxy for the relative emissions price, $\ln \frac{\tau_i}{\omega_{i0}}$. In particular, I use the indicator variable for Annex I status under the Kyoto Protocol. A number of previous studies have utilized the same measure as a proxy of the stringency of climate change policies (Aichele & Felbermayr, 2010; Yörük and Zaim, 2008). The underlying assumption is that there is a link between a country's Kyoto commitment and actual climate change policies that result in higher emissions prices. The Kyoto commitment is more of a signal of more stringent climate change policies rather than a direct policy measure by itself. This measure may be correlated with other country characteristics or institutional measures that may potentially affect trade patterns, some of which I will control for in robustness checks. Moreover, because it is a bivariate variable, only the average effect of Annex I membership to the Kyoto Protocol on the patterns of trade can be estimated with potential country heterogeneity remaining undisclosed. For the industry emissions share s_E^k, I will use the measure of CO_2 emissions intensity, i.e., the amount of CO_2 emitted per unit of production, which will be described in detail in the next section.

In this paper, I use U.S. imports data for empirical estimation. When estimating equation (1.2) with only one importer, all the bilateral distance variables $\beta_d D_{ni}$ will be absorbed into the exporter fixed effect α_i. Following the standard approach in the literature (Romalis, 2004), I use factor endowment ratios $\ln \frac{V_{if}}{V_{i0}}$ to proxy for factor price ratios $\ln \frac{\omega_{if}}{\omega_{i0}}$. Note that this will reverse the sign of β_E, since the two are inversely

correlated. The main cross-sectional estimation equation is now

$$\ln(M_i^k) = \beta_E CP_i s_E^k + \sum_{f=1}^{F} \beta_f \left(\ln \frac{V_{if}}{V_{i0}} \right) s_f^k + \alpha_i + \alpha_k + \upsilon_{ni}^k \tag{1.3}$$

where log U.S. imports, $\ln(M_i^k)$, are regressed on the interaction of Annex I status, CP_i, and CO_2 emissions intensities, s_E^k, the factor interactions $\left(\ln \frac{V_{if}}{V_{i0}} \right) s_f^k$ and exporter and industry fixed effects α_i and α_k. Standard errors are two-way clustered by exporting country and industry for two considerations. First, because of data availability at the level of analysis, I do not include many institutional forces identified as determinants of comparative advantage in the recent literature. This will not be a serious problem for estimating the parameter of interest, β_E, as long as these forces are not correlated with the emissions interaction. However, the omitted unobserved variables may make error terms correlate for a given exporter or an industry. The other concern is of the type illustrated by Moulton (1990). Since the regression attempts to measure the effects on country-industry trade flows by country and industry characteristics, which are measured at a more aggregated level, even small levels of correlation of errors within countries or industries can cause OLS standard error to be seriously biased downward.

As mentioned before, using a binary policy measure in the regression assumes homogeneous responses in trade patterns to Kyoto commitment. However, there are substantial differences between the Annex I countries in many dimensions. One important observation is that the EIT countries have substantially lower emissions levels compared to the baseline of 1990 (or earlier years) when the Kyoto Protocol was adopted (see Table 1.1 for the change between the baseline and year 1998 levels), hence the quantified emissions targets specified in the Protocol may not be binding at all for these countries. Therefore it is likely that there is meaningful heterogeneity within the Annex I countries in trade patterns. To explore whether this is the case,

I estimate the following regression,

$$\ln(M_i^k) = \sum_{j=1}^{J} \beta_j I_j s_E^k + \sum_{f=1}^{F} \beta_f \left(\ln \frac{V_{if}}{V_{i0}} \right) s_f^k + \alpha_i + \alpha_k + \upsilon_{ni}^k \tag{1.4}$$

where the emissions interaction term, $CP_i s_E^k$, in equation (1.3) is replaced with a set of interactions of emissions intensity, s_E^k, and the series of indicator variables for each of the Annex I countries, I_j. I examine the estimated coefficient, β_j, for each country to check if there is an interesting pattern in heterogeneity within the Annex I group.

All the estimation equations specified above exploit the difference in the stringency of climate change policies between the Annex I and the non-Annex I countries to identify a differential pattern in industry trade flows. It is also informative to separately analyze the pattern of specialization with respect to industry emissions intensity for the two groups of countries. The last cross-sectional analysis I do is to estimate the following equation for the respective groups,

$$\ln(M_i^k) = \beta_E s_E^k + \sum_{f=1}^{F} \beta_{fs} s_f^k + \sum_{f=1}^{F} \beta_f \left(\ln \frac{V_{if}}{V_{i0}} \right) s_f^k + \alpha_i + \upsilon_{ni}^k \tag{1.5}$$

where log imports, $\ln(M_i^k)$, are regressed on emissions intensity, s_E^k, industry factor shares, s_f^k, and factor interactions, $\left(\ln \frac{V_{if}}{V_{i0}} \right) s_f^k$, with country fixed effects, α_i. Since there is no variation in Annex I status within the Annex I and the non-Annex I groups, the emissions interaction term, $CP_i s_E^k$, in previous equations reduces to emissions intensity s_E^k. Therefore industry fixed effects cannot be included while industry factor shares s_f^k are added in. Standard errors are two-way clustered by exporter and industry. Estimating equation (1.5) allows comparison between the Kyoto Protocol's direct effect on committed countries and the indirect effect on non-committed countries with respect to specialization in emissions-intensive industries. If the Kyoto-induced carbon leakage is strong enough and there is a composition effect of emissions-intensive

sectors relocating to the non-Annex I countries, one would expect β_E to be negative for the Annex I countries and positive for the non-Annex I countries. In addition, this approach allows the coefficients on the H-O forces to differ for the two groups of countries, which is consistent with the theoretical model behind the estimation equations. If the prices of emissions in the non-Annex I countries are so small that emissions do not matter for firms' decisions, then the impact of other factor interactions will be more pronounced compared to countries with more stringent climate change policies.

1.3.2 Endogeneity

So far, I have described the strategy for a cross-sectional analysis using data for a particular year. One potential concern for such estimation is that of endogenous selection. Countries did not randomly become Annex I Parties to the UNFCCC and take on commitments under the Kyoto Protocol. First, it is conceivable that the countries that were already specializing in less emissions-intensive industries, for other reasons than more stringent climate change policies, self-selected to become Annex I Parties to the UNFCCC. If this is true, then despite statistical significance, the cross-sectional estimation cannot establish a valid relationship between climate change policies and patterns of trade. Second, since Annex I status is determined in 1992 with the adoption of the UNFCCC, years before the Kyoto Protocol, it is possible that the Annex I Parties had already implemented stringent climate change policies and their economy had shifted away from emissions-intensive production prior to signing and ratifying the Kyoto Protocol. In this scenario, commitments by the Annex I parties are a mere reflection of their existing stringent climate change policies rather than signifying further tightening. Nonetheless, the cross-sectional estimation can still identify the effects of climate change policies on patterns of trade, though it will not be evidence for Kyoto Protocol having any influence. To explore if any of

these concerns are indeed the case, I examine data from years prior to and after the adoption of the Kyoto Protocol in the following three ways.

First, I pool the yearly cross-sectional data and carry out a regression using the full panel spanning the period of 1990 to 2010. I introduce two versions of the indicator variable for Annex I status, and run the following regression

$$\ln(M_{i,t}^k) = \beta_E^R CP_{i,t}^R s_E^k + \beta_E CP_i s_E^k + \sum_{f=1}^{F} \beta_f \left(\ln \frac{V_{if}}{V_{i0}} \right) s_f^k + \alpha_{i,t} + \alpha_{k,t} + \upsilon_{i,t}^k \qquad (1.6)$$

where trade flows $M_{i,t}^k$ are now also indexed by year t, and the fixed effects are now specified as exporter-year effect, $\alpha_{i,t}$, and industry-year effect, $\alpha_{k,t}$, to allow for changes of the country and industry specific factors over time. Standard errors are still two-way clustered by exporter and industry, now allowing for potential autocorrelation of the error term in addition to the issues for the cross-sectional specification. CP_i is the same time-invariant indicator for Annex I status, assigned 1 if country i has committed to a quantified emissions target under the Kyoto Protocol. $CP_{i,t}^R$ is a time-varying indicator, only positive for years after the country ratified the Kyoto Protocol. It has been used by other studies in panel specifications (Aichele & Felbermayr, 2010; Grunewald & Martínez-Zarzoso, 2011). By including both versions of interaction terms as explanatory variables, the estimation can provide evidence on the extent to which there were preexisting patterns of specialization in emissions-intensive industries before the signing of the Kyoto Protocol, captured by β_E, and the extent to which there were changes in the pattern following the ratification of the Protocol, captured by β_E^R. If β_E is not significantly different from zero, one can rule out both types of concerns discussed earlier. A significant β_E implies that there were significant differences in patterns of specialization in emissions-intensive industries even before the Kyoto Protocol, though it cannot distinguish the source of these differences. On the other hand, if β_E^R is significantly below zero, one can infer that

Kyoto commitments did have an impact on top of any preexisting patterns. This way, I can identify if an Annex I Party's ratification of the Kyoto Protocol indeed institutes more stringent climate change policies that significantly affects patterns of trade.

A second approach is to estimate equation (1.3) for every year from 1990 to 2010. I then check whether the time-varying β_E is significantly different from zero for years before the signing of the of the Kyoto Protocol or it is only the case after the Protocol entered into force. If it is indeed the case that β_E is not significantly different from zero prior to Kyoto but only moves into the negative territory as countries ratified the Protocol, then there is evidence that Kyoto commitments mattered for patterns of specialization. Compared with the single regression of equation (1.6) using the full panel, the approach with a series of regressions is more flexible to the extent that β_E and the coefficients on the factor interactions, β_f's, are all allowed to differ over time, which is consistent with the idea that the same Annex I status signifies varying level of stringency of the climate change policy at different stages with respect to the Kyoto Protocol. On the other hand, it does not directly utilize information on the variation in the year that each Annex I Party ratified the Kyoto Protocol. To provide evidence on the effect of the Kyoto Protocol on industry specialization for the Annex I and the non-Annex I countries separately, I analyze time-varying coefficients for equation (1.5) in a similar fashion.

The last approach I adopt is to estimate a long-difference specification. I analyze the difference of log industry trade flows before and after the Kyoto Protocol. The previous specifications explore the potential change in the effect of Annex I status on the patterns of trade over time, while this approach attempts to assess the differential impact of the Kyoto Protocol on the growth rates of trade flows for high and low emissions-intensive industries. By first differencing the log trade flows between two years before and after the Kyoto Protocol entered into force and regressing them on

the interaction of Annex I status and emissions intensity, I test if there is a significant impact of the change in climate change policy on the change in trade patterns. This method controls for all time-invariant factors that affect the levels of trade flows. I obtain the following specification by first differencing equation (1.3) (or equation (1.6)),

$$\Delta \ln(M_i^k) = \beta_E CP_i s_E^k + \sum_{f=1}^{F} \Delta\beta_f \left(\ln \frac{V_{if}}{V_{i0}} \right) s_f^k + \Delta\alpha_i + \Delta\alpha_k + \Delta\upsilon_{ni}^k \tag{1.7}$$

where $\Delta \ln(M_i^k)$ is the log difference, or the growth rate, of imports from country i in industry k, CP_i (or equivalently ΔCP_i^R) is the same measure of Annex I status but now represents a change in climate change policy, and the fixed effects $\Delta\alpha_i$ and $\Delta\alpha_k$ now control for country or industry specific factors that result in heterogeneous average growth rates of country or industry trade flows, such as a country signing a trade agreement with the U.S. or an increase in U.S. demand for a particular industry. Considering the relatively short time period of several years, I have assumed that other country and industry specific characteristics, including industry emissions intensity, s_E^k, factor shares, s_f^k's, and relative factor endowments, $\left(\ln \frac{V_{if}}{V_{i0}} \right)$, have not changed over the period. Hence the factor interaction terms will disappear if β_f's remain unchanged. One complication is that before Kyoto, the cost of emissions may not be internalized in private firms' optimization process, and therefore the coefficient for other factor interaction terms may indeed be different from those after Kyoto. For robustness, I report estimation results with and without the factor interaction terms. The estimated $\Delta\beta_f$'s represents change in the coefficients in the baseline cross-sectional specification. A statistically significantly negative β_E estimate implies that Kyoto commitments had an impact on the evolution of trade patterns in the immediate aftermath of the introduction of the Protocol. It is consistent with the idea that the Kyoto Protocol fostered more stringent climate change policies in the Annex

I countries and the patterns of international trade have changed in the several years after the adoption of the Protocol as firms adjust to the more stringent policies. To explore whether there is any evidence of a preexisting trend in the Annex I countries toward specializing in less emissions-intensive products prior to the Kyoto Protocol, I conduct a similar regression on first-differenced log trade flows between two years before the Kyoto Protocol entered into force.

1.4 Data

1.4.1 CO_2 Emissions Intensities

In this section, I describe the data used in the analysis. I focus on the data on CO_2 emissions intensities for disaggregated industries. Due to data availability, industry level CO_2 emissions intensities are created based on only U.S. data from a recent report by the Economics and Statistics Administration of the U.S. Department of Commerce (ESA, 2010). The report analyzes energy-related CO_2 emissions and intensities for all Iliad industries,[9] government and households in the U.S. for the years of 1998, 2002 and 2006. The Iliad model is a detailed input-output model with 360 input-output sectors based on the 2002 North American Industry Classification System (NAICS). Out of these sectors, 255 correspond to industries in agriculture, mining and manufacturing, with exposure to merchandise trade. The data provide the most detailed account of CO_2 emissions intensities available to my knowledge. These disaggregated industries will be the level of analysis in this paper.

The dataset on emissions intensities is derived from detailed data on energy use by industries. The majority of the energy-related emissions are attributable to heat and power. Direct input of energy to production, such as natural gas used in producing fertilizer, and process emissions for a small number of industries, namely cement

[9]Iliad stands for *Interindustry Large-scale Integrated And Dynamic model of the U.S.*.

and lime, are also considered. The intensities are measured in the amount of CO_2 emissions produced per unit value of gross output, and are reported in both the direct emissions by an industry and the total emissions embodied in the final goods of an industry taking into account emissions embodied in domestic and imported intermediates.[10] For manufacturing industries, I am able to adjust such measures by the gross output to value added ratios of individual industries to obtain a value added based measure. Unfortunately, data on value added for agricultural and mining industries are only available at a more aggregated level.

It is important to choose an appropriate measure of emissions intensity for use in the estimation. The two candidates both seem viable: the intensity of total emissions embodied in the final goods of an industry, $s^k_{E,T}$, measured in tons of total embodied CO_2 emissions per \$1000 of gross output in constant year 2000 dollars; and the intensity of direct emissions of an industry, $s^k_{E,D}$, measured in tons of direct CO_2 emissions by the industry per \$1000 of value added in constant year 2000 dollars. (Henceforth, I suppress the units of the emissions intensities for brevity.) The theoretical model on which the estimation equations are based does not offer direct guidance for the choice as the model does not include intermediate inputs. The output-based measure, $s^k_{E,T}$, is available for all industries and takes into account the entire production cycle of the final output of an industry. Ignoring imported inputs, $s^k_{E,T}$, probably provides a more comprehensive measure of an industry's dependence on climate change policies, assuming the emissions charges to upstream industries are transferred through the cost of intermediate inputs. However, the cost of the embedded emissions may not be fully passed through and imported inputs may be important for certain industries. Furthermore $s^k_{E,T}$ may be less accurately measured as estimating embedded emissions involve more complicated analysis than that for direct emissions. On the other hand, the value added-based measure, $s^k_{E,D}$, seems to be more in line with the theoretical

[10]The ESA (2010) report assumes that the CO_2 emissions intensities of imported goods and services are the same as domestically produced ones.

model if intermediate inputs are ignored. Emissions intensities are used to proxy for the share of the emissions-associated charges in production cost, s_E^k, based on a Cobb-Douglas value added production function. Provided that the emissions price τ^k is high enough to matter in the firms' decision making process, s_E^k can be expressed as $s_E^k = \frac{\tau^k E^k}{Y^k}$, where E^k is the amount of emissions and Y^k is the value added for an industry. In the context of a country with lax or no emissions regulations, like the U.S., the emissions price is zero or non-binding. However, it is assumed that the emissions are nonetheless supplied perfectly elastically at a positive shadow price, which ensures that the countries cannot "pollute to prosperity." If all industries are subject to a uniform (shadow) price τ for CO_2 emissions in the U.S. and τ is high enough for all industries, then $s_{E,D}^k = \frac{E^k}{Y^k}$ will be a rescaled measure for s_E^k. In reality, this is unlikely the case as emissions-associated costs are small and vary across industries, in addition to the issue of intermediate inputs. Hence each measure has its advantages and shortcomings. I will therefore use both when applicable. Thankfully, for manufacturing industries for which both measures are available, the correlation between the output- and the value added-based measures is very high. As Table 1.3 shows, it is at about 0.98 for the intensities and 0.85 for the ranking of intensities. Therefore, the choice of an emissions intensity measure is unlikely to alter estimation results in a meaningful way.

I treat emissions intensity as a time- and country-invariant characteristic of each industry and use the average of the measures over 1998, 2002 and 2006 for all of the analysis. For this approach to be valid, the crucial assumption is that the relative emissions intensities do not vary over time or across countries. Over the period for which data are available, the measured emissions intensities are on a general decreasing trend and the average emissions intensity of the U.S. economy went down by about 20%. Therefore, if I were to analyze the evolution of total CO_2 emissions over time, I could not overlook the fact that technological advances are the main reason

for emissions reduction in the U.S., compared to industry relocation or composition changes (Levinson, 2009; Wang, 2014). However, since the main objective of this paper is to explore the potential effect of variation in climate change policies on the patterns of trade in relation to the relative emissions intensities across industries, I only need these relative intensities to remain stable over time, i.e., an emissions-intensive industry before the Kyoto Protocol kept being emissions intensive relative to other industries in the economy afterwards. As shown in Table 1.4, this is indeed the case for the U.S. as the correlation between the measures from the three years (panel (1) and (2), over 0.96) as well as the ranking of these measures (panels (3) and (4), over 0.88) are all very high. Therefore it seems safe to use an average measure of emissions intensities as a time-invariant measure for analysis on data from all years.

Similar to previous studies, since I only have detailed data on emissions for U.S. industries, I also need to assume that the relative intensities are the same across economies, i.e., a country can be clean and have a less emissions-intensive economy than others, but an industry that is relatively emissions intensive elsewhere still entails more emissions relative to the cleaner industries in that country. I recognize that there are substantial differences in emissions intensities across countries, due to technological access, energy sources and within industry composition. However, if the advances in energy efficiency, abatement technology and clean energy options are not biased toward some particular industries, but apply in general to all industries, then it is conceivable that the relative emissions intensities will be similar across countries. This may indeed be true if most of the developments in the CO_2 emissions abatement technologies are applied in the energy sector, as all other industries consume the produced electricity or fuel and all benefit from the technological advances. To verify that the relative intensities are stable across countries, I analyze available country specific data with more aggregated industries. Since data on emissions intensities are not readily available, I use data on industry energy use and output from the Global

Trade Analysis Project (GTAP) to calculate energy intensities for different countries and check the correlations to see if there is significant variation across countries. Since most of the CO_2 emissions are attributable to energy use (ESA, 2010), results on energy intensities should carry over to emissions intensities. Table 1.5 presents the correlation coefficients between the energy intensity measures for 42 sectors in food and manufacturing in the GTAP model for 12 countries in year 1997. The selected countries are the G8+5 group (excluding South Africa for which data are not separately available), i.e., the major economies of the world. It is clear that industry energy intensities are indeed highly correlated across countries. Except for pairings involving Germany (in the 0.8 to 0.9 range), all the correlations are well above 0.9. Based on these findings, I use the emissions intensity measures derived from U.S. data for analysis of all countries.

For a first look at the emissions intensity data, Table 1.2 lists the 20 most and the 20 least CO_2 emissions-intensive industries, ranked by $s^k_{E,T}$. The most emissions-intensive industries fall into three categories: those with substantial process emissions in production, namely lime and cement; the ones that use large amount of fossil fuels as feedstock for production, such as fertilizer and industrial gas; and the energy-intensive industries including several mining industries and metal products. The list is broadly consistent with those identified as industries that may be affected the most by climate change regulations in a report by the U.S. Environmental Protection Agency (EPA) (2009) and studies elsewhere (Grubb et al., 2009). The least emissions-intensive industries tend to be high-tech industries that are capital and skill intensive. They usually produce high value added products so that energy or emissions cost will be a small fraction of the value of output. High value added is also probably the reason why tobacco products claim the crown of the cleanest good in terms of CO_2 emissions. Another observation from Table 1.2 is that a few most emissions-intensive industries have intensities well above the rest, while the least emissions-intensive industries tend

to have very similar levels of intensities. The 20th least intensive industry has an intensity that is only 0.13 higher than the very least intensive industry. On the other hand, the gap in intensities between the 3rd and the 20th most intensive industries is 4.3, more than 30 times larger. Indeed, the distribution of industry CO_2 emissions intensities is highly skewed to the right. Figure 1.3 shows the distribution of the log of the emissions intensities for both the output and value added based measures. Even in logs, the distribution clearly has a fat right tail. Since the log function is a concave transformation, the distribution for the original measures is even more skewed to the right. A potential concern resulting from this feature of the distribution of the intensities data is that the estimation results could be driven by a few outliers, i.e., the most emissions-intensive industries. I will address the issue by checking whether excluding outliers significantly alters the estimation results.

1.4.2 Climate Change Policies

Another variable of central interest in the analysis is the measure for stringency of climate change policies. I use a country's Annex I status to the UNFCCC and its commitment to a quantified GHG emissions target under the Kyoto Protocol as an indicator of a country's climate change policies. As discussed in Section 1.3, I use two versions of the measure. The time-invariant Annex I indicator, CP_i, assigns 1 to country i if it is currently (as of October, 2011) an Annex I Party with a quantified target under the Kyoto Protocol. The time-varying indicator, $CP^R_{i,t}$, assigns 1 to an Annex I Party starting from the year after it ratified the Kyoto Protocol. There are other ways of assigning the time varying Annex I status with respect to the Kyoto Protocol: according to when a country signs the Protocol (before ratification), when the Protocol actually went into force for the country (the later of February 2005 or 90 days after ratification), or adopting a uniform break with a year between the adoption of the Protocol (1997) and when it went into effect (2005). All yield similar results

for our estimation. As for the non-Annex I economies, I do not distinguish if they are Parties to the UNFCCC or the Kyoto Protocol, as both treaties have almost universal coverage for UN members (with the United States being the only notable exception).

1.4.3 Other variables

The dependent variables used in the estimation are log trade flows or long-differenced log trade flows. For the main analyses, I use U.S. import data in Harmonized System (HS) 10-digits from the U.S. Census Bureau. The data for years 1990 to 2005 are obtained from Schott (2008), and those for years 2006 to 2010 are from data disks published by the Census Bureau (2007-2011). Data are then aggregated to the Iliad industry level, using HS to NAICS concordances provided by the Census Bureau and Pierce and Schott (2009), and NAICS to Iliad concordances from the Interindustry Forecasting Project at the University of Maryland (Inforum). 238 Iliad industries record positive trade flows in the data, out of which 215 are manufacturing industries. The panel of trade flows is unbalanced. There are many zeros or missing data for possible exporter-industry pairs, so the estimation results must be interpreted as conditional on positive trade flows.

Data on factor endowments, factor intensities of production and other country characteristics are from standard sources. Relative capital endowment is proxied by the capital-labor ratio from the Extended Penn World Tables (EPWT) (Marquetti, 2011), averaged for years 1990 to 2009. Relative human capital abundance is proxied by average years of education from Barro & Lee (2001). I use the data from 2000, which is the latest available. Capital and skill shares are calculated from value added, total payroll and production worker payroll data. The shares are averaged over 1990 to 2009. Data from 1990 to 2005 are from NBER CES manufacturing industry database (Becker & Gray, 2009); data from 2006 to 2009 are obtained from the Annual Survey of Manufactures (ASM) and 2007 Economic Census and Surveys by the U.S. Census

Bureau (2007, 2009-2010, 2008). Since the focus of the paper is on the cross-sectional pattern of trade and the time series variation over this short interval of time is likely to be small relative to cross-sectional variation across countries, I treat these country and industry specific measures as time invariant.

I also obtain income per capita, CO_2 emissions per capita and CO_2 intensity of GDP for each year from the EPWT (Marquetti, 2011). The survey based measure of stringency of a country's environmental regulations is from the Global Competitiveness Report (World Economic Forum (WEF), 2007).

1.5 Empirical Results

1.5.1 Baseline Results

In this section, I report results based on estimation of the cross-sectional specifications of equations (1.3)-(1.5). I first present here as baseline result a pure cross-sectional analysis of the data on U.S. imports in 2007 based on equation (1.3). I choose 2007 because it is the last year before the collapse of trade in the Great Recession, while late enough for the economies to adjust for policy changes brought about by the Kyoto Protocol. Regressions based on data from other years in mid to late 2000s yield similar results. The estimated coefficient for the interaction $CP_i s_E^k$ is negative and statistically significant, suggesting that the Annex I countries export less to the U.S. in emissions-intensive industries relative to the non-Annex I countries, which is consistent with the hypothesis that climate change policies are important for comparative advantage. In particular, it implies that for an industry with an emissions intensity half a standard deviation above the mean, such as the glass containers industry, an Annex I country will export on average just over 20% less to the U.S. than an non-Annex I country, controlling for general effects of country characteristics on all industries and common effects of industry specific factors on all countries This

effect is similar whether I consider all industries (column (1) of Table 1.6) or only manufacturing industries (column (2)), or whether I use the output based measure (columns (1) and (2)) or the value added based measure (column (3)) of emissions intensity.

CO_2 emissions-intensive industries are mostly energy-intensive industries, which are also likely capital intensive and less skill intensive. the Annex I countries are high income countries, generally with higher capital labor ratio as well as better education than the non-Annex I countries. Therefore one would worry that the results presented above are only a reflection of the factor endowments as determinants of comparative advantage. Regression results with controls for interactions of country factor endowment ratios and industry factor shares are reported in column (4) of Table 1.6. Adding controls for capital and skill interactions does reduce the magnitude of the estimated coefficient on the emissions interaction, however, it remains significant at five percent level, which suggests that the effect found for the interaction of emissions intensity and Annex I status is not merely capturing other classical determinants of comparative advantage. In addition, the magnitude of the effect of the emissions intensity interaction is similar to the factor intensity interactions. The estimated coefficient implies that an Annex I country would export about 29% less to the U.S. than a non-Annex I country in an industry with an emissions intensity one standard deviation above the mean. On the other hand, a country with one standard deviation above the mean in average schooling would export 38% more, than a country with a mean level of education, in an industry with a skill share one standard deviation above the mean. The interaction of capital-labor ratio and capital shares does not seem to have a significant effect.

1.5.2 Robustness

To ensure that the findings of the cross-sectional estimation are valid, I carry out some robustness analysis. Including country and industry fixed effects in the estimation already addresses a number of concerns, such as neutral differences in technology levels across countries that have common effect on exports across industries, or differences in the relative volume of U.S. imports across industries. One potential remaining problem in the estimation of equation (1.3) is that environmental regulation is partially determined by other country characteristics. In particular, it is possible that richer citizens care more about potential damages of climate change and demand more stringent climate change policies. Alternatively, it is possible that countries with higher emissions per capita feel more responsible to address climate change related issues. This leads to a positive correlation between climate change regulation and those country characteristics. If emissions intensity is also correlated with other industry characteristics, the omission of these other determinants of comparative advantage might bias the estimated effect of climate change policy on comparative advantage. To address this concern, I estimate equation (1.3) including controls for interactions of emissions intensity with emissions per capita, emissions intensity of the overall economy and income per capita. The results are reported in columns (2)-(4) and (6)-(8) of Table 1.7. The coefficient on the original interaction does not change a lot in magnitude but becomes less significant, yet none of the added interactions are significant, suggesting difficulty in isolating the effect associated with Kyoto commitment from others. Part of the reason could be the moderate correlation between these country characteristics and Annex I status. The Annex I countries are precisely the high income industrialized countries. Another possible issue could be nonlinearities similar to the environmental Kuznets curves (Grossman & Krueger, 1993; 1995; Dinda, 2004). A country could be specializing in less emissions-intensive industries because it actively mitigates emissions as a high-income country or because it does

not have the capacity for more emissions-intensive industries as a low-income country. It's possible such forces made the model less suitable when including such interactions, and large standard errors emerge. Nonetheless, since the main objective is to identify possible effects of climate change policies rather than the Kyoto Protocol per se, the results presented for the cross-sectional regressions remain meaningful as long as the emissions intensity is not highly correlated with other industry characteristics through which the omitted country characteristics have a differential effect on high and low emissions-intensive industries.

One potential issue related to variables used in the analysis is that of the highly skewed distribution of industry CO_2 emissions intensities, as described in section 1.4. There are no industries with intensities more than one standard deviation below the mean using either measure, while there are some industries with intensities more than two standard deviations above the mean, such as the lime, cement and fertilizer industries. Since these handful of industries have emissions intensities that are far from the rest, one potential concern is that the pattern of trade presented above may be driven solely by the small number of industries. To provide evidence on whether this is the case, I replicate the analysis on equation (1.3) excluding data from the industries with an emissions intensity more than 1.5 standard deviations above the mean based on the output based measure.[11] This translates into leaving out the 7 most emissions-intensive industries listed in Table 1.2. The results are presented in Table 1.8. All the results are qualitatively the same as those with full data (see Table 1.6). In fact, the estimated coefficients on the emissions interaction terms are substantially larger in magnitude compared to the baseline estimation. Therefore it seems that rather than driving the relationship between climate change policies and

[11]Iglewicz and Hoaglin (1993) recommend using the modified Z-score $M_i = 0.6745(x_i - \tilde{x})/\text{MAD}$ with MAD denoting the median absolute deviation and $\tilde{x}$ denoting the median, and label modified Z-scores with an absolute value of greater than 3.5 as potential outliers. Industries with an intensity measure $s^k_{E,T}$ 1.5 standard deviation above the mean have a modified Z-score of more than 4 based on log intensities.

trade patterns, the most emissions-intensive industries seem to be lagging in response. This echoes with previous findings that the most emissions-intensive industries often receive protection from national climate change policies in the form of subsidies or exceptions, and the actual effect on such industries are much smaller compared to other unprotected industries (World Bank, 2008).

Table 1.9 presents the results of the baseline estimation using an alternative measure of the stringency of a country's climate change regulations. A survey based measure of stringency of environmental policy is used in the place of the indicator variable for Kyoto commitment. It is not surprising that a similar pattern is found in that a country with more stringent environmental regulations tends to export less to the U.S. in more CO_2 emissions-intensive industries. After all climate change policies are part of environmental regulations. Indeed, Annex I status is highly correlated with the stringency of a country's environmental regulations, at about 0.8. In addition, the survey measure provides much finer detail than the binary indicator for Annex I status. The advantage of using the Kyoto commitment as the variable for the estimation, however, is that it is directly related to an actual policy commitment that specifically addresses the issue of climate change, allowing the results to have a more meaningful interpretation.

Another concern arises regarding the particular composition of the Annex I and the non-Annex I groups. Countries were not randomly assigned to be Annex I parties and there are substantial differences between the two groups. In particular, the Annex I countries are industrialized countries which tend to have higher income per capita and a more developed manufacturing sector, both of which are closely related to international trade flows. Therefore, it is not easy to find the perfect comparison group among the non-Annex I countries. To partly address this concern, I present results using different comparison groups in Table 1.10. The reported pattern of specialization remains the same when excluding the observations on low income countries, low and

lower-middle income countries, or low and middle income countries. In addition, it is noted that including or excluding any particular country, such as China or Germany, does not alter the reported results.

Lastly, I report estimation results using an alternative set of data. Since the previously reported results are based on U.S. imports data only, one may question the generality of the findings. I conduct the same analysis using data from the Industrial Demand-Supply Balance (IDSB) database from United Nations Industrial Development Organization (UNIDO). As Table 1.11 shows, the results exhibit a similar pattern whether industrial output or exports to the rest of the world are used, suggesting the reported relationship between Kyoto commitment and trade patterns is not solely driven by using U.S. data and offering some direct evidence that climate change policy is related to industry composition.

1.5.3 Within-Annex I Heterogeneity

As discussed in section 1.3, a concern of using Annex I status, a binary variable, as the measure for climate change policies is that only an average effect is identified. It is informative to investigate if there are substantial variations in the effects within the Annex I group. To explore the potential differences, I regress log imports on interactions of emissions intensity with indicator variables for each of the Annex I countries, as specified in equation (1.4). I plot the estimated coefficients on the interaction term of emissions intensity with individual Annex I country indicators against a crude measure of the restrictiveness of their Kyoto commitment in figure 1.4. The restrictiveness is proxied by the difference between the level of a country's GHG emissions in 1998 and its quantified target level specified in the Kyoto Protocol, as a percentage of the country's emissions in the baseline year.[12] A positive number means

[12]This restrictiveness measure is calculated by taking the difference between the change from baseline to 1998 (column Δ(90-98)) and the emissions reduction target (column Target) reported in table 1.1. The year 1998 is chosen since the Kyoto Protocol was adopted in December of 1997

that the country is emitting more in 1998 than its target level in the commitment period of 2008-2012 and needs to actively reduce emissions for compliance; the higher the number the more restrictive is the country's commitment. A weakness of this measure is that it does not take into account the heterogeneity in expected growth rates among the countries. With a same (positive or not very negative) score, a country expecting to grow at a higher rate into the commitment period will face a tougher challenge of meeting the emissions target compared to one with a slower growth rate. Nonetheless, it is a convenient measure that offers interesting insights.

Figure 1.4 shows a clear correlation between the restrictiveness of a country's Kyoto commitment and its patterns of specialization. Countries whose commitment actually entails active reduction of emissions (those on the right half of the graph) tend to specialize in less emissions-intensive industries (in the bottom half of the graph) relative to non-Annex I countries in 2007, hence the concentration in the lower right quadrant. On the other hand, Russia, Belarus, Ukraine and a few others (in the upper left quadrant) have a significantly positive coefficient on the emissions interaction term, suggesting that they actually tend to specialize in emissions-intensive industries relative to an average non-Annex I country. Not surprisingly, these are the EIT countries with plenty of room to spare based on their commitments under the Kyoto Protocol. With their economies in drastic transition in the 1990s, these countries have a much lower emissions level compared to the base years around 1990 (see figure 1.2 and Table 1.1). Therefore, there is not much pressure for them in meeting the commitment in the 2008-2012 period and consequently little incentive to ramp up climate change regulations. The substantial within-Annex I heterogeneity found in this analysis suggest that the actual restrictiveness needs to be considered when assessing climate change policies. In the case of the Kyoto Protocol, the impact on EIT and non-EIT countries can be very different.

and countries were deciding whether to sign the Protocol in 1998. Using other years in late 1990s or early 2000s does not alter the main feature of the plot.

1.5.4 Comparison between Country Groups

The analyses above have provided strong evidence that stringent climate change policies signified by commitment under the Kyoto Protocol is associated with exporting relatively less in CO_2 emissions-intensive industries. As discussed in section 1.3, in addition to exploiting the difference between the Annex I and the non-Annex I countries, it is also informative to separately analyze the pattern of specialization with respect to industry emissions intensity for the two groups. Since the previous analysis has identified substantial heterogeneity within the Annex I countries, particularly between the EIT and non-EIT countries, I will estimate equation (1.5) for three groups of countries: Annex I non-EIT, Annex I EIT and non-Annex I countries. Results are reported in Table 1.12 for all industries and manufacturing industries respectively. The patterns found are very similar whether or not the interaction terms of factor shares and relative factor endowments are included. The only statistically significant coefficient of interest is the one on the emissions intensity for the Annex I non-EIT countries. On average, these countries export about 25% less to the U.S. in an industry compared to another that has an emissions intensity one standard deviation lower. The fact that those countries with restrictive Kyoto commitments do tend to specialize in less emissions-intensive industries suggests that the Kyoto Protocol is indeed associated with more stringent climate change policies with discernible effects on economic activities in countries with meaningful commitment to reduce emissions. On the other hand, the coefficients for emissions intensity for the Annex I EIT and the non-Annex I countries are not statistically significant from zero. Therefore there is insufficient evidence that countries with less stringent climate change policies are specializing in emissions-intensive industries. Nonetheless it is the difference across the groups of countries that matters in assessing the effects of the policy, as specified in the baseline regression.

1.6 Endogeneity

As discussed in section 1.3, one must be cautious in interpreting the cross-sectional results presented in the previous section. This is because causality may run from trade flows to climate change policy. Countries may have chosen to become Annex I Parties to the UNFCCC and commit to quantified targets under the Kyoto Protocol when they were already specializing in less emissions-intensive industries. To address this concern, I exploit the time dimension of the data on trade flows and present three sets of results that provide evidence against this potential alternative explanation.

1.6.1 Panel Specification

As explained in section 1.3, I pool the cross sectional data for each year and use the full panel for an estimation of equation (1.6). I characterize the change in the regression coefficient of the interaction term of emissions intensity and Annex I status before and after a country ratified the Kyoto Protocol, by including two sets of interaction variables: a time-invariant one, based on a country's commitment under the Protocol, and the other time-varying one, only positive for years after a country's ratification. The regression includes industry-year fixed effects, which capture any factor that affects export in all countries in the same way in a given industry year, as well as country-year fixed effects, which capture the factors that influence exports in all industries in the same manner for a given country year.

Results are shown in Table 1.13. In columns (1) and (3), only the time-varying interaction term is included in the panel regression, implicitly assuming that there was nothing special about an Annex I country prior to ratifying the Kyoto Protocol, with respect to specialization in (less) emissions-intensive industries. The significantly negative coefficient is of comparable magnitude to the coefficients found in the cross-sectional regression with data from 2007, suggesting that the results of the cross-

sectional regression presented in section 1.5 are representative of the period after most Annex I countries' ratification of the Kyoto Protocol. In columns (2) and (4), both the time-varying and the time-invariant interactions are included. The coefficient on the time-varying term is still highly significant and is about a little less than half of the magnitude of that as a single regressor. The significant coefficient represents a change in patterns of the Annex I countries' specialization relative to the non-Annex I countries after the Kyoto Protocol. It is consistent with the idea that ratifying the Protocol does signal a more stringent climate change policy and the resulting higher cost of emissions makes the Annex I countries export less than before in CO_2 emissions-intensive industries. On the other hand, the coefficient on the time-invariant term is of larger magnitude than that on the time-varying term, but is only significant at the 10level, lending only weak support to the hypothesis that the Annex I countries had been exporting relatively less in emissions-intensive industries prior to ratifying the Kyoto Protocol. When the factor interactions are included (column (5)), the coefficient on the time-varying term is smaller in magnitude but remains significant at five percent level, while that on the time-invariant term becomes insignificant. This suggest that at the specialization pattern of the Annex I countries prior to Kyoto can be largely explained by differences in relative factor endowment, particularly skill abundance, while the change in the trade patterns after Kyoto likely comes from sources other than relative factor endowment, for instance, the more stringent climate change policies. In sum, the evidence provided by the full panel estimation suggests that the cross-sectional results in section 1.5 indeed represent an effect that can be associated with the Kyoto Protocol and controlling for factor interactions likely takes care of the weak pre-Kyoto specialization patterns.

1.6.2 Time-varying Coefficients

A closely related approach to address the selection issue is to estimate equation (1.3) for each year from 1990 to 2010 and check whether the patterns of trade with respect to varying emissions intensities have changed before and after the Kyoto Protocol. As discussed in section 1.3, this approach is more general than the full panel specification to the extent that it allows the coefficient on emissions interactions to vary flexibly over time, enabling a closer look for possible pre-trends and the evolution in the aftermath of the Kyoto Protocol. Figure 1.5 presents the series of the estimated coefficients on the emissions interaction term along with 95underlying regressions include factor interactions in addition to exporter and industry fixed effects. Standard errors are two-way clustered by country and industry.

The series seems to be rather flat and not different from zero until the year 2000, after which there is a clear downward trend, coinciding with the period that the Annex I countries ratified the Kyoto Protocol. Eventually, it becomes statistically different from zero. This is consistent with the previous findings that there is little evidence that the Annex I countries were exporting less emissions-intensive goods before the Kyoto Protocol, and the policy change signified by the ratification of the Protocol does have a statistically significant effect. Namely, the pattern that an Annex I country exports less in emissions-intensive industries relative to an non-Annex I country emerged after the adoption of the Kyoto Protocol in late 1997 and eventually becomes statistically significant as it approaches the commitment period of the Protocol. The fact that the coefficient is close to zero and not moving much prior to Kyoto provides evidence that there was not a preexisting trend for the Annex I countries to shift toward cleaner exports. Thus there is no evidence that endogenous selection into Annex i status is driving the results.

I further analyze the two sets of countries separately, estimating equation (1.5) for the Annex I and the non-Annex I countries separately. This allows me to analyze

the evolution of the trade patterns of the two groups separately. The series of the coefficients on emissions intensity are presented in figure 1.6. It is clear that although the coefficient for the Annex I countries is generally below zero and that for the non-Annex I countries above zero, they are not significantly different from each other until later in the period. Starting in the late 1990s, concurrent with the adoption of the Kyoto Protocol, there seems to be a diverging trend. Most of the increasing differences between the two groups are attributed to the decreasing trend of the coefficient for the Annex I Parties. It suggests that the more stringent climate change policies indeed mainly affect economic activities in countries that adopt them. There seems to be little evidence that the non-Annex I countries are moving toward specializing in more emissions-intensive industries, corroborating similar findings by Douglas and Nishioka (2009). This is an interesting observation since it suggests the general equilibrium relocation of production does not seem to have happened. Therefore the dreaded carbon leakage may not be as serious as some have feared, at least not through a composition channel. Since the data used are U.S. imports, this could be explained by either the U.S. domestic production moving toward more emissions-intensive industries or the U.S. demand moving toward less emissions-intensive industries. It warrants further analysis to see if the general equilibrium effect is indeed lacking in more comprehensive data. To summarize, the analysis on time-varying coefficients for both equations (1.3) and (1.5) confirms the findings in the panel specification and suggest that endogenous selection is unlikely a serious problem for the cross-sectional analysis in section 1.5.

1.6.3 Long Difference Specification

Another way to examine the impact of the Kyoto Protocol in changing export patterns is to estimate equation (1.7), with the specification in long differences. As discussed in section 1.3, the estimation is based on the intuition that the ratification

of Kyoto Protocol constitutes a policy change for the Annex I countries. The fixed effects in the regression now control for the average growth rate of industry trade flows for each exporter and each industry. In reality it takes time for the real economy to respond to policy changes, therefore I exploit the changes in trade flows before and after the adoption (ratification) of the Kyoto Protocol to see if taking on a quantified emissions target under the Kyoto Protocol as an Annex I Party mattered for the patterns of trade. I look at changes between 1992 and 1999 and between 2000 and 2007. The reason for choosing 1999/2000 as the breaking point is that most countries signed the Protocol in 1998 or 1999 but did not ratify it until the early 2000s. In addition, the Protocol did not enter into force until 16 February 2005. Choosing other reasonable years yields similar results. Table 1.14 shows that the effect of Annex I status of an exporter on the growth of U.S. imports is significant for the Kyoto period, suggesting that committing to emissions abatement under the Protocol does make a country shift away from exporting emissions-intensive goods relative to non-committed economies. On the other hand, no effect is found for the pre-Kyoto period, again providing strong evidence that there had not been a pre-Kyoto trend for the Annex I countries to specialize in less emissions-intensive industries.

Exploiting the time dimension of the trade data, I am able to address the potential selection issue with a number of approaches. I find no evidence that the Annex I countries exported less in emissions-intensive industries prior to the adoption of the Kyoto Protocol. Rather, there is a statistically significant decline in their export in such industries following the ratification of the Protocol. This pattern is consistent with an impact of the Kyoto Protocol on patterns of specialization across industries and on overall emissions through a change in the composition of exports and production.

1.7 Conclusion

In this paper I empirically assess the impact of climate change policies on economic activities using detailed data on industry CO_2 emissions intensities and U.S. imports from 1990 to 2010. Using estimation strategies informed by recent developments in quantitative general equilibrium models of international trade, I find that climate change regulations are an important determinant of comparative advantage in emissions-intensive industries. In particular, the Annex I countries which commit to quantified emissions targets under the Kyoto Protocol export less in CO_2 emissions-intensive industries. The pattern is particularly strong for countries that have restrictive emissions targets which call for active mitigation in compliance. The result is robust to a variety of specification checks out of concern for the particular variables used in the estimation. The magnitude of the effect is comparable to that of traditional determinants of comparative advantage, namely relative factor endowments. Exploiting the panel structure of the data, I show that the pattern found for years after the Kyoto Protocol went into effect (in 2005) was absent in years prior to or immediately after the adoption of the Protocol (in 1997). It gradually emerged as countries signed and ratified the Protocol in the early 2000s. This result suggests that more stringent climate change policies can affect industry composition in countries that administer such policies. On the other hand, there is insufficient evidence that countries not committed to reduce carbon emissions are becoming more specialized in emissions-intensive industries. Policy makers should take into account such effects on industry structure when evaluating climate change policies, particularly the unilateral mitigation schemes. With a truly global mechanism, the effects on industry structure and patterns of trade could be quite different from those found here.

Bibliography

Aichele, R. & Felbermayr, G. (2010). "Kyoto and the carbon content of trade," FZID Discussion Paper 10-2010.

Atkinson, G., Hamilton, K., Ruta, G., & van der Mensbrugghe, D. (2010).. "Trade in 'virtual carbon': Empirical results and implications for policy," Background paper to the 2010 World Development Report, Policy Research Working Paper No. 5194.

Barro, R.J. & Lee, J.W. (2000). "International Data on Educational Attainment: Updates and Implications", CID Working Paper No. 42.

Becker, R.A. & Gray, W.B. (2009). "NBER-CES manufacturing industry database." Available at http://www.nber.org/data/nbprod2005.html.

Boden, T.A., Marland, G., & Andres, R.J. (2011). "Global, regional, and national fossil-fuel CO_2 emissions," Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tenn., USA. doi 10.3334/CDIAC/00001_V2011

Broner, F., Bustos, P., & Carvalho, V. M. (2011). "Sources of comparative advantage in polluting industries." Unpublished.

Chor, D. (2010). "Unpacking sources of comparative advantage: A quantitative approach," *Journal of International Economics*, *82*, 152-167.

Chua, S. (1999) "Economic growth, liberalization, and the environment: A review of the economic evidence," *Annual Review of Energy and the Environment*, *24*, 391-430.

Copeland, B.R. & Taylor, M.S. (2001). "International trade and the environment: A framework for analysis," NBER Working Paper No. 8540.

Copeland, B.R. & Taylor, M.S. (2005). "Free trade and global warming: A trade theory view of the Kyoto Protocol," *Journal of Environmental Economics and Management*, *49*, 205-234.

Demailly, D. & Quirion, P. (2006).. "Leakage from climate policies and border tax adjustment:lessons from a geographic model of the cement industry," Working Papers halshs-00009337, HAL.

Demailly, D. & Quirion, P. (2008). "European Emission Trading Scheme and competitiveness: A case study on the iron and steel industry," *Energy Economics*, *30*, 2009-2027.

Dinda, D. (2004). "Environmental Kuznets curve hypothesis: A survey," *Ecological Economics*, *49*, 431-455.

Douglas, S. & Nishioka, S. (2009). "International differences in emissions intensity and emissions content of global trade," Working Papers 09-02, Department of Economics, West Virginia University.

Eaton, J. & Kortum, S. (2002). "Technology, geography, and trade," *Econometrica*, *70*, 1741-1779.

Economics and Statistics Administration, U.S. Department of Commerce. (2010). "US carbon dioxide emissions and intensities over time: A detailed accounting of industries, government and households." Available at: http://www.esa.doc.gov/Reports/u.s.-carbon-dioxide.

Ederington, J., Levinson, A., & Minier, J. (2005). "Footloose and pollution-free," *Review of Economics and Statistics*, *87*, 92-99.

Frankel, J. (2009). "Environmental effects of international trade," HKS Faculty Research Working Paper RWP09-006.

Gerlagh, R. & Mathys, N.A. (2011). "Energy abundance, trade and industry location," Fondazione Eni Enrico Mattei Working Papers #554.

Grossman, G.M. & Krueger, A.B. (1993). "Environmental impacts of a North American free trade agreement," in Garber, P. (ed.), *The Mexico-U.S. Free Trade Agreement*, M.I.T Press, 1993.

Grossman, G.M. & Krueger, A.B. (1995). "Economic growth and the environment," *Quarterly Journal of Economics*, *110*, 353-377.

Grubb, M. (2003). "The economics of the Kyoto Protocol," *World Economics*, 4, 143-189.

Grubb, M., Brewer, T., Sato, M., Heilmayr, R., & Fazekas, D. (2009). "Climate policy and industrial competitiveness: Ten insights from Europe on the EU Emissions Trading System," German Marshall Fund. Available at: http://www.climatestrategies.org/component/reports/category/61/204.html.

Grunewald, N. & Martínez-Zarzoso, I. (2011). "How well did the Kyoto Protocol work? A dynamic-GMM approach with external instruments," Ibero America Institute for Econ. Research (IAI) Discussion Paper 212.

Iglewicz, B. & Hoaglin, D.C. (1993). "How to detect and handle outliers," *The ASQC Basic References in Quality Control: Statistical Techniques*, Volume 16, Milwaukee, WI: ASQC Quality Press.

Intergovernmental Panel on Climate Change (IPCC). (2007). "Summary for policymakers," in Metz, B., Davidson, O.R., Bosch, P.R., Dave, R., & Meyer, L.A. (eds.), *Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press.

Minx, J.C., Wiedmann, T., Wood, R. Peters, G.P. Lenzen, M., Owen, A., ..., Ackerman, F. (2009). "Input-output analysis and carbon footprinting: An overview of applications," *Economic Systems Research*, *21*, 187-216.

Karp, L. (2010). "Reflections on carbon leakage." Unpublished.

Karp, L. (forthcoming). "The environment and trade: A review," forthcoming, *Annual Review of Resource Economics*.

Keller, W. & Levinson, A. (2002). "Pollution abatement costs and foreign direct investment inflows to US states," *Review of Economics and Statistics*, *84*, 691-703.

Levchenko, A. (2007). "Institutional quality and international trade," *Review of Economic Studies*, *74*, 791-819.

Levinson, A. (2009). "Technology, international trade, and pollution from US manufacturing," *American Economic Review*, *99*, 2177-2192.

Levinson, A. & Taylor, M. S. (2008). "Unmasking the pollution haven effect," *International Economic Review*, *49*, 223-254.

List, J.A., Millimet, D.L., Fredriksson, P.G., & McHone, W.W. (2003). "Effects of environmental regulations on manufacturing plant births: Evidence from a propensity score matching estimator," *Review of Economics and Statistics*, *85*, 944-952.

Marquetti, A. (2011). "Extended Penn world tables." Available at http://homepage.newschool.edu/~foleyd/epwt/.

Nunn, N. (2007). "Relationship-specificity, incomplete contracts, and the pattern of trade," *Quarterly Journal of Economics*, *122*, 569-600.

Peters, G.P. & Hertwich, E.G. (2008). "CO_2 embodied in international trade with implications for global climate," *Environmental Science and Technology*, *42*, 1401-1407.

Pierce, J.R. & Schott, P.K. (2010). "Concording US Harmonized System codes over time." Available at: http://faculty.som.yale.edu/peterschott/sub_international.htm.

Reinaud, J. (2008). "Climate policy and carbon leakage: Impacts of the European Emisisons Trading Scheme on Aluminium," *International Energy Agency Information Paper*. Available at: http://www.iea.org/publications/free_new_Desc.asp?PUBS_ID=2055.

Romalis, J. (2004). "Factor proportions and the structure of commodity trade," *American Economic Review*, *94*, 67-97.

Schott, P.K. (2008). "The relative sophistication of Chinese exports," *Economic Policy*, *23*, 5-49.

Sinn, H.W. (2008). "Public policies against global warming: A supply side approach," *International Tax and Public Finance*, *15*, 360-394.

Su, B., Huang, H.C., Ang, B.W., and Zhou, P. (2010). "Input–output analysis of CO_2 emissions embodied in trade: The effects of sector aggregation," *Energy Economics*, *32*, 166–175.

UNFCCC. (2011). *Total CO_2 Equivalent Emissions without Land Use, Land-Use Change and Forestry.* Available at: http://unfccc.int/ghg_data/ghg_data_unfccc/time_series_annex_i/items/3814.php.

UNIDO. (2011). *Industrial Demand-Supply Balance Database*, Vienna, Austria: Statistics and Information Networks Branch, UNIDO.

U.S. Census Bureau. (2007-2011). *US Imports Merchandise Trade, 2006-2010*, Washington, DC: US Census Bureau.

U.S. Census Bureau. (2007, 2009-2010). *Annual Survey of Manufactures (ASM), 2006, 2008-2009.* Available at: http://factfinder.census.gov/servlet/DatasetMainPageServlet?_program=EAS.

US Census Bureau. (2008). *2007 Economic Census and Surveys.* Available at: http://factfinder.census.gov/servlet/DatasetMainPageServlet?_program=ECN.

U.S. Environmental Protection Agency. (2009). "The effects of H.R. 2454 on international competitiveness and emission leakage in energy-intensive trade-exposed industries." Available at: http://www.epa.gov/climatechange/economics/pdfs/InteragencyReport_Competitiveness-EmissionLeakage.pdf.

Wang, T. (2014). "Technology, international trade, and carbon emissions from US industry." Unpublished.

World Economic Forum. (2007). *The Global Competitiveness Report 2007-2008.* Geneva: World Economic Forum.

Wiedmann, T., Lenzen, M., Turner, K. & Barrett, J. (2007). "Examining the global environmental impact of regional consumption activities – Part 2: Review of input-output models for the assessment of environmental impacts embodied in trade," *Ecological Economics*, *61*, 15-26.

Yörük, B.K. & Zaim, O. (2008). "International regulations and environmental performance," *Applied Economics*, *40*, 807-822.

Zeng, K. & Eastin, J. (2007). "International economic integration and environmental protection: The case of China," *International Studies Quarterly*, *51*, 971-995.

Zhou, X., Kojima, S., & Yano, T. (2010). "Addressing carbon leakage by border adjustment measures: Review of current studies," mimeo, Institute for Global Environmental Strategies. Available at: http://enviroscope.iges.or.jp/modules/envirolib/view.php?docid=3290.

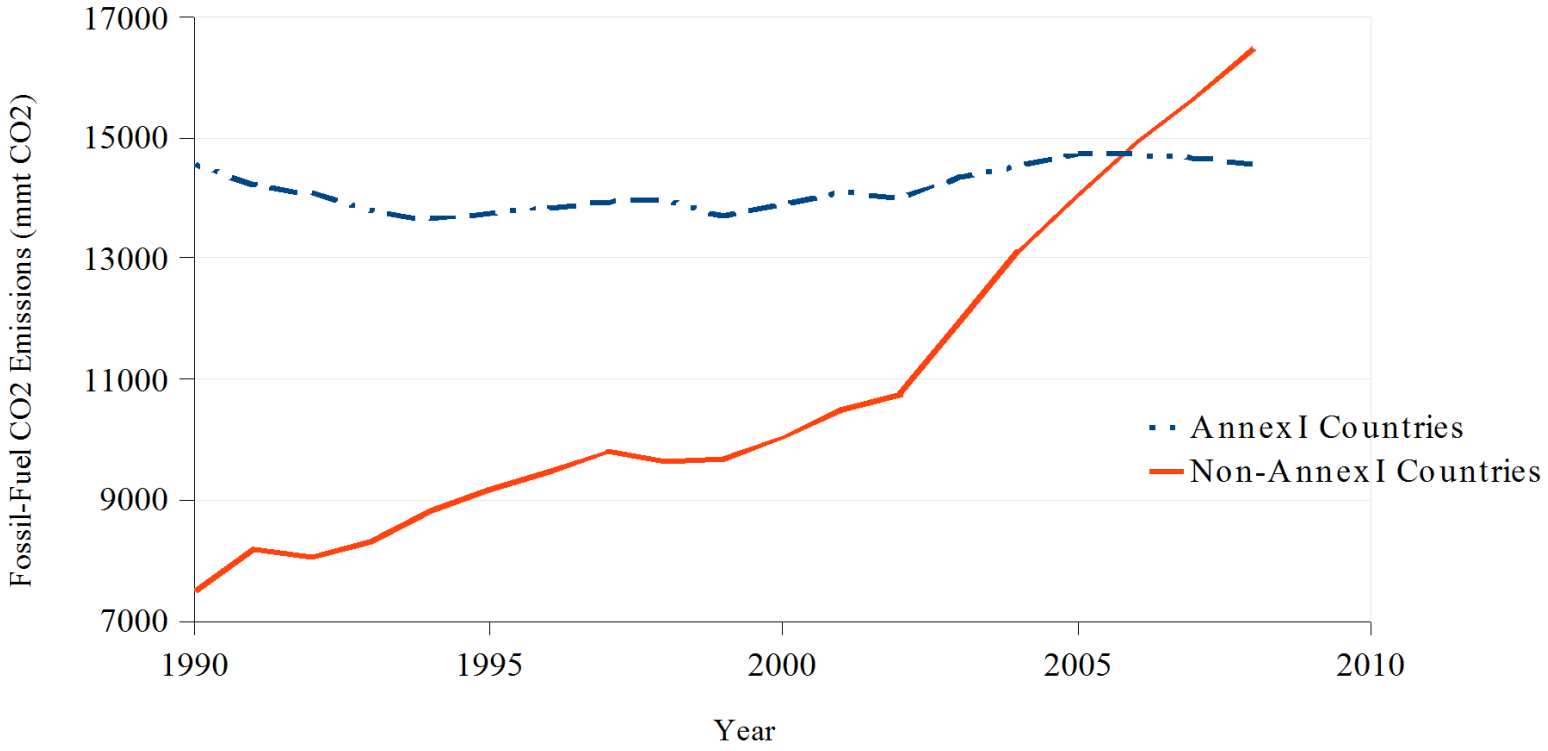


Figure 1.1: Fossil-Fuel CO_2 Emissions From Annex I and non-Annex I Countries

Data source: Boden, Marland, & Andres, 2011.

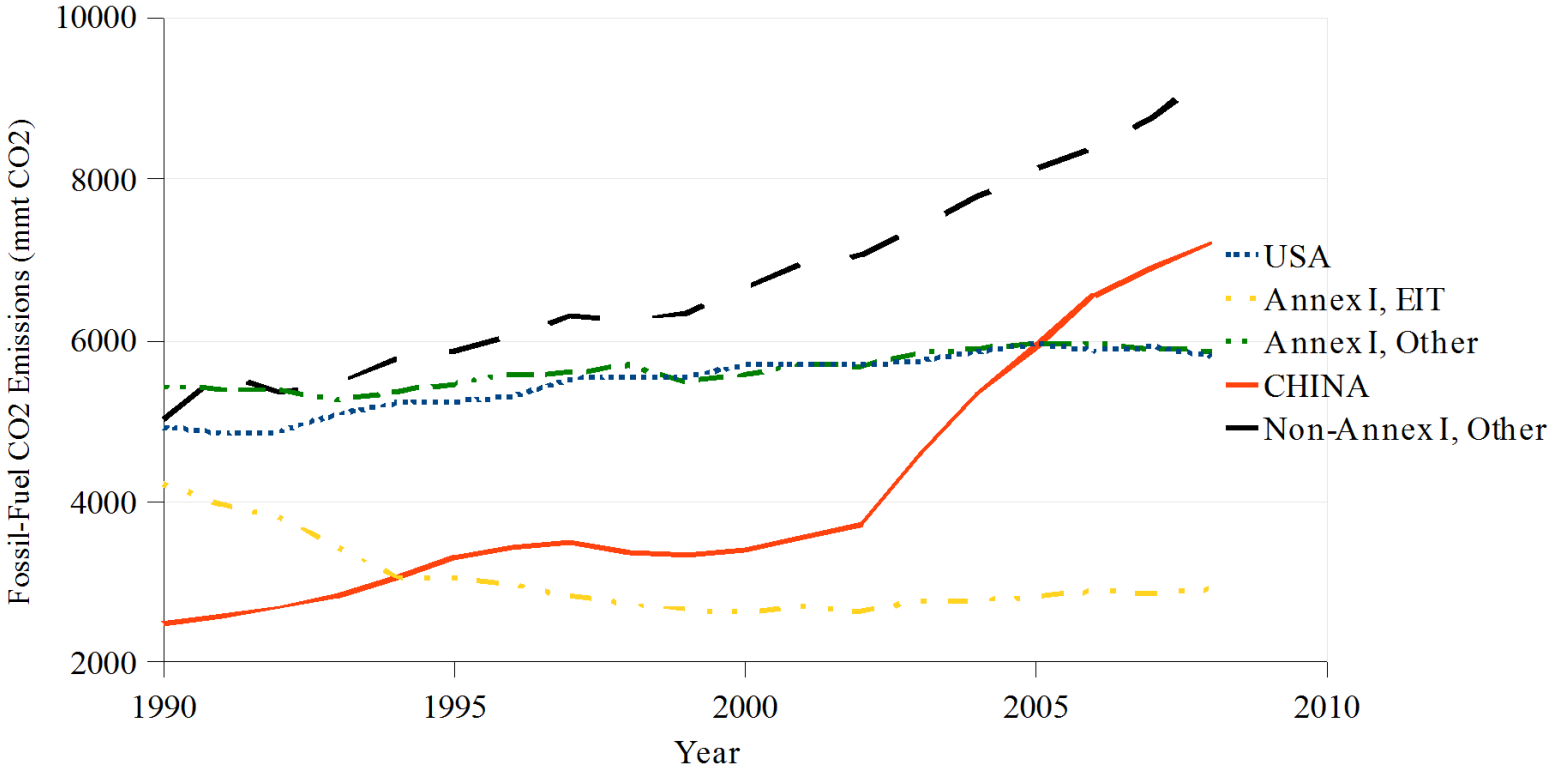


Figure 1.2: Fossil-Fuel CO_2 Emissions from Selected Country Groups

Data source: Boden, Marland, & Andres, 2011.

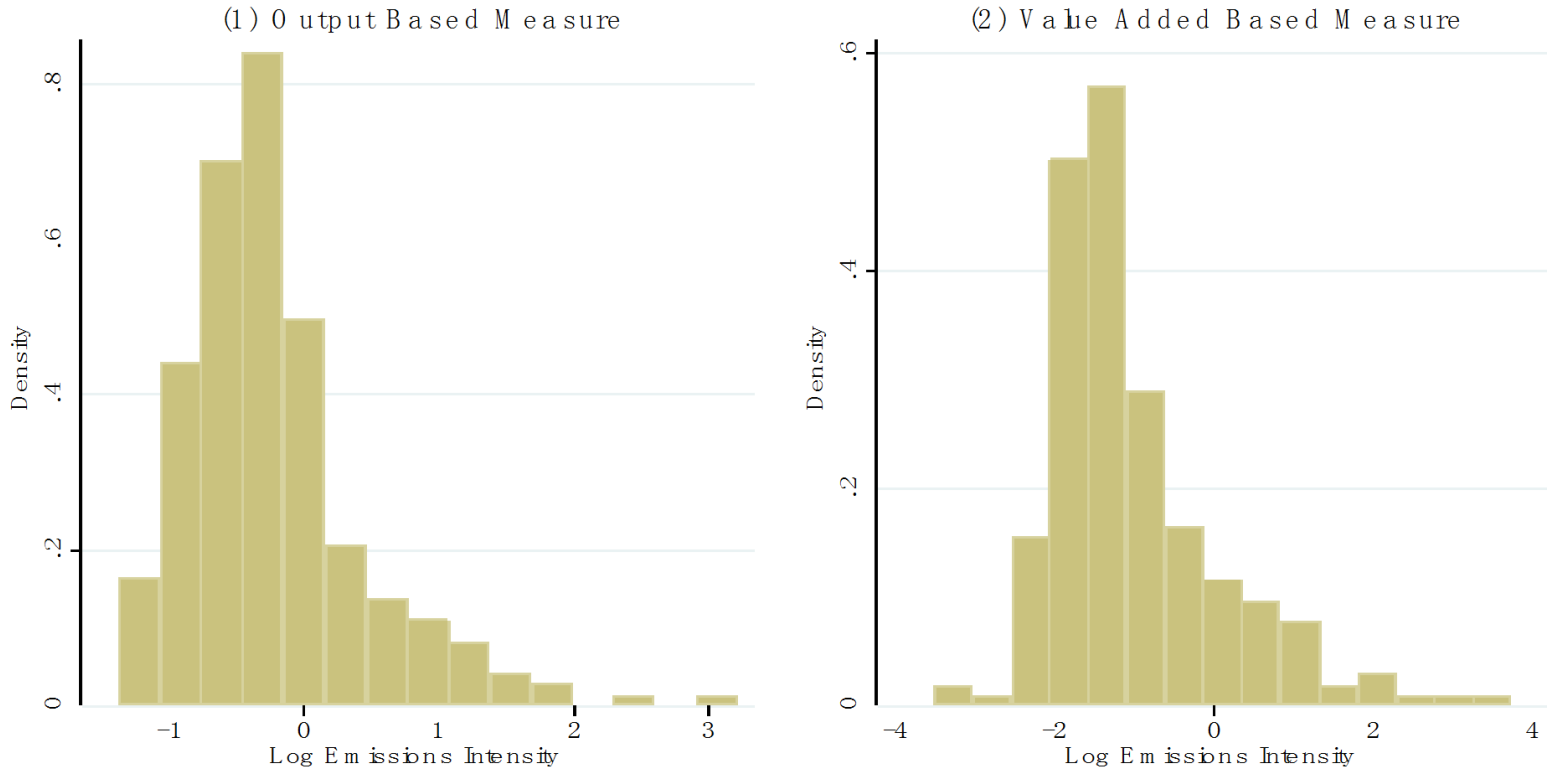


Figure 1.3: Distribution of CO_2 Emissions Intensities

Note: Histograms shown are for log of the emissions intensities.
Data source: ESA, 2010; Becker & Gray, 2009.

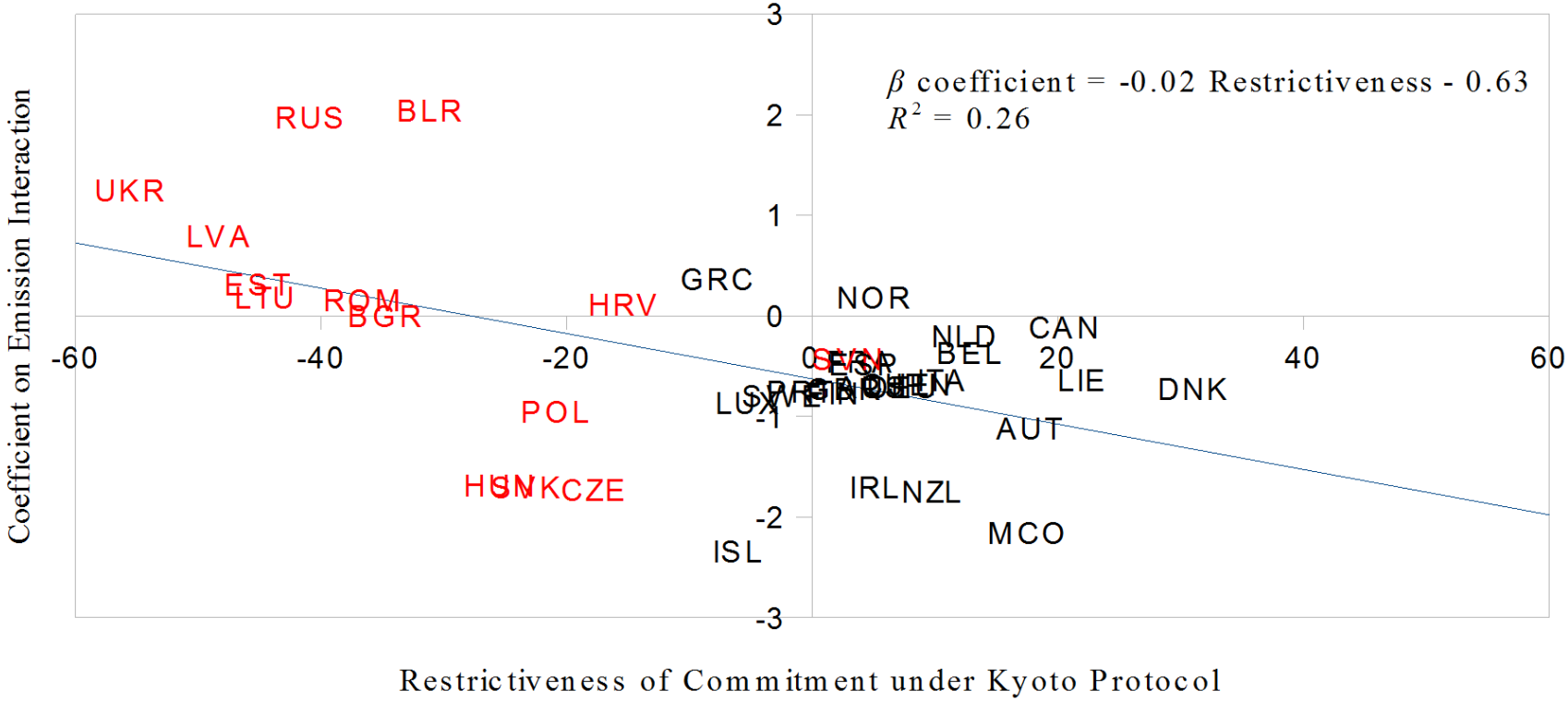


Figure 1.4: Heterogeneity and Restrictiveness of Kyoto Commitment

Note: Each data point is an Annex I country. Regression coefficients are obtained from estimating equation (1.4) using data for manufacturing industries in 2007. Factor interactions are not included as data are not available for all Annex I countries. Restrictiveness is measured as the difference between 1998 emissions level and the target level for 2008-2012 as a percentage of baseline emission level (1990).

Red country codes denote EIT countries. Equation for trend line is given at top right.

Data source: UNFCCC and author's calculation.

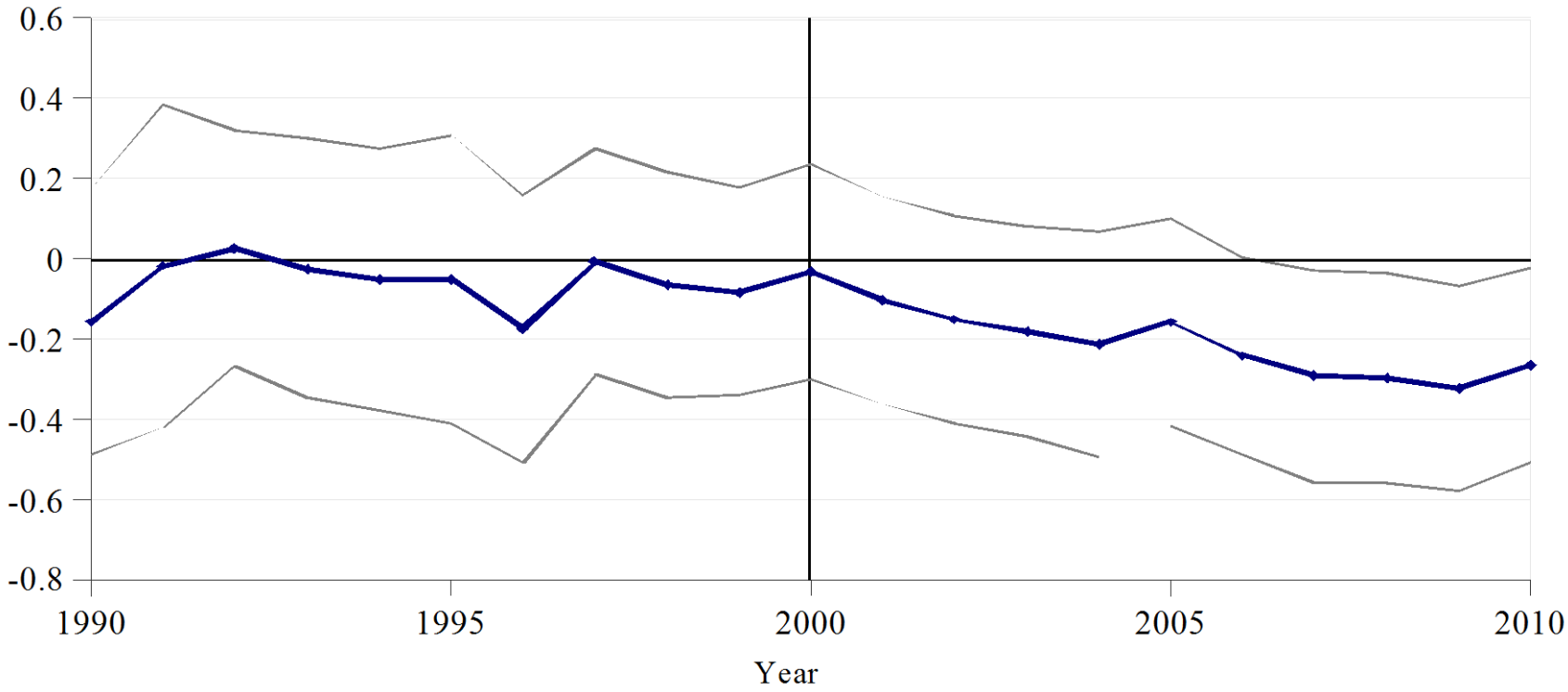


Figure 1.5: Time-varying Coefficient on Emissions Intensity × Annex I Status

Note: Coefficients are obtained from estimating equation (1.3) using data on manufacturing industries for each year. Factor interactions and exporter and industry fixed effects are included. Confidence intervals are based on standard errors two-way clustered by exporter and industry.

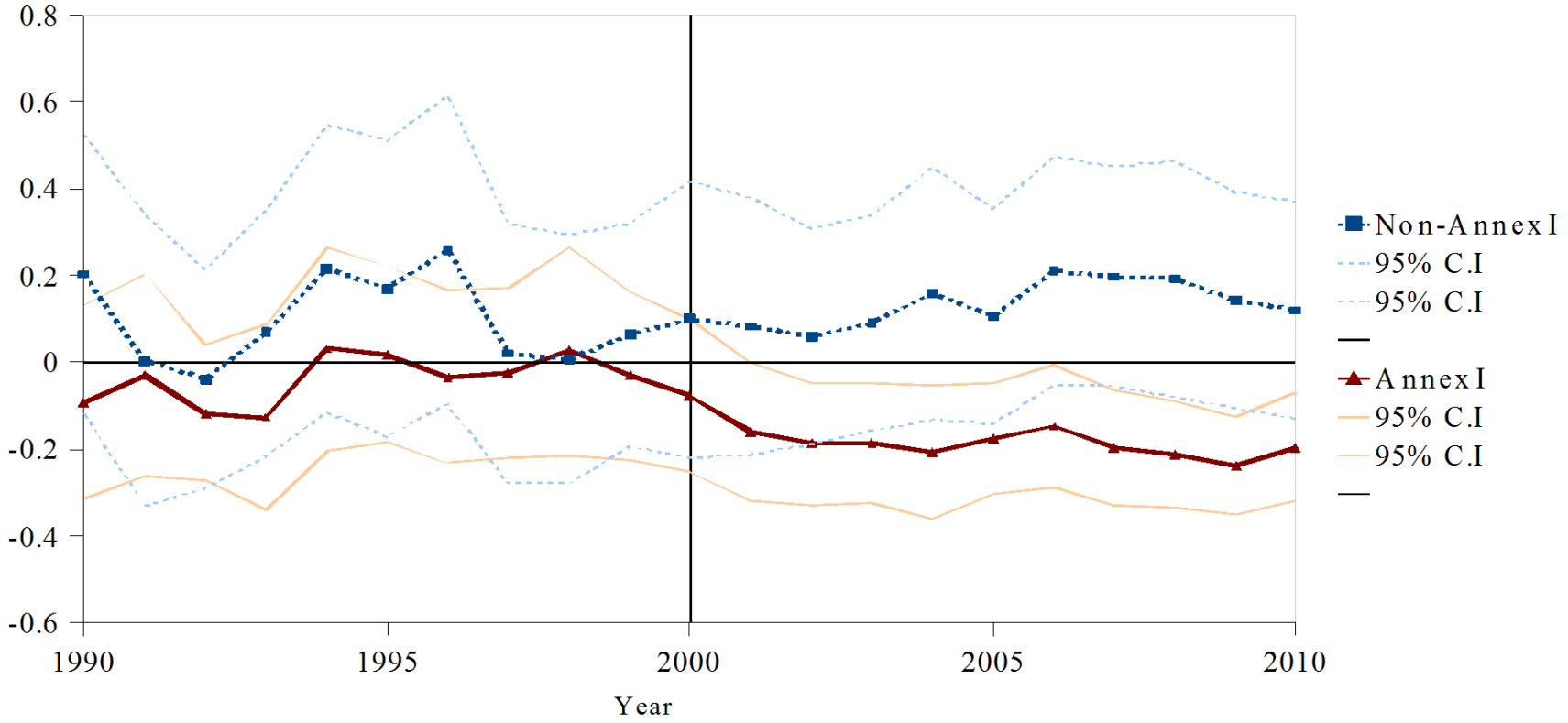


Figure 1.6: Time-varying Coefficient on Emission Intensity by Annex I Status

Note: Coefficients are obtained from estimating equation (1.5) using data on manufacturing industries for each year. Factor shares, factor interactions and exporter fixed effects are included. Confidence intervals are based on standard errors two-way clustered by exporter and industry.

Table 1.1: Annex I Parties to the UNFCCC and Commitments under the Kyoto Protocol

Party	Date of Ratification	Target[a] Ax.B	Target[a] Art.4[b]	Base Level[c]	Δ 90-98[d]	Party	Date of Ratification	Target Ax.B[a]	Base Level[c]	Δ 90-98[d]
EU (15).[b]	May 2002	-8	-8		-1.7	Croatia*	May 2007	-5		-20.3
Austria	May 2002	-8	-13	0.4	4.7	Czech*	Nov 2001	-8	1.2	-25.7
Belgium	May 2002	-8	-7.5	0.8	5.4	Estonia*	Oct 2002	-8	0.3	-53.0
Denmark	May 2002	-8	-21	0.4	10.2	Hungary*[a]	Aug 2002	-6	0.5	-31.4
Finland	May 2002	-8	0	0.4	1.8	Iceland	May 2002	10	0.0	4.1
France	May 2002	-8	0	2.7	4.1	Japan	Jun 2002	-6	8.5	2.8
Germany	May 2002	-8	-21	7.4	-13.6	Latvia*	Jul 2002	-8	0.2	-56.1
Ireland	May 2002	-8	13	0.2	18.2	Liechtenstein	Dec 2004	-8	0.0	14.2
Italy	May 2002	-8	-6.5	3.1	4.2	Lithuania*	Jan 2003	-8		-52.4
Greece	May 2002	-8	25	0.6	17.3	Monaco	Feb 2006	-8	0.0	9.7
Luxembourg	May 2002	-8	-28	0.1	-33.2	New Zealand	Dec 2002	0	0.2	9.9
Netherlands	May 2002	-8	-6	1.2	6.5	Norway	May 2002	1	0.3	6.2
Portugal	May 2002	-8	27	0.3	26.1	Poland*	May 2002	-6	3.0	-26.7
Spain	May 2002	-8	15	1.9	19.3	Romania*	Mar 2001	-8	1.2	-44.4
Sweden	May 2002	-8	4	0.4	1.8	Russia*	Nov 2004	0	17.4	-40.7
U.K.	May 2002	-8	-12.5	4.3	-9.7	Slovakia*	May 2002	-8	0.4	-31.0
Australia	Dec 2007	8		2.1	13.0	Slovenia*	Aug 2002	-8		-5.0
Belarus*#	Aug 2005	-8			-39.0	Switzerland	Jul 2003	-8	0.3	-1.0
Bulgaria*	Aug 2002	-8		0.6	-42.7	Ukraine*	Apr 2004	0		-55.5
Canada	Dec 2002	-6		3.3	14.7	U.S^		-7	36.1	10.8

[a] This column reports the emissions target, as a percentage change from the base-year levels, specified in Annex B to the Kyoto Protocol. [b] 15 member States of the E.U. at the time of adoption of the Kyoto Protocol agreed to meet their targets jointly in accordance with Article 4. The column "Art.4" reports their respective targets. [c] This column reports a country's base-year emissions levels as a percentage of total emissions from all Annex I countries. [d] This column reports changes in CO_2 -equivalent GHG emissions without land use, land-use change and forestry from the base year to 1998 as a percentage of the base-year emissions. * A Party undergoing the process of transition to a market economy. An Annex I EIT party may choose a base year other than 1990. # The amendment to include Belarus in Annex B to the Kyoto Protocol (with a quantified emissions reduction commitment of eight percent) has not yet entered into force. ^The U.S. is not a Party to the Kyoto Protocol. *Note*: Malta and Turkey are currently Annex I Parties to the UNFCCC, however, they do not have commitments under the Kyoto Protocol. Data source: UNFCCC.

Table 1.2: The Most and the Least CO_2 Emissions Intensive Industries

Most Emissions-Intensive Industries	Intensities		Least Emissions-Intensive Industries	Intensities	
	$s^k_{E,T}$	$s^k_{E,D}$		$s^k_{E,T}$	$s^k_{E,D}$
Lime	24.9	41.7	Tobacco products	.26	.04
Cement	12.1	17.4	Support activities for printing	.29	.13
Fertilizers	6.6	10.4	Propulsion units, parts for space vehicles, guided missiles	.29	.20
Iron ore mining	6.0	-	Computer storage devices	.29	.16
Gold, silver, and other metal ore mining	4.9	-	Electricity and signal testing instruments	.31	.13
Other nonmetallic mineral mining	4.6	-	Other ordnance and accessories	.31	.13
Primary aluminum production	4.6	7.8	Guided missiles and space vehicles	.31	.22
Industrial gas	3.6	5.6	Telephone apparatus	.32	.06
Sand, gravel, clay and refractory mining	3.6	-	Surgical and medical instruments	.32	.09
Wet corn milling	3.4	6.9	Electronic computers	.33	.03
Aluminum products	3.2	1.8	Search, detection, and navigation instruments	.33	.12
Primary ferrous metal products	3.2	4.3	Distilleries	.33	.15
Ready-mix concrete	3.1	.63	Packaging machinery	.35	.15
Copper, nickel, lead, and zinc mining	2.9	-	Metal cutting and forming machine tool	.35	.12
Primary copper	2.8	2.0	Analytical laboratory instruments	.35	.11
Other basic inorganic chemicals	2.8	3.5	Broadcast and wireless communications equipment	.36	.13
Petrochemicals	2.8	3.7	Ophthalmic goods	.37	.13
Other basic organic chemicals	2.5	3.7	Musical instruments	.37	.19
Plastics material and resins	2.4	3.0	Pharmaceuticals and medicines	.39	.12
Stone mining and quarrying	2.3	-	Forestry and logging	.39	-

Note: $s^k_{E,T}$ measures total emissions per output, $s^k_{E,T}$ measures direct emissions per value added. Units are in metric tons of CO_2 per $1000 in constant year 2000 dollars. Industries are ranked by the output based emissions intensity $s^k_{E,T}$. The value added based measure $s^k_{E,D}$ is only available for manufacturing industries.

Data source: Output based CO_2 emissions intensities from ESA, 2010; output and value added from Becker & Gray, 2009.

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Table 1.3: Correlation Between Output and Value Added Based Measures

	1998	2002	2006	Average
Correlation, $s^k_{E,T}$, $s^k_{E,D}$	0.9774	0.9789	0.9792	0.9804
Correlation, ranks	0.8424	0.8519	0.8850	0.8667

Note: $s^k_{E,T}$ measures total emissions per output, $s^k_{E,T}$ measures direct emissions per value added. Units are in metric tons of CO_2 per \$1000 in constant year 2000 dollars.

Data source: ESA, 2010; Becker & Gray, 2009.

Table 1.4: Correlations of CO_2 Emissions Intensities Across Time

	1998	2002	2006	Average	1998	2002	2006	Average
	(1) $s^k_{E,T}$				(2) $s^k_{E,D}$			
1998	1				1			
2002	0.9846	1			0.9915	1		
2006	0.9655	0.9640	1		0.9859	0.9916	1	
Average	0.9928	0.9927	0.9856	1	0.9960	0.9981	0.9955	1
	(3) Rank $s^k_{E,T}$				(4) Rank $s^k_{E,D}$			
1998	1				1			
2002	0.9189	1			0.9127	1		
2006	0.8865	0.9331	1		0.8851	0.9287	1	
Average	0.9687	0.9745	0.9608	1	0.9643	0.9714	0.9598	1

Note: $s^k_{E,T}$ measures total emissions per output, $s^k_{E,T}$ measures direct emissions per value added. Units are in metric tons of CO_2 per \$1000 in constant year 2000 dollars.

Data source: ESA, 2010; Becker & Gray, 2009.

Table 1.5: Correlations of Energy Intensities Across Countries

	G8								+5[a]			
	CAN	FRA	DEU	ITA	JPN	RUS	GBR	USA	BRA	CHN	IND	MEX
Canada	1											
France	.98	1										
Germany	.87	.86	1									
Italy	.98	.99	.88	1								
Japan	.98	.98	.90	.99	1							
Russia	.96	.95	.83	.96	.95	1						
UK	.99	.98	.87	.99	.98	.95	1					
USA	.96	.96	.90	.97	.97	.93	.95	1				
Brazil	.99	.99	.88	.99	.99	.96	.99	.96	1			
China	.92	.96	.80	.92	.92	.92	.91	.91	.93	1		
India	.98	.95	.83	.97	.95	.94	.98	.92	.97	.91	1	
Mexico	.99	.98	.88	.99	.99	.97	.99	.97	.99	.93	.98	1

[a] South Africa is not included because data is not available for it as a separate country.

Note: Correlations reported for energy intensity measures for 42 food and manufacturing industries in the GTAP model for year 1997.

Data source: GTAP 5.4 Data Base.

Table 1.6: Climate Policy and Comparative Advantage: Baseline Estimation

Dependent variable:	All Industries	Manufacturing		
log imports	(1)	(2)	(3)	(4)
emissions intensity	-.455**	-.418**	-.462**	-.291**
× Annex I status	(.192)	(.168)	(.187)	(.140)
capital intensity				.029
× capital-labor ratio				(.096)
skill intensity				.394***
× year of schooling				(.105)
exporter fixed effect	Yes	Yes	Yes	Yes
industry fixed effect	Yes	Yes	Yes	Yes
intensity measure	$s^k_{E,T}$	$s^k_{E,T}$	$s^k_{E,D}$	$s^k_{E,D}$
R^2	.607	.640	.640	.631
# observations	18587	17230	17230	13667
# exporters	226	225	225	116

Note: Dependent variable is the log of U.S. imports in 2007. $s^k_{E,T}$ is the output based measure and $s^k_{E,T}$ is the value added based measure. Observations are exporter by industry for 2007. Standard errors two-way clustered by exporter and industry are in brackets. *** indicates significance at 0.01 level, ** at 0.05 level, * at 0.1 level.

Table 1.7: Robustness Check: Country Characteristics

Dependent variable:	All Industries				Manufacturing Industries			
log imports	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
emissions intensity								
× Annex I status	-.455**	-.521**	-.349*	-.325	-.291**	-.419**	-.188	-.248
	(.192)	(.223)	(.198)	(.212)	(.140)	(.189)	(.140)	(.203)
× emissions per capita		.149				.272		
		(.244)				(.281)		
× emissions per GDP			.287				.266	
			(.188)				(.207)	
× income per capita				-.149				-.052
				(.183)				(.189)
factor interactions	No	No	No	No	Yes	Yes	Yes	Yes
exporter fixed effect	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
industry fixed effect	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
R^2	.607	.596	.597	.596	.631	.632	.632	.631
# observations	18587	17359	17359	17367	13667	13659	13659	13667
# exporters	226	172	172	173	116	115	115	116

Note: Dependent variable is the log of U.S. imports in 2007. Observations are exporter by industry for 2007. Standard errors two-way clustered by exporter and industry are in brackets. *** indicates significance at 0.01 level, ** at 0.05 level, * at 0.1 level.

Table 1.8: Robustness Check: Excluding Outliers in CO_2 Emissions Intensities

Dependent variable:	All Industries	Manufacturing		
log imports	(1)	(2)	(3)	(4)
emissions intensity	-.723**	-.893**	-.939***	-.584*
× Annex I status	(.345)	(.374)	(.353)	(.353)
capital intensity				.037
× capital-labor ratio				(.059)
skill intensity				.386***
× year of schooling				(.086)
exporter fixed effect	Yes	Yes	Yes	Yes
industry fixed effect	Yes	Yes	Yes	Yes
intensity measure	$s^k_{E,T}$	$s^k_{E,T}$	$s^k_{E,D}$	$s^k_{E,D}$
R^2	.619	.648	.648	.639
# observations	18268	17045	17045	13559
# exporters	226	225	225	116

Note: Dependent variable is the log of U.S. imports in 2007. $s^k_{E,T}$ is the output based measure and $s^k_{E,T}$ is the value added based measure. Observations are exporter by industry for 2007. Observations in the 7 most emissions-intensive industries are excluded. Standard errors two-way clustered by exporter and industry are in brackets. *** indicates significance at 0.01 level, ** at 0.05 level, * at 0.1 level.

Table 1.9: Robustness Check: Using Survey Measure on Env. Regulation

Dependent variable:	All Industries	Manufacturing		
log imports	(1)	(2)	(3)	(4)
emissions intensity	-.351***	-.340***	-.368***	-.238**
× env. regulation	(.127)	(.129)	(.141)	(.104)
capital intensity				.116
× capital abundance				(.108)
skill intensity				.506***
× skill abundance				(.112)
exporter fixed effect	Yes	Yes	Yes	Yes
industry fixed effect	Yes	Yes	Yes	Yes
intensity measure	$s^k_{E,T}$	$s^k_{E,T}$	$s^k_{E,D}$	$s^k_{E,D}$
R^2	.590	.622	.622	.624
# observations	15917	14788	14788	13062
# exporters	127	127	127	98

Note: Dependent variable is the log of U.S. imports in 2007. $s^k_{E,T}$ is the output based measure and $s^k_{E,T}$ is the value added based measure. Observations are exporter by industry for 2007. Standard errors two-way clustered by exporter and industry are in brackets. *** indicates significance at 0.01 level, ** at 0.05 level, * at 0.1 level.

Table 1.10: Robustness Check: Varying Comparison Country Groups

	Excl. low income		Excl. low and		Excl. low and	
Dependent variable:	countries		lower mid. income		middle income	
log imports	(1)	(2)	(3)	(4)	(5)	(6)
emissions intensity	-.474**	-.275**	-.513**	-.295**	-.647**	-.408
× Annex I status	(.190)	(.132)	(.205)	(.134)	(.301)	(.372)
capital intensity		.132		.082		.050
× capital abundance		(.111)		(.154)		(.205)
skill intensity		.645***		.685***		.531***
× skill abundance		(.116)		(.140)		(.190)
exporter fixed effect	Yes	Yes	Yes	Yes	Yes	Yes
industry fixed effect	Yes	Yes	Yes	Yes	Yes	Yes
R^2	.593	.618	.609	.624	.646	.649
# observations	16805	12751	13424	10463	8112	6508
# exporters	164	93	111	66	59	38

Note: Dependent variable is the log of U.S. imports in 2007. Observations are exporter by industry for 2007. Standard errors two-way clustered by exporter and industry are in brackets. *** indicates significance at 0.01 level, ** at 0.05 level, * at 0.1 level.

Table 1.11: Robustness Check: ISDB Data

Dependent variable:	Industrial Output		Export to ROW	
log output/export	(1)	(2)	(3)	(4)
emissions intensity	-.251***	-.137**	-.161***	-.143**
× Annex I status	(.069)	(.066)	(.052)	(.044)
capital intensity		.080		.076
× capital abundance		(.077)		(.083)
skill intensity		.149		.272***
× skill abundance		(.112)		(.094)
country fixed effect	Yes	Yes	Yes	Yes
industry fixed effect	Yes	Yes	Yes	Yes
R^2	.828	.811	.786	.776
# observations	4983	3934	7598	6218
# countries	58	45	82	65

Note: Dependent variable is the log of industrial output or export to the rest of world in 2007. Observations are country by industry for 2007. Standard errors two-way clustered by country and industry are in brackets. *** indicates significance at 0.01 level, ** at 0.05 level, * at 0.1 level.

Table 1.12: Export Patterns by Country Groups

	All Industries			Manufacturing		
	Annex I		Non-	Annex I		Non-
Dependent variable:	non-EIT	EIT	Annex I	non-EIT	EIT	Annex I
log imports	(1)	(2)	(3)	(1)	(2)	(3)
emissions intensity	-.285***	.493	.153	-.256**	.373	.198
× Annex I status	(.103)	(.497)	(.207)	(.126)	(.426)	(.259)
capital intensity				.294	-.153	.068
× capital-labor ratio				(.248)	(.210)	(.083)
skill intensity				.543**	.012	.242**
× year of schooling				(.219)	(.393)	(.103)
factor intensities	Yes	Yes	Yes	Yes	Yes	Yes
exporter fixed effect	Yes	Yes	Yes	Yes	Yes	Yes
R^2	.442	.148	.503	.408	.160	.479
# observations	4279	1914	10587	4463	1522	7682
# exporters	26	13	186	23	10	83

Note: Dependent variable is the log of U.S. imports in 2007. Observations are exporter by industry for 2007. Standard errors two-way clustered by exporter and industry are in brackets. *** indicates significance at 0.01 level, ** at 0.05 level, * at 0.1 level.

Table 1.13: Kyoto Ratification and Comparative Advantage

Dependent variable:	All industries		Manufacturing		
log imports	(1)	(2)	(3)	(4)	(5)
emissions intensity	-.455***	-.193***	-.438***	-.189***	-.138**
	(.122)	(.071)	(.125)	(.069)	(.062)
emissions intensity		-.275*		-.260*	-.108
× Annex I status		(.142)		(.142)	(.139)
capital share					.007
× capital endowment					(.057)
skill share					.457***
× skill endowment					(.092)
exporter-year fixed effect	Yes	Yes	Yes	Yes	Yes
industry-year fixed effect	Yes	Yes	Yes	Yes	Yes
R^2	.576	.578	.611	.611	.606
# observations	341160	341160	313576	313576	255103
# exporters	238	238	238	238	118

Note: Dependent variable is the log of yearly U.S. imports from 1990 to 2010. Observations are exporter by industry by year. Standard errors two-way clustered by exporter and industry are in brackets. *** indicates significance at 0.01 level, ** at 0.05 level, * at 0.1 level.

Table 1.14: Changes in Trade Flows

Dependent variable:	2000-2007		1992-1999	
diff. log imports	(1)	(2)	(3)	(4)
emissions intensity	-.167**	-.221**	-.028	-.015
× Annex-I Status	(.069)	(.094)	(.065)	(.078)
capital intensity		.058**		.120***
× capital-labor ratio		(.028)		(.037)
skill intensity		-.019		.158***
× year of schooling		(.038)		(.055)
exporter fixed effect	Yes	Yes	Yes	Yes
industry fixed effect	Yes	Yes	Yes	Yes
R^2	.141	.156	.156	.164
# observations	14126	11295	11208	9169
# exporters	210	116	198	109

Note: Dependent variable is the difference of log of U.S. imports between the specified years. Observations are exporter by industry for each period. Standard errors two-way clustered by exporter and industry are in brackets. *** indicates significance at 0.01 level, ** at 0.05 level, * at 0.1 level.

Chapter 2

Carbon-motivated Border Adjustment in Combating Carbon Leakage

2.1 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

Meeting these targets is certainly difficult. The issue with greenhouse gas (GHG) involves a two-fold public good problem. The first level of externalities 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 coordination. 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 of emissions intensive goods from countries with lax climate change 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 tax and accompanying border measures on emissions and real compensation. The results suggest that border adjustment 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 2.3 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 2.4 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.

2.2 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 schemes, such as the Kyoto Protocol. These unilateral policies can lead to carbon leakage, through

[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.

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," as 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." The countries that experience expansions of emissions-intensive sectors also tend to employ more emissions-intensive production technologies, or they may not have access to the latest abatement technologies. Hence the resulting increase in emissions as a result of relocation of production can sometimes exceed the amount of emissions reduced 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 abating countries may induce more consumption in non-abating 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 mitigating 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, Peterson, Portney & Starvins, 1995 for a summary) only finds small, insignificant or non-robust effects of environmental regulations 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, Levinson & Minier, 2005; Levinson and Taylor, 2008) as well as FDI flows (see e.g. Keller and Levinson, 2002; List, Millimet, Fredriksson & McHone, 2003; Dean, Lovely & Wang, 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) analyzes data on a cross-section of countries and finds 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. Wang (2014) finds similar results for the declining U.S. industrial carbon emissions from 1990 to late 2000s.

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 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, therefore further

distorting the market (Alexeeva-Talebi, Anger & Löschel, 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 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.

2.3 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 the World Bank's (2008) estimates, 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 homogeneous 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 modeling 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 r_i and w_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 modeling 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 homogeneous 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

[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.

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 on emissions are lax or absent,

$$c^X(w_i, r_i, \tau_i) = c^F(w_i, r_i) + \tau_i \tag{2.1}$$

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.

$$X_i^C \equiv \left[n_i (x_{ii})^{\frac{\sigma-1}{\sigma}} + n_j (x_{ji}/\gamma)^{\frac{\sigma-1}{\sigma}} \right]^{\frac{\sigma}{\sigma-1}} \tag{2.2}$$

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 (2.2). The price index for the composite X_i^C in country i is then given by

$$\begin{aligned} P_i &= \left[n_i p_i^{1-\sigma} + n_j p_{ij}^{1-\sigma} \right]^{\frac{1}{1-\sigma}} \\ &= \left[n_i p_i^{1-\sigma} + n_j (p_i \gamma)^{1-\sigma} \right]^{\frac{1}{1-\sigma}} \end{aligned} \tag{2.3}$$

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 quasiconcave 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.

$$u(X_i^C, y_i^C) = e(1, P_i)v_i \tag{2.4}$$

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 total emissions, $Z = \sum_i Z_i$ 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.

2.3.1 Equilibrium

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

$$c^Y(w_i, r_i) \geq 1 \quad \perp \quad y_i \geq 0 \tag{2.5}$$

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

$$\pi_i = p_i(x_{ii} + x_{ij}) - c^X(w_i, r_i, \tau_i)(f + x_{ii} + x_{ij}) \tag{2.6}$$

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

$$p_i(1 - 1/\sigma) = c^X(w_i, r_i, \tau_i) \tag{2.7}$$

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

$$f(\sigma - 1) \geq x_{ii} + x_{ij}, \quad \perp \quad n_i \geq 0 \tag{2.8}$$

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,

$$E_i = e(1, P_i)v_i = w_i L_i + r_i K_i + \tau_i Z_i \tag{2.9}$$

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

$$\begin{aligned} x_{ii} &= p_i^{-\sigma} P_i^{\sigma-1} E_i P_i e_P(1, P_i)/e(1, P_i) && (2.10) \\ x_{ij} &= \gamma p_{ij}^{-\sigma} P_j^{\sigma-1} E_j P_j e_P(1, P_j)/e(1, P_j) && (2.11) \\ &= p_i^{-\sigma} \gamma^{1-\sigma} P_j^{\sigma-1} E_j P_j e_P(1, P_j)/e(1, P_j) \end{aligned}$$

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 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

$$y_i^C = (1 - \xi(P_i))E_i \tag{2.12}$$

Lastly, factor market clearing yields,

$$L_i = y_i c_w^Y(w_i, r_i) + n_i(x_{ii} + x_{ij} + f)c_w^X(w_i, r_i, \tau_i) \quad (2.13)$$

$$K_i = y_i c_r^Y(w_i, r_i) + n_i(x_{ii} + x_{ij} + f)c_r^X(w_i, r_i, \tau_i) \quad (2.14)$$

$$Z_i = \begin{cases} n_i(x_{ii} + x_{ij} + f)c_\tau^X(w_i, r_i, \tau_i) \text{ if } \tau_i \text{ is binding} \\ n_i(x_{ii} + x_{ij} + f) \qquad \text{otherwise} \end{cases} \quad (2.15)$$

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 (2.13) and (2.14) 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 (2.3), (2.5), (2.7), (2.8), (2.10), (2.11), (2.12), (2.13), (2.14) and (2.15), 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 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

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

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 (2.5) and (2.8) 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 (2.13) and (2.14), substituting out $x_{ii} + x_{ij}$ using the free entry condition (2.8).

$$y_i = \frac{c_r^X(w_i, r_i, \tau_i)L_i - c_w^X(w_i, r_i, \tau_i)K_i}{c_w^Y(w_i, r_i)c_r^X(w_i, r_i, \tau_i) - c_r^Y(w_i, r_i)c_w^X(w_i, r_i, \tau_i)} \tag{2.16}$$

$$n_i = n_i(w_i, r_i) = \frac{1}{\sigma f}\frac{c_w^Y(w_i, r_i)K_i - c_r^Y(w_i, r_i)L_i}{c_w^Y(w_i, r_i)c_r^X(w_i, r_i, \tau_i) - c_r^Y(w_i, r_i)c_w^X(w_i, r_i, \tau_i)} \tag{2.17}$$

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 (2.17) to substitute out n_i and n_j in the price indices (2.3), and use the variety demand equations (2.10) and (2.11) to substitute out x_{ii} and x_{ij} in the free entry condition (2.8). Together with equations (2.5) and (2.7) 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 (2.7)) and the price indices P_i and P_j (using equation (2.3)) can be further substituted out of

[4]There are possibilities that conditions (2.5) and (2.8) bind with equality in an equilibrium at a corner solution (i.e. with complete specialization), which are limit cases of the interior solutions.

equation (2.8) to obtain, after simplification,

$$1 = \frac{c^X(w_i, r_i, \tau_i)^{-\sigma} E_i \xi(P_i(w_i, r_i, w_j, r_j))}{\sigma f n_i(w_i, r_i) c^X(w_i, r_i, \tau_i)^{1-\sigma} + o f n_j(w_j, r_j) c^X(w_j, r_j, \tau_j)^{1-\sigma} \gamma^{1-\sigma}} + \frac{c^X(w_i, r_i, \tau_i)^{-\sigma} E_j \xi(P_j(w_i, r_i, w_j, r_j))}{\sigma f n_i(w_i, r_i) c^X(w_i, r_i, \tau_i)^{1-\sigma} + o f n_j(w_j, r_j) c^X(w_j, r_j, \tau_j)^{1-\sigma} \gamma^{\sigma-1}} \quad (2.18)$$

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, (2.18) and (2.5) 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.

2.3.2 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

$$c^X(w_S, r_S, 0) = c^F(w_S, r_S) \quad (2.19)$$

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

$$Z_S = n_S(x_{SS} + x_{SN} + f) = \sigma f n_S \quad (2.20)$$

[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.

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 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

$$p_{SN} = p_S\gamma(1+t) \tag{2.21}$$

$$p_{NS} = p_N\gamma(1-s) \tag{2.22}$$

which in turn affects the price indices (equation (2.3)) and the variety demand (equations (2.10) and (2.11)). 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 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

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

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 (2.6) to remain unchanged.

The North's tariff revenue is

$$T = tn_S p_S x_{SN} \tag{2.23}$$

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

$$E_S = w_S L_S + r_S K_S + tn_S p_S x_{SN} \tag{2.24}$$

The North's subsidy cost is

$$S = sn_N p_N x_{NS} \tag{2.25}$$

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

$$E_N = w_N L_N + r_N K_N + \tau_N Z_N - sn_N p_N x_{NS} \tag{2.26}$$

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.

An important issue is how the tariff rate is set, as there are different options. 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,

$$t = \frac{\tau_N c_\tau^X(w_N, r_N, \tau_N)}{c^X(w_N, r_N, \tau_N) - \tau_N c_\tau^X(w_N, r_N, \tau_N)} = \frac{\alpha_X}{1 - \alpha_X} \tag{2.27}$$

where $\alpha_X = \tau_N c_\tau^X(w_N, r_N, \tau_N)/c^X(w_N, r_N, \tau_N)$ 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

$$t' = \frac{\tau_N}{c^X(w_S, r_S, \tau_S)} = \frac{\tau_N}{c^F(w_S, r_S)} \tag{2.28}$$

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.

It is worth pointing out that a key underlying 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 calculated the carbon tariff rate based 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.

2.3.3 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 effects 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, is given by

$$-\Delta Z_N = \sigma f(-\Delta n_N) + \sigma f n'_N(1 - c_\tau^X(w_N, r_N, \tau_N)) \tag{2.29}$$

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 (2.29) by $-\Delta Z_N$ will give the effect in fractions, which are reported in the simulation analysis.

[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 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.

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 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,

$$\sigma f \Delta n_S = \sigma f \Delta n_S c_\tau^X(w_N, r_N, \tau_N) + \sigma f \Delta n_S (1 - c_\tau^X(w_N, r_N, \tau_N)) \tag{2.30}$$

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.

$$1 = c_\tau^X(w_N, r_N, \tau_N) + (1 - c_\tau^X(w_N, r_N, \tau_N)) \tag{2.31}$$

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 disproportionately 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.

2.3.4 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 (2.24) and (2.26).

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 (2.10), (2.11) and (2.3),[8]

$$\begin{aligned} \frac{x_{ii}}{x_{ij}} &= \frac{E_i \xi(P_i)}{E_j \xi(P_j)} \frac{P_i^{\sigma-1}}{\gamma^{1-\sigma} P_j^{\sigma-1}} \\ &= \frac{E_i \xi(P_i)}{E_j \xi(P_j)} \left(\frac{1 + (n_j/n_i)(p_j/p_i)^{1-\sigma} \gamma^{\sigma-1}}{1 + (n_j/n_i)(p_j/p_i)^{1-\sigma} \gamma^{1-\sigma}} \right) \end{aligned} \tag{2.32}$$

[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 (2.18).

which is greater than $E_i\xi(P_i)/\left(E_j\xi(P_j)\right)$, 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 (2.32) shows that the magnitude of the trade cost is an important factor that helps determine the size of carbon leakage. To the extent that a higher trade cost biases the firms' sales more 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 (2.32), 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 (2.17) 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,

$$\frac{c_r^Y(w_i, r_i)}{c_w^Y(w_i, r_i)} < \frac{c_r^X(w_i, r_i, \tau_i)}{c_w^X(w_i, r_i, \tau_i)} = \frac{c_r^F(w_i, r_i)}{c_w^F(w_i, r_i)} \tag{2.33}$$

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

$$\frac{K_N}{L_N} > \frac{K_S}{L_S} \tag{2.34}$$

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 (2.32) 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 (2.32) 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.

2.3.5 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 modeled. 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.

2.4 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.

2.4.1 Functional Forms and Parameters

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

$$e(1,P) = P^{\xi} \tag{2.35}$$

$$C^Y(w,r) = (r/\alpha_Y)^{\alpha_Y}(w/(1-\alpha_Y))^{1-\alpha_Y} \tag{2.36}$$

$$C^F(w,r) = (r/\alpha_F)^{\alpha_F}(w/(1-\alpha_F))^{1-\alpha_F} \tag{2.37}$$

$$C^X(w,r,\tau) = (\tau/\alpha_X)^{\alpha_X}(c^F(w,r)/(1-\alpha_X))^{1-\alpha_X} \tag{2.38}$$

The Cobb-Douglas form allows an easy interpretation of the choice of modeling emissions as an input. As shown in Appendix A, it is equivalent to modeling 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., 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:

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

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

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 10production cost when the emissions tax is binding.

2.4.2 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 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.

[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.

Low Carbon Tax

The first set of results, shown in Table 2.1 and in Figure 2.1, 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 six percent 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 (2.31) 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

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

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 eight percent, 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.

[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 eight percent with the current set of parameters.

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 (2.27). 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 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 (2.28), 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 2.1.

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 four percent, 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 2.1. 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 four percent 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 2.2 and Figure 2.2, 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 two percent 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 five percent 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 2.2 and Figure 2.2 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 two percent.

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.

2.4.3 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, Inklaar & Timmer, 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 line goes through the midpoint of the endowment box and has a slope dL/dK smaller than the ratio

[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.

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 2.3 and 2.4 and Figures 2.3 and 2.4 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.

2.4.4 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 (2.32). 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 2.5 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 2.5 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 2.6 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 2.7 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 (2.32), 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 2.8 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.

2.4.5 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.

2.5 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.

Bibliography

Acemoglu, D., Aghion, P., Bursztyn, L., & Hemous, D. (2012). "The environment and directed technical change," *American Economic Review*, *102*, 131-166.

Aichele, R. & Felbermayr, G. (2010). "Kyoto and the carbon content of trade," FZID Discussion Paper 10-2010.

Alexeeva-Talebi, V., Anger, N., & Löschel, A. (2008). "Alleviating adverse implications of EU climate policy on competitiveness: The case for border tax adjustments or the clean development mechanism?" ZEW-Centre for European Economic Research Discussion Paper, 08-095.

Anderson, J.E. & van Wincoop, E. (2004). "Trade costs," *Journal of Economic Literature*, *42*, 691-751

Atkinson, G., Hamilton, K., Ruta, G., & van der Mensbrugghe, D. (2010).. "Trade in 'virtual carbon': Empirical results and implications for policy," Background paper to the 2010 World Development Report, Policy Research Working Paper No. 5194.

Babiker, M.H. (2005). "Climate change policy, market structure, and carbon leakage," *Journal of International Economics*, *65*, 421-445.

Broda, C. & Weinstein, D.E. (2006). "Globalization and the gains from variety," *Quarterly Journal of Economics*, *121*, 541-585.

Chua, S. (1999) "Economic growth, liberalization, and the environment: A review of the economic evidence," *Annual Review of Energy and the Environment*, *24*, 391-430.

Copeland, B.R. & Taylor, M.S. (2001). "International trade and the environment: A framework for analysis," NBER Working Paper No. 8540.

Copeland, B.R. & Taylor, M.S. (2005). "Free trade and global warming: A trade theory view of the Kyoto Protocol," *Journal of Environmental Economics and Management*, *49*, 205-234.

Dean, J.M., Lovely, M.E., & Wang, H. (2009). "Are foreign investors attracted to weak environmental regulations? Evaluating the evidence from China," *Journal of Development Economics*, *90*, 1-13.

Demailly, D. & Quirion, P. (2006).. "Leakage from climate policies and border tax adjustment: Lessons from a geographic model of the cement industry," Working Papers halshs-00009337, HAL.

Demailly, D. & Quirion, P. (2008). "European Emission Trading Scheme and competitiveness: A case study on the iron and steel industry," *Energy Economics*, *30*, 2009-2027.

Dong, Y., & Walley, J. (2012). "How large are the impacts of carbon motivated border tax adjustments?" *Climate Change Economics*, *3*, 1250001.

Ederington, J., Levinson, A., & Minier, J. (2005). "Footloose and pollution-free," *Review of Economics and Statistics*, *87*, 92-99.

Feenstra, R.C., Inklaar, R., & Timmer, M.P. (2015), "The next generation of the Penn World Table," forthcoming *American Economic Review*, available at www.ggdc.net/pwt.

Frankel, J. (2009). "Environmental effects of international trade," HKS Faculty Research Working Paper RWP09-006.

Frankel, J.A. & Rose, A.K. (2005). "Is trade good or bad for the environment? Sorting out the causality," *Review of Economics and Statistics*, *87*, 85-91.

Fischer, C., & Fox, A. (2011). "Comparing policies to combat emissions leakage: Border carbon adjustments versus rebates," Resources for the Future Discussion Paper, 09-02-REV.

Gerlagh, R. & Mathys, N.A. (2011). "Energy abundance, trade and industry location," Fondazione Eni Enrico Mattei Working Papers #554.

Helpman, E. & Krugman, P. (1985). *Market structure and foreign trade: Increasing returns, imperfect competition, and the international trade*, Cambridge, Mass.: MIT Press.

Hummels, D. (2007). "Transportation costs and international trade in the second era of globalization," *Journal of Economic Perspectives*, *21*, 131–154.

Intergovernmental Panel on Climate Change (IPCC). (2007). "Summary for policymakers," in Metz, B., Davidson, O.R., Bosch, P.R., Dave, R., & Meyer, L.A. (eds.), *Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press.

Jaffe, A.B., Peterson, S., Portney, P., & Stavins, R.N. (1995). "Environmental regulation and the competitiveness of U.S. manufacturing: What does the evidence tell us?" *Journal of Economic Literature*, *33*, 132–163.

Markusen, J.R., & Venables, A.J. (2000). "The theory of endowment, intra-industry and multi-national trade," *Journal of International Economics*, *52*, 209-234.

Karp, L. (2010). "Reflections on carbon leakage." Unpublished. Available at http://areweb.berkeley.edu/~karp/KarpLeakage.pdf.

Keller, W. & Levinson, A. (2002). "Pollution abatement costs and foreign direct investment inflows to US states," *Review of Economics and Statistics*, *84*, 691-703.

Levinson, A. (2009). "Technology, international trade, and pollution from US manufacturing," *American Economic Review*, *99*, 2177-2192.

Levinson, A. & Taylor, M. S. (2008). "Unmasking the pollution haven effect," *International Economic Review*, *49*, 223-254.

List, J.A., Millimet, D.L., Fredriksson, P.G., & McHone, W.W. (2003). "Effects of environmental regulations on manufacturing plant births: Evidence from a propensity score matching estimator," *Review of Economics and Statistics*, *85*, 944-952.

McKibbin, W.J. & Wilcoxen, P.J. (2009). "The economic and environmental effects of border tax adjustments for climate policy," *Brookings Trade Forum*, *Climate Change, Trade, and Competitiveness: Is a Collision Inevitable? (2008/2009)*, 1-34.

Melo, J.D., & Mathys, N.A. (2010). "Trade and climate change: The challenges ahead,". CEPR Discussion Papers, No. 8032.

Paltsev, S.V. (2001). "The Kyoto Protocol: Regional and sectoral contributions to the carbon leakage," *Energy Journal*, *22*, 53-79.

Peters, G.P. & Hertwich, E.G. (2008). "CO_2 embodied in international trade with implications for global climate," *Environmental Science and Technology*, *42*, 1401-1407.

Reinaud, J. (2008). "Climate policy and carbon leakage: Impacts of the European Emisisons Trading Scheme on Aluminium," *International Energy Agency Information Paper*. Available at http://www.iea.org/publications/free_new_Desc.asp?PUBS_ID=2055.

Rutherford, T. (1992). "The welfare effects of fossil carbon restrictions: Results from a recursively dynamic trade model," OECD Economics Department Working Papers, No. 112.

Sijm, J.P.M., Kuik, O.J., Patel, M., Oikonomou, V., Worrell, E., Lako, P., Annevelink, E., Nabuurs, G.J., & Elbersen, H. W. (2004). "Spillovers of climate policy: An assessment of the incidence of carbon leakage and induced technological change due to CO_2 abatement measures," Netherlands Research Programme on Climate Change Scientific Assessment and Policy Analysis Report 500036 002.

Sinn, H.W. (2008). "Public policies against global warming: A supply side approach," *International Tax and Public Finance*, *15*, 360-394.

U.S. Environmental Protection Agency. (2009). "The effects of H.R. 2454 on international competitiveness and emission leakage in energy-intensive trade-exposed industries." Available at http://www.epa.gov/climatechange/economics/pdfs/InteragencyReport_Competitiveness-EmissionLeakage.pdf.

Wang, T. (2012). "Climate change policy and patterns of international trade." Unpublished.

Wang, T. (2014). "Technology, international trade, and carbon emissions from US industry." Unpublished.

World Bank. (2008). *International Trade and Climate Change: Economic, Legal, and Institutional Perspectives*. Washington, DC: International Bank for Reconstruction and Development/The World Bank.

World Bank. (2014). *World Development Indicators 2014*. Washington, DC: World Bank.

Zhou, X., Kojima, S., & Yano, T. (2010). "Addressing carbon leakage by border adjustment measures: Review of current studies," mimeo, Institute for Global Environmental Strategies. Available at http://enviroscope.iges.or.jp/modules/envirolib/view.php?docid=3290.

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

$$X = Z^{\alpha} \left[F(K_X, L_X)\right]^{1-\alpha} \tag{2.39}$$

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 (2.39)

Appendix B: Equations for Simulation

With the use of Cobb-Douglas expenditure (utility) and cost (production) functions (equations (2.35) through (2.38)), 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)

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

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 2.1: 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	

$^{\wedge}$ See equations (2.29) and (2.31). $^{\#}$ After-policy value. * Value is for each variety. $^{\&}$ Both are based on importer intensity.
Parameter values: ξ =1/2; σ =5; f=1/4; γ =1.2; α_Y=1/3; α_F =2/3; α_X =1/10; $K_S = L_S = K_N = L_N = 1$, τ_N =0.1148.

Table 2.2: 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 (2.29) and (2.31). $^{\#}$ After-policy value. * Value is for each variety. $^{\&}$ Both are based on importer intensity.
Parameter values: ξ =1/2; σ =5; f=1/4; γ =1.2; α_Y=1/3; α_F =2/3; α_X =1/10; $K_S = L_S = K_N = L_N = 1$, τ_N =2.4187.

Table 2.3: 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$^{\wedge\#}$	0.6213	0.8603	0.5208	0.8734	0.5053	0.8750	0.5414	0.8712	0.3787	0.8846
technology effect$^{\wedge\#}$	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	

$^{\wedge}$ See equations (2.29) and (2.31). $^{\#}$ After-policy value. * Value is for each variety. $^{\&}$ Both are based on importer intensity.
Parameter values: ξ =1/2; σ =5; f=1/4; γ =1.2; α_Y=1/3; α_F =2/3; α_X =1/10; $K_S = L_S = 1$, $K_N = L_N = 2$, τ_N =0.1269.

Table 2.4: 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 (2.29) and (2.31). $^{\#}$ After-policy value. * Value is for each variety. $^{\&}$ Both are based on importer intensity.
Parameter values: ξ =1/2; σ =5; f=1/4; γ =1.2; α_Y=1/3; α_F =2/3; α_X =1/10; $K_S = L_N = 1$, $K_N = L_S = 2$, τ_N =0.1263.

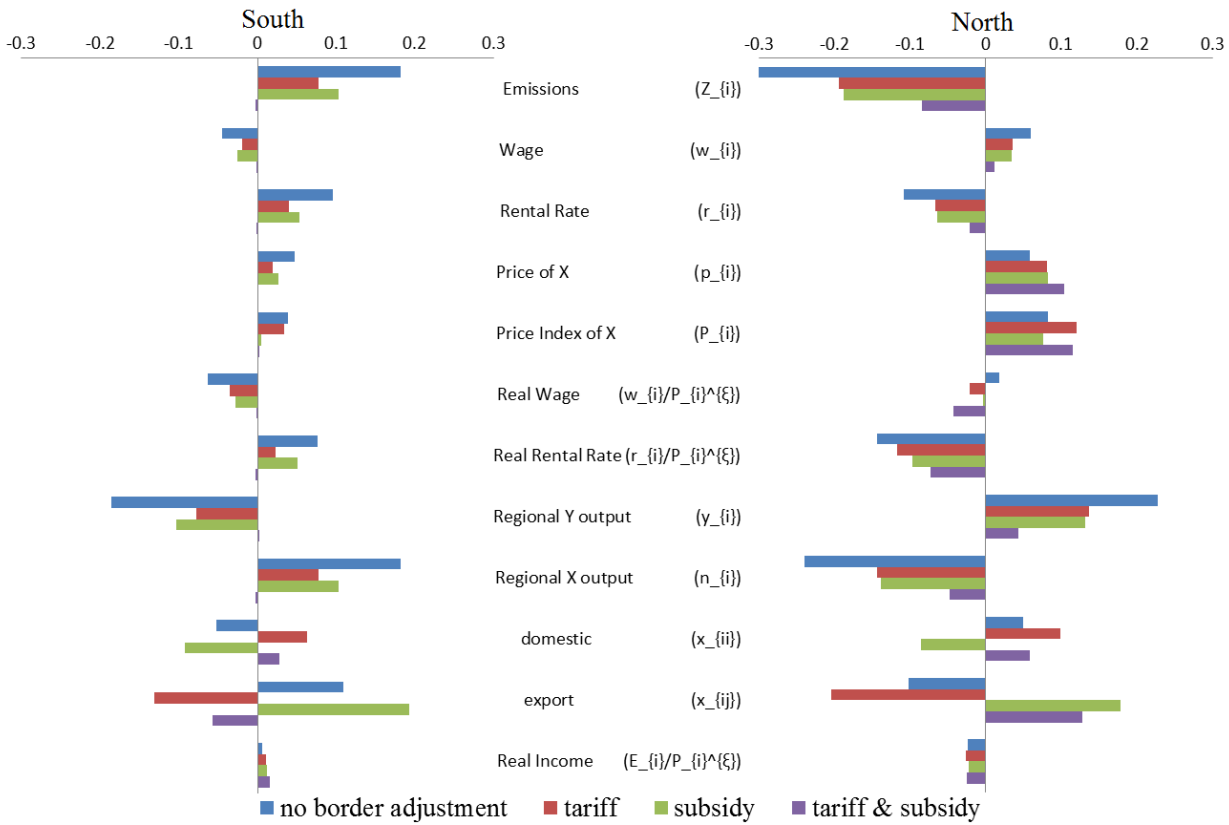


Figure 2.1: Simulation Results: Symmetric Economies with a Low Emissions Tax

Note: The bars represent the fractional changes of the regional variables under respective policies from the baseline no-regulation equilibrium.

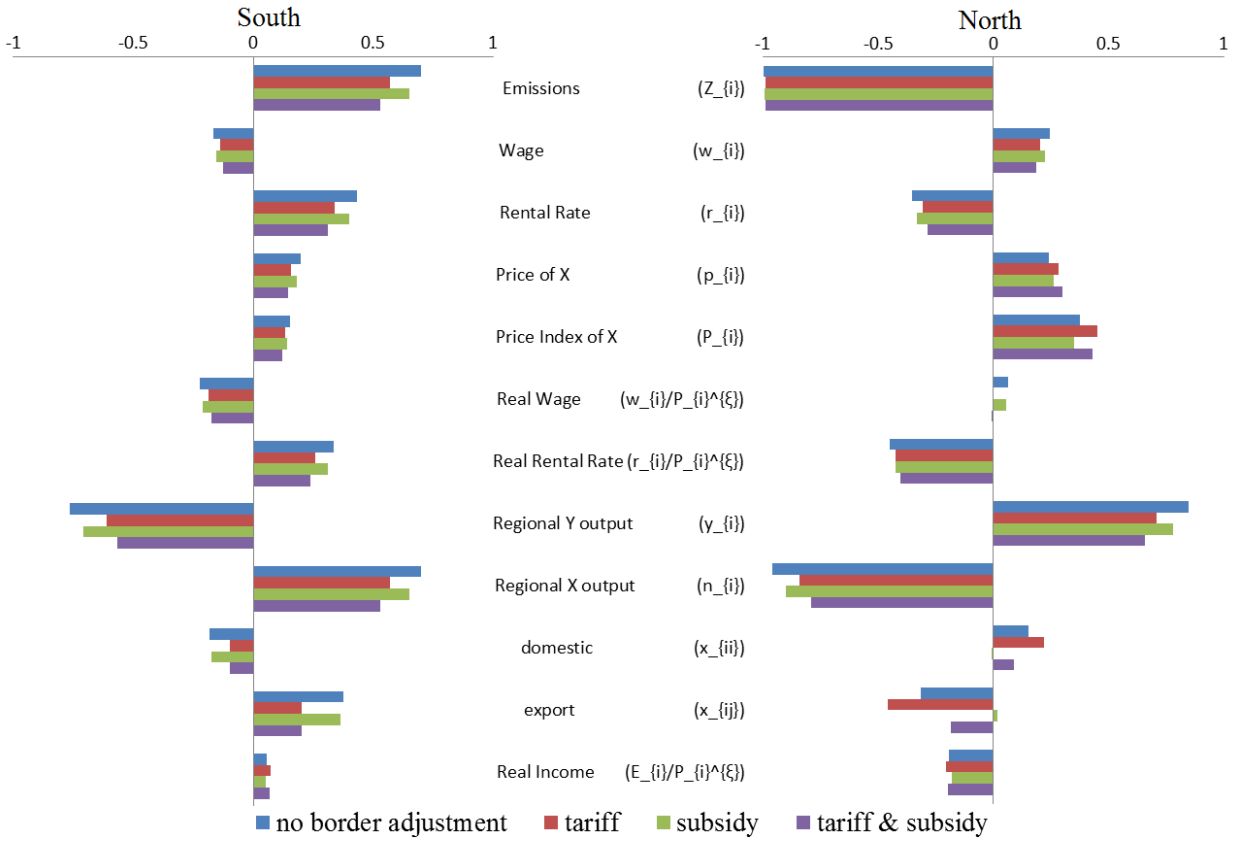


Figure 2.2: Simulation Results: Symmetric Economies with a High Emissions Tax

Note: The bars represent the fractional changes of the regional variables under respective policies from the baseline no-regulation equilibrium.

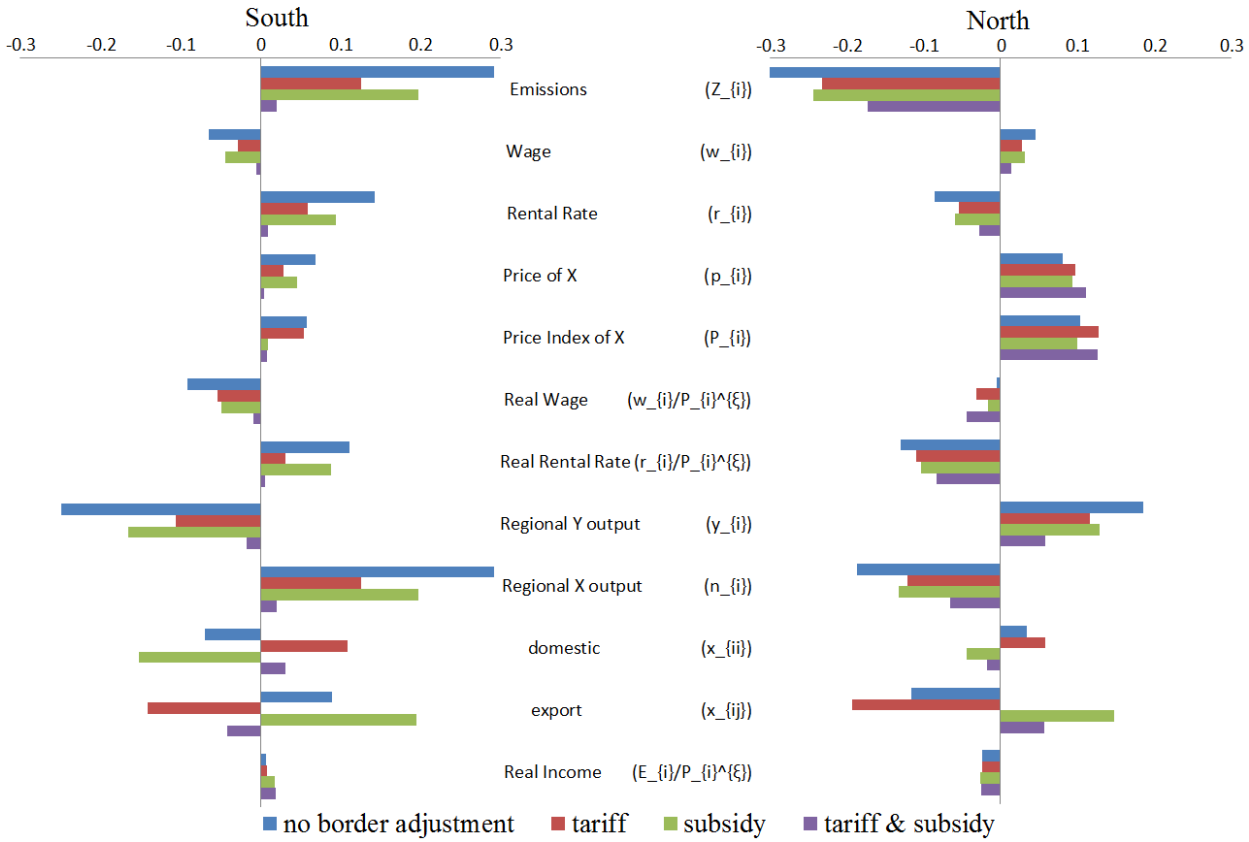


Figure 2.3: Simulation Results: Economies with Asymmetric Sizes but Same Endowment Ratio

Note: The bars represent the fractional changes of the regional variables under respective policies from the baseline no-regulation equilibrium.

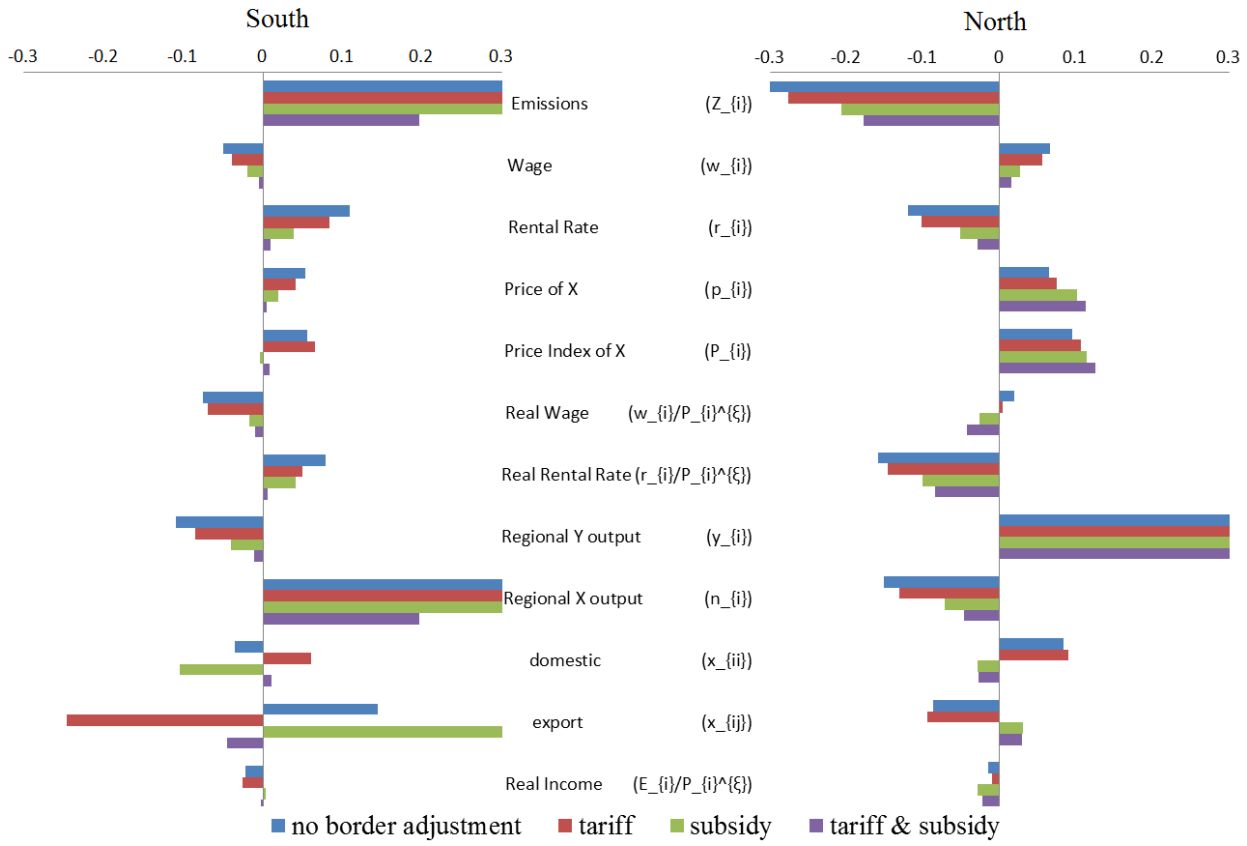


Figure 2.4: Simulation Results: Economies of Similar Size but with Asymmetric Endowment Ratios

Note: The bars represent the fractional changes of the regional variables under respective policies from the baseline no-regulation equilibrium. The changes in the South's emissions, its X output level and export ratios, and the North's Y output level are outside of the range shown on the axes. Please check Table 4 for exact values.

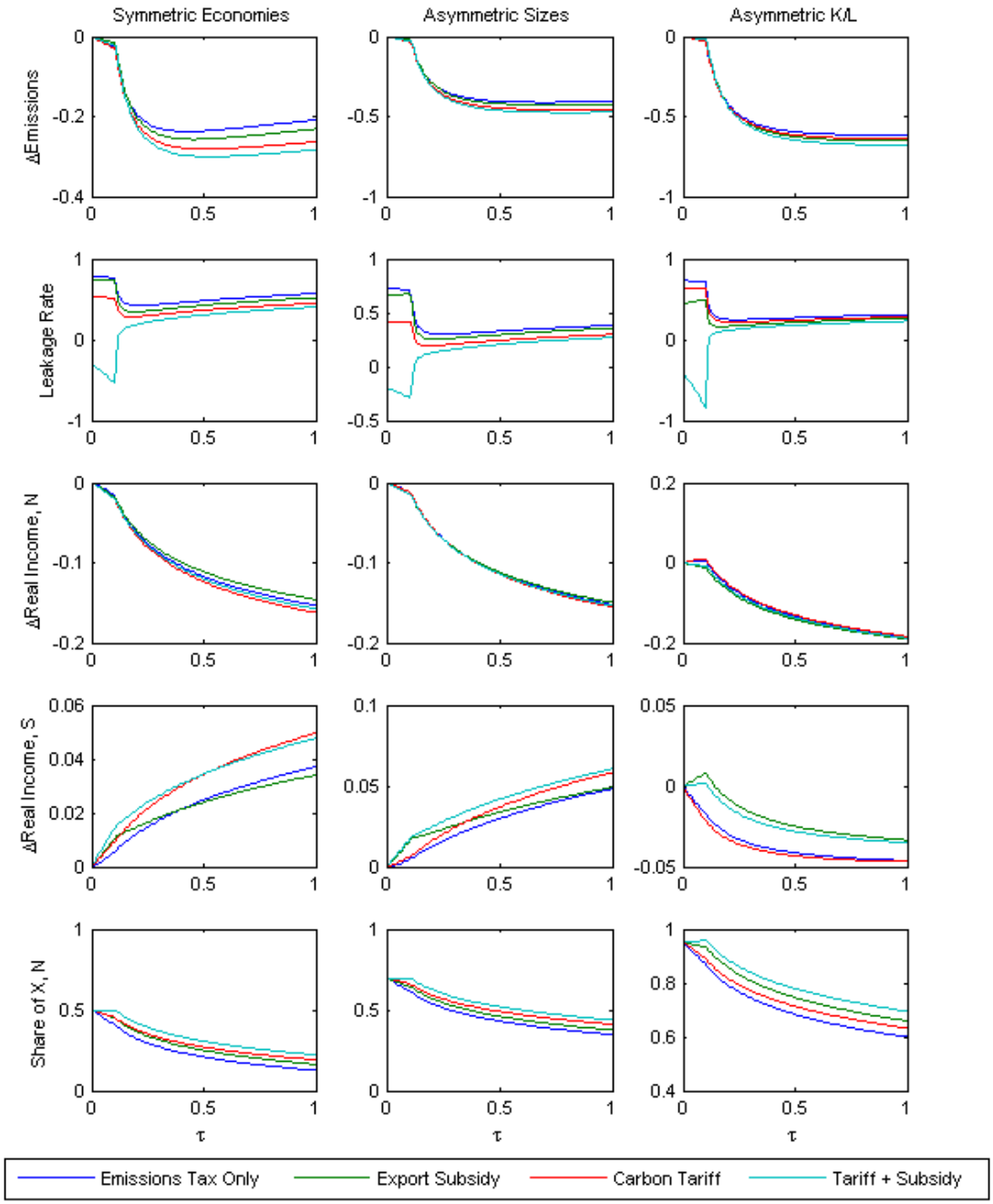


Figure 2.5: Sensitivity Analysis: Emissions Tax Level τ_N
Parameter values: ξ =1/2; σ =5; f=1/4; γ =1.2; α_Y=1/3; α_F =2/3; α_X =1/10.
Symmetric economies: $K_S = L_N = K_N = L_S = 1$; Asymmetric sizes: $K_S = L_S = 1$, $K_N = L_N = 2$;
Asymmetric K/L: $K_S = L_N = 1$, $K_N = L_S = 2$.

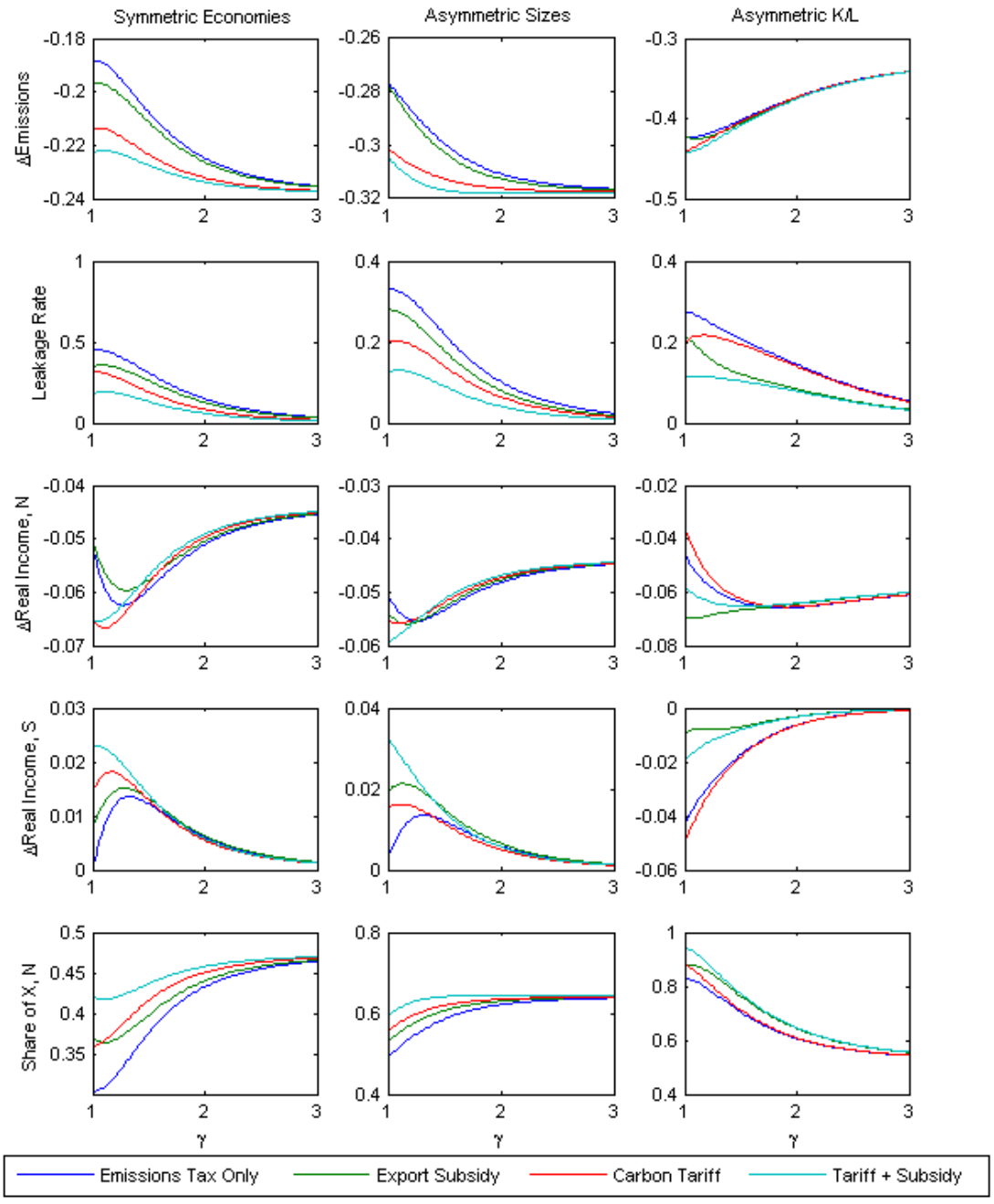


Figure 2.6: Sensitivity Analysis: Trade Cost γ
Parameter values: ξ =1/2; σ =5; f=1/4; τ_N =1.2; α_Y=1/3; α_F =2/3; α_X =1/10.
Symmetric economies: $K_S = L_N = K_N = L_S = 1$; Asymmetric sizes: $K_S = L_S = 1$, $K_N = L_N = 2$;
Asymmetric K/L: $K_S = L_N = 1$, $K_N = L_S = 2$.

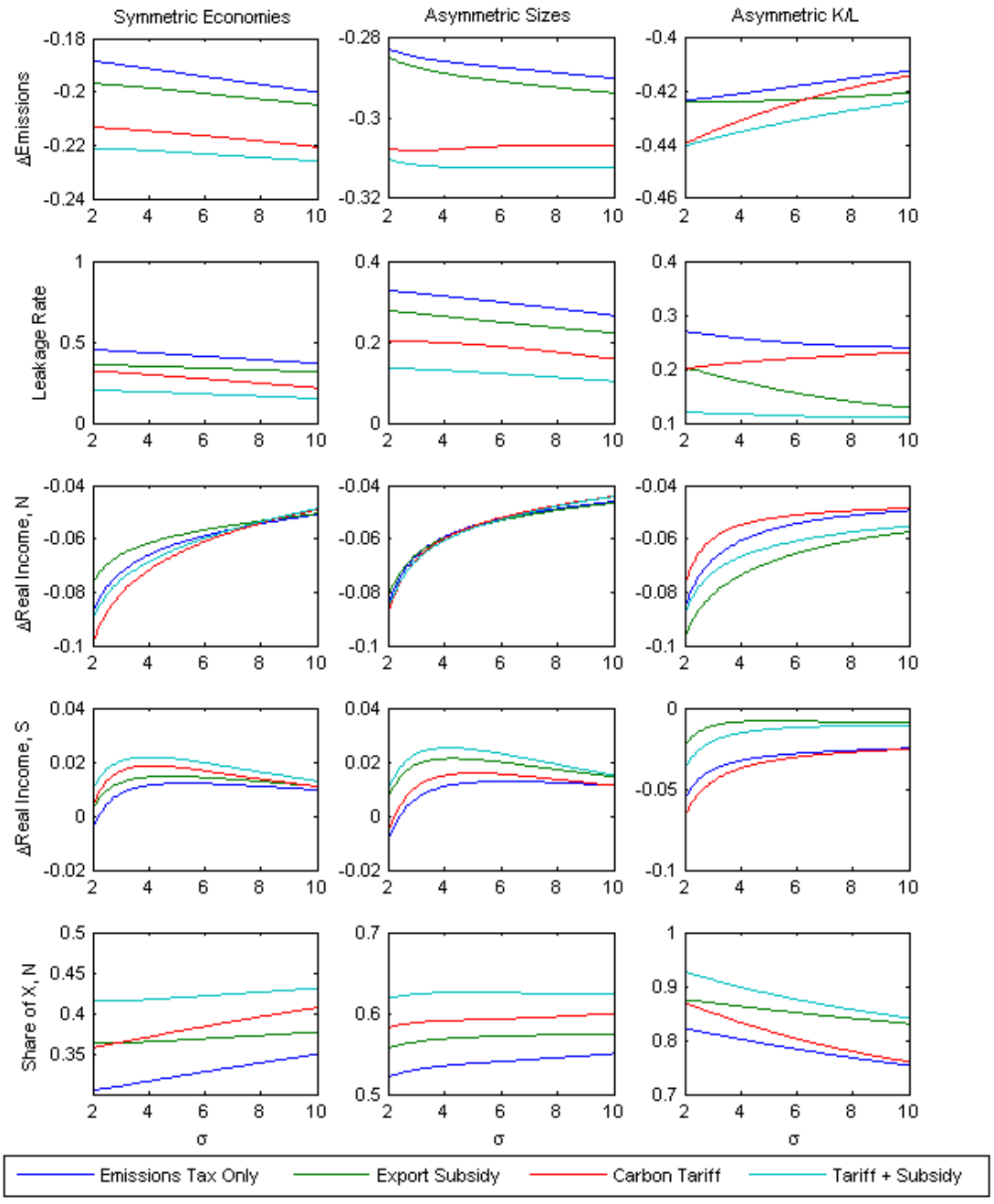


Figure 2.7: Sensitivity Analysis: Elasticity of Substitution σ
Parameter values: ξ =1/2; f=1/4; γ = 1.2; τ_N =1.2; α_Y=1/3; α_F =2/3; α_X =1/10.
Symmetric economies: $K_S = L_N = K_N = L_S = 1$; Asymmetric sizes: $K_S = L_S = 1$, $K_N = L_N = 2$;
Asymmetric K/L: $K_S = L_N = 1$, $K_N = L_S = 2$.

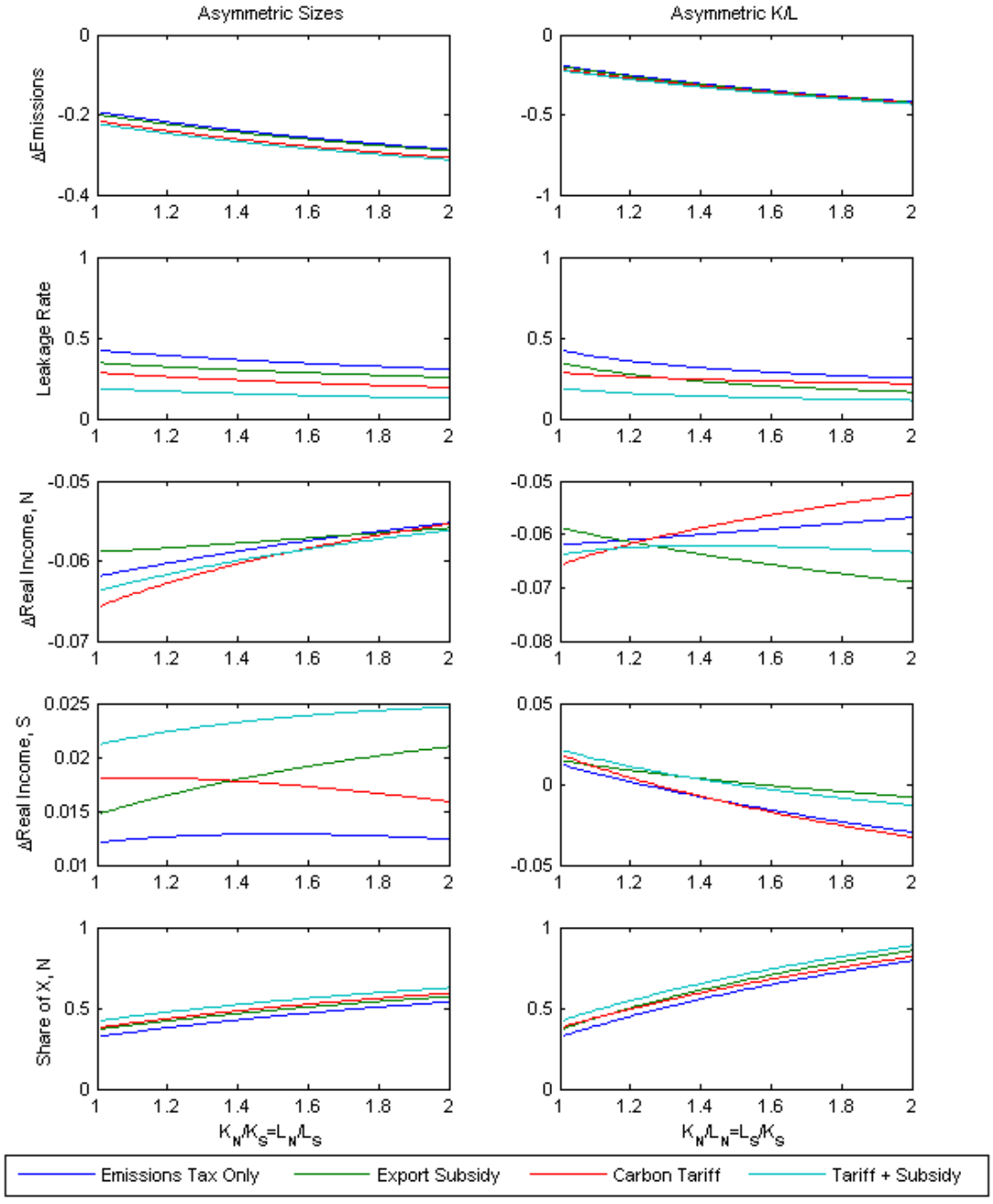


Figure 2.8: Sensitivity Analysis: Endowment Values
Parameter values: ξ =1/2; σ=1.2; f=1/4; γ = 1.2; τ_N =1.2; α_Y=1/3; α_F =2/3; α_X =1/10.

Chapter 3

Technology, International Trade, and Carbon Emissions from U.S. Industry

3.1 Introduction

The overall greenhouse gas (GHG) emissions in the United States have been on a slowing growth path in the past two decades. As depicted in Figure 3.1, the average growth rate dropped from about two percent per year in the 1990s to about half a percent in the mid-2000s. In particular, carbon dioxide (CO_2) emissions, the most important GHG accounting for about five sixths of total emissions,[1] seemed to have reached a plateau before the Great Recession of 2008 and 2009. In the meantime, U.S. Gross Domestic Product (GDP) averaged about three percent annual growth in real terms (U.S. Bureau of Economic Analysis (BEA), 2012) from 1990 to 2007. These differential growth rates imply that the U.S. economy has become "greener" with its

[1]From 1990 to 2010, CO_2 emissions, excluding land use, land-use change, and forestry (sinks), represent on average 83.5% of total US GHG emissions measured in terms of Global Warming Potential using weights from the IPCC Second Assessment Report (EPA, 2012).

emissions intensity[2] on a downward trend. Common explanations include a general shift from a manufacturing-based economy to a service-based economy,[3] as well as an overall increases in energy efficiency (U.S. Environmental Protection Agency (EPA), 2012).

While most of the decomposition studies on U.S. CO_2 emissions have been conducted for the aggregate economy, this paper takes a closer look at one particular sector, industry, which appears to have contributed the most to the overall clean-up process. Industry, or the industrial sector, which includes activities in manufacturing, mining, construction and agriculture,[4] is responsible for a significant portion of CO_2 emissions in the United States. As shown in Figure 3.2, while CO_2 emissions from the transportation, commercial and residential sectors were all on the rise until the financial crisis hit, industrial CO_2 emissions have been on a steady decline after reaching a peak in 1997. The emissions displayed a 4.6% drop from 1998 to 2007 despite a 7.9% increase in real gross output.[5] During this period, industry's share of total CO_2 emissions decreased from 35% to 31%, double the two percentage point drop in the sector's share of total economic activity (BEA, 2012). As a result, the industrial sector has become less emission intensive at a substantially faster pace than the overall U.S. economy.

What drives this greening trend of U.S. industry? There are two major potential sources, advances in production or abatement processes, i.e., the technique or technology effect, and changes in the composition of goods produced, i.e., the composition effect. Most of the CO_2 emissions in industry, as well as in other sectors, are related

[2]The emissions intensity is defined as the amount of emissions per unit of GDP or gross output, typically measured in metric tons of CO_2-equivalent per $1,000 of real GDP or gross output.

[3]In 1990, private goods-producing industries accounted for about 24% of US GDP, and this share was in steady decline, reaching below 20% by mid-2000s. Meanwhile, the service industries' share increased from 62% in 1990 to about 68% in the mid-2000s (BEA, 2012).

[4]The classification adopted in this paper is consistent with energy consumption data from the US Energy Information Administration (EIA).

[5]The increase in real GDP, or value added, is even larger at 16.7% from 1998 to 2007 (BEA, 2012).

to energy, and come from fossil fuel use either directly in the production process or indirectly through electricity consumption.[6] Hence, technological advances can come in two ways, improvements in energy efficiency, or substitution in the energy mix, in both direct energy use and electricity generation. On the other hand, the compositional changes in production can also be further distinguished into two sources, a decrease in the final demand for carbon-intensive goods, or an increase in the share of such goods that are imported.[7] The latter scenario is often the basis for such concerns that the United States and other high-income countries have reduced their GHG emissions intensity by shipping "dirty" industries to the developing countries.

It is important to allocate credit for the clean-up of U.S. industry among the various trends in technology, product mix, and international trade. If it is simply a result of importing more carbon-intensive products and producing less of them domestically, then the U.S. experience cannot be replicated globally. The least developed countries will not be able to find even poorer countries from which to import the carbon-intensive products. The world will run out of "pollution havens" as all countries strive to become greener. On the other hand, if it has resulted from technological advances, particularly efficiency improvements, the clean-up can be replicable, and will provide promising opportunities to address climate change. In addition, alternative perspectives on the greening process can have significant implications for the potential of energy policy to influence future energy efficiency trends. Energy-efficiency programs are more likely to influence energy trends within specific industries, while changes due to shifts in the overall economic structure are less likely to be swayed by energy policy mandates.

[6]From 1990 to 2010, emissions from fossil fuel combustion represent on average 93.6% of overall US CO_2 emissions, excluding land use, land-use change, and forestry (sinks). Other sources include non-energy use of fuels, natural gas systems and process emissions, mostly in metal and lime and cement production (EPA, 2012).

[7]The final demand for U.S. goods includes domestic consumption and exports. In the decomposition presented later in this paper, I separate the effects of the changes in domestic consumption, which is termed the composition effect, and that of the net imports.

It needs to be kept in mind that industrial activities are not the only source of GHG emissions in the United States. By the late 2000s, industrial CO_2 emissions represent just about 30% of all CO_2 emissions and 25% of total GHG emissions. Nonetheless, industry, and manufacturing in particular, accounts for a large share of the rhetoric in the public and political debate on the economic and environmental consequences of climate change regulations in the context of global trade, centering on issues like carbon leakage and competitiveness concerns.[8] Meanwhile, the transportation, commercial and residential sectors are not subject to such concerns about pollution havens or international competition. This paper therefore focuses on the industrial sector. It is also noted that although data through 2010 are presented whenever possible, most of the analysis focuses on the period from 1998 to 2007, between the peak of industrial CO_2 emissions and the onset of the Great Recession.

The rest of the paper is organized as follows, the next section of the paper briefly reviews the recent literature on decomposition analysis applied to related issues. Section 3.3 describes the data used for the analyses. Section 3.4 shows that technology accounted for the majority of the clean-up from 1998 to 2007, while changes in the composition of industries had a negligible effect. Section 3.5 looks at the fossil fuel consumption of the industrial sector and illustrates that most of the technique effect was manifested in reduced energy use, while fuel switching and improved efficiency in the power sector did not make much of a contribution. Section 3.6 shows that over the same period, emissions embodied in the increased net imports of the United States amounted to less than one third of the clean-up due to the technique effect. Therefore, shifting carbon-intensive production overseas contributed at most a minor share, less than one fourth, of the overall clean-up of U.S. industry. The last section concludes.

[8]See Onder (2012) for a review on key issues on trade and climate change.

3.2 Related Literature

Decomposition analysis has deep roots in economics, dating back to Leontief's (1970) analysis with an extended input-output framework. A large number of studies have applied the decomposition methodology to analyze pollution, energy use, as well as other issues to understand trends over time or differences across regions.[9] It provides an intuitive tool to attribute the changes in a variable of interest to a number of different factors, for instance, the previously mentioned composition and technique effects. Generally, the decomposition exercise is viewed as a preliminary step for the analysis of fundamental determinants of the movement in the variable of interest. The next step involves relating the decomposed effects to elements such as government policies or market forces, using an equilibrium model of the economy. The decomposition exercise can be particularly useful if the fundamental determinants that matter for structural change are substantially independent from those that matter for technological change. In the case of carbon emissions, the compositional shift is typically driven by product market considerations, namely the demand-side factors in both domestic and international markets; while the changes in emissions intensities are usually due to factor market or supply-side reasons such as fuel switching or innovations in the production and abatement technologies. While these factors are not completely independent, as they may all be tied to the relative prices of the goods from different industries, decomposition analysis does offer valuable information on the nature of the movement in overall emissions levels.

[9]Decomposition analysis has also been widely used in labor economics (see Fortin, Lemieux & Firpo, 2011, for an overview). A key difference between the application in that literature and the application to emissions or energy use is that the former case lacks a clear structure unlike the latter. As to be shown in the paper, the overall emissions can be written as a deterministic function of the emissions intensities and industry outputs, which are then related to the decomposed effects. There can be interactions between these effects, and hence the decomposition can include a residual term. However, this is different from the unexplained component of a decomposition without a clear structural form and the structural coefficients need to be estimated. Because of this difference, there is less concern for identifying causality in the current application. The causes that lead to the decomposed effects are beyond the scope of the decomposition analysis itself.

The usefulness of the methodology as an analytical tool for policy making on national energy and environmental issues has been widely acknowledged, though there is yet to be a consensus on which decomposition method is the best. Most of the decomposition studies fall into one of two categories, index decomposition analysis (IDA) or structural decomposition analysis (SDA). The IDA, sometimes referred to as "index number analysis," adopts methodologies based on economic indices such as the Divisia or the Laspeyres indices. Over the years researchers have proposed various improvements (for a summary, see Ang, 2004), and a selection of the IDA formulations are presented in the appendix to this paper. The IDA has always been a popular tool with its relatively low data requirements. It only needs industry-level data within the disaggregated industries, i.e., it uses output per industry for the economic decomposition. Not surprisingly it has been applied to a large number of time periods and countries (for reviews, see Ang and Zhang (2000) and Liu and Ang (2007)). On the other hand, the SDA, also referred to as the "input-output decomposition analysis," combines industry-level data with input-output tables. The decomposition is therefore based on the input–output coefficients (matrix) in addition to the final demand of each industry. Thus, the SDA is capable of distinguishing between a range of technological effects and final demand effects that are not possible in the IDA framework (Hoekstra and Van der Bergh, 2003). With increased availability of input-output tables and further methodological improvements, the SDA has become more widely adopted in recent years (for reviews, see Rose (1999), Liu (2004) and Su (2011)).

The literatures on the IDA and the SDA have been developed largely independently of each other. However, despite their differences, the techniques employed in the analyses, particularly the various weighting methods, can be transferred from IDA to SDA, and vice versa (Hoekstra and Van der Bergh, 2003).[10] In the current

[10]For example, Lenzen (2006) shows the similarity, in additive form, between the Shapley/Sun method in IDA (Ang, Liu & Chew., 2003) and the Dietzenbacher-Los (1998) method in SDA. In multiplicative decomposition, de Boer (2009) shows that the generalized Fisher Index (Ang, Liu & Chung, 2004) in IDA is identical to the multiplicative form of Dietzenbacher-Los in SDA.

paper, elements from both the IDA and the SDA approaches are utilized. The main analytical tool is an IDA method similar to a Laspeyres index, following Levinson (2009). When analyzing the emissions embodied in international trade, the emissions intensities used are derived from an input-output framework akin to SDA.

With the popularity of decomposition analysis, there have been quite a few applications to U.S. CO_2 emissions. Studies published prior to 2004 cover various periods spanning the 1960s through the 1990s. Studies focusing on specific sectors found that a decline in energy intensity contributed the most to reducing carbon intensity of U.S. manufacturing, while structural change had a smaller but significant impact (Torvanger, 1991; Golove and Schipper, 1996; Greening, Davis & Schipper, 1997; Schipper, et al., 2001). In the transportation sector, similar conclusions were reached (Scholl, Schipper & Kiang, 1996; Lakshmanan and Han, 1997) except for freight (Greening, Ting & Davis, 1999). The story is no different in the residential sector (Schipper, Hass, & Sheinbaum, 1996; Greening, Ting & Krackler, 2001). Therefore, it is not surprising that, at the level of the aggregate economy, energy intensity was identified as the most important driver behind the downward trend of emissions intensity (Golove and Schipper,1997; Schipper, Ting, Khrushch & Golove, 1997; Sun and Malaska,1998; Hamilton and Turton, 2001). All the aforementioned studies used IDA methods. Casler and Rose (1998) provides a rare study using SDA applied to U.S. CO_2 emissions and shows that substitution within the energy sector and between energy and other inputs were the leading causes of the decline in emissions from 1972 to 1982.

More recent studies of CO_2 emissions have provided alternative perspectives to the issue. Vinuya, DiFurio & Sandoval (2010) decomposes CO_2 emissions by each state in the United States and shows that efficiency gains, a lower share of fossil fuels in total energy consumption, and lower emissions intensities of fuels, all contributed to decelerating emissions growth in the United States from 1990 to 2004. Malla and

Im (2011) decomposes CO_2 emissions from power generation in the United States from 1990 to 2005 and attempts to forecast future emissions with estimates of component factors. Unlike older studies, neither includes an effect of structural change in economic activities.

Since most of CO_2 emissions are energy related, studies on energy use and energy intensity should shed light on the evolution of emissions as well. Earlier research has shown that the changes in the energy mix and the emissions factors of fuels are not important drivers for emissions trends for the United States largely from the 1960s to the 1990s. Therefore, the forces behind the trends in energy use or energy intensity should translate into factors affecting CO_2 emissions and carbon intensity. Among the large number of decomposition studies of U.S. energy use or energy intensity covering similar periods, the majority agree that declining sector-specific energy intensities were the most important factor contributing to lowering the overall energy intensity of the U.S. economy, with structural change taking a secondary role (Liu and Ang, 2007).

Interestingly, since the mid-2000s, there have not been as many published decomposition studies of U.S. energy use, despite its continued popularity in applications to other economies. A number of recent studies of the aggregate U.S. economy seem to suggest that structural change has become more important since the 1990s. A study by the Office of Energy Efficiency and Renewable Energy of the U.S. Department of Energy (2012) analyzes the U.S. energy intensity trend from 1985 to 2004 and concludes that, out of a 27% decrease in energy to GDP ratio during the period, a shift in the composition of the economy caused a 17% decline, while the remaining 10% was achieved by improving energy intensity within individual subsectors or industries. Huntington (2010) finds that shifts between 65 industries in the commercial, industrial and transportation sectors accounted for almost 40% of the reduction in the U.S. economy's aggregate energy intensity from 1997 to 2006, with the figure rising to 54%

when transportation is excluded. Weber (2009) uses both IDA and SDA methods to analyze the changes in U.S. energy use from 1997 to 2002 and concludes that changes in the structure of the economy explain the 12% drop in energy intensity more than increased energy efficiency. On the other hand, Metcalf (2008) suggests that roughly 75% of the decline in U.S. energy intensity from 1970 to 2003 resulted from efficiency improvements.

There are several potential reasons that empirical results from different studies may not agree. First, since the authors may use data from different sources, adopt different measures of economic activities, or cover different time periods and/or different sectors of the economy, some differences are natural. Though it may well be the case that, for the overall economy, structural shifts between the major sectors have become more important, efficiency improvements may still be the driving force in reducing sector-level energy or emissions intensity. This paper attempts to determine whether this is the case in the industrial sector. The analysis also employs the most recently available emissions and production data, which may reveal patterns different from earlier data.

Second, the relative importance of technology, or energy efficiency, and industrial structure, or product mix, often depends on the level of aggregation in the decomposition analysis (Weber, 2009; Su, Huang, Ang & Zhou, 2010). Some studies conduct the analysis at a more aggregated level lacking detailed industry classification due to data limitations. Since most studies can only assess technology indirectly as a residual, after accounting for composition effects, analyses at more aggregated levels inevitably misclassify some within-sector compositional variations as technique changes. The finer industry disaggregation used in this study makes it less likely to exaggerate the role of technology in emissions abatement.

A recently developed literature, closely related to the decomposition and input-output analysis is the one on emissions embodied in international trade (for reviews,

see Wiedmann, Lenzen, Turner & Barrett (2007) and Wiedmann (2009)). Adopting the methods used to analyze the traditional factor content of trade, these studies try to assess the emissions content of goods traded between economies and calculate a balance of emissions traded for certain individual economies, as well as pairs or groups of countries. The results are used to assess the impacts of trade on countries' carbon footprint and potential carbon leakage of climate change policies. The United States and other industrialized countries have been found to be large net importers of embedded carbon (see, for instance, Peters and Hertwich (2008)). Naturally, this observation and the increase in global trade have been linked to the structural change of the United States and other high-income economies and it has been suggested that rich countries have become cleaner by relocating production of pollution-intensive products elsewhere.

Interestingly, despite such broad claims, few studies have directly addressed the role of international trade in reducing the emissions intensity of developed economies. This paper attempts to fill this gap by assessing the importance of international trade on the clean-up of U.S. industry. One recent study that offered particular insights used in this paper is Levinson's (2009) analysis on air pollution from U.S. manufacturing. Using data on disaggregated industries, he shows that the technique effect dominates in the clean-up of U.S. manufacturing in the past several decades. Increased international trade explains less than one third of the reduction in pollution from composition changes, and only one-tenth of the overall pollution reduction of the sector. This paper draws on Levinson's method of presenting time trends and provides a more complete picture of the evolution of CO_2 emissions from U.S. industry, in addition to decomposition results between end years. The SDA approach for analyzing embodied emissions in international trade is also adopted.

3.3 Data

This section describes the data used in the analysis. Data on total industrial CO_2 emissions are obtained from the U.S. Greenhouse Gas Inventory Report by the EPA (2012). To conform to the definition of industry adopted in this study as well as the energy use data from the EIA, the sum of the reported CO_2 emissions from the industrial and agricultural sectors is used as the total for industry. Emissions from power generating industries are distributed to end-use sectors. Hence, the overall industrial CO_2 emissions used here include direct emissions from agriculture, mining, construction and manufacturing, as well as indirect emissions embodied in purchased electricity used in those activities. The majority of CO_2 emissions from this aggregated sector come from manufacturing, accounting for just about 80%.[11]

CO_2 emissions intensities of disaggregated industries are drawn from a report by the Economics and Statistics Administration (ESA) (2010). The underlying data are those from the Manufacturing Energy Consumption Survey (MECS) by the EIA for the years 1998, 2002 and 2006 as well as the EIA and the EPA's emissions inventory data for the relevant years. Direct emissions are estimated by distributing the reported emissions of more aggregated sectors to disaggregated Iliad[12] industries based on energy use data. As with the case of overall emissions, emissions from power generating industries are distributed to end-use industries. In addition to energy-related emissions, major process emissions and emissions from non-energy use are also accounted for. Total embodied emissions in the output of each industry, taking into consideration the emissions content of intermediate inputs, are estimated using an input-output framework similar to SDA. Emissions embodied in imported inputs

[11] The percentage is calculated using data from the Economics and Statistics Administration (ESA) for the years 1998, 2002 and 2006.

[12] Iliad stands for *Interindustry Large-scale Integrated And Dynamic model of the US*. It is a detailed input-output model developed by the Interindustry Forecasting Project at the University of Maryland (Inforum). Based on the 2002 North American Industry Classification System (NAICS), it has 360 input-output sectors, out of which 265 are in agriculture, mining, construction and manufacturing,

are assumed to be the same as their domestic counterparts. The emissions data are combined with real gross output data from the BEA (2012) to estimate the emissions intensities of respective industries. Gross output is chosen as the unit of economic activity rather than value added for two reasons. First, value added or GDP data are only available for disaggregated industries in manufacturing, but not for those in agriculture, mining or construction. Second, international trade data are typically reported as the value of shipments, which corresponds more closely to gross output rather than value added.

International trade data are taken from the U.S. Census Bureau.[13] The raw data in the 8-digit Harmonized System (HS) classification are then aggregated to the 6-digit North American Industry Classification System (NAICS), using concordances provided by the Census Bureau and Pierce and Schott (2009).

Sectoral energy use by fuel type, the CO_2 emissions conversion factors of the various energy sources, and the related CO_2 emissions are obtained from the Annual Energy Review of the EIA (2012). Note that these emissions are less than those reported by the EPA, since they only include CO_2 emissions from energy use, and not process emissions, etc.

The units of analysis are the BEA's input-output industries, based on NAICS. With 237 industries, it is the most detailed common disaggregation of the data assembled for this study. All data are converted using appropriate concordances. This level of disaggregation provides far more detail than recent decomposition analysis of U.S. CO_2 emissions or energy use. Although there were studies using more than 480 industries in the 1980s, more recent studies typically use fewer than 50 industries in the aggregate economy and fewer than 30 industries in the industrial sector (Liu and Ang, 2007). More importantly, this approach helps to mitigate the aggregation issue discussed in section 3.2 and allows a clearer interpretation of the result.

[13]The data for years 1990 to 2005 are obtained from Schott (2008), and those for years 2006 to 2010 are from data disks published by the Census Bureau (2007-2011).

It is worth noting that there are a few potential issues with the data. The first is the limited availability of emissions data by disaggregated industries, which limits the analysis to a short time span. The greening process of U.S. industry has been ongoing since the 1970s. According to the EIA's emissions data, industrial CO_2 emissions from energy use hit its highest level in 1979. From then until 2007, emissions have decreased by more than 12%, while real GDP of private goods producing industries has almost doubled. The EPA's earliest emission data go back to 1990. From then until 2007, industrial emissions increased by two percent while real GDP grew 55%. Nonetheless, the available period from 1998 to 2006 coincides with the time between the most recent peak of industrial emissions in 1997 and the Great Recession. It should provide valuable information without having to worry about the economy in a severe crisis, and may reveal new patterns different from those previously discovered. In addition, following Levinson (2009), the scale and composition effects can be projected using only the base-year (1998) emissions intensities, and a series of yearly decompositions can be presented for a more complete illustration of the process.

A second issue is the discrepancies between the emissions data provided by the various sources. CO_2 emissions from energy use, directly from the EIA, are only used in decomposing the fuel mix. The emissions data from the EPA and the ESA are reasonably similar. Overall CO_2 emissions attributed to the industrial sector by the ESA are larger than those reported by the EPA in 1998 and 2002, by about two percent and three percent respectively. The figures for 2006 are almost the same, with the ESA number exceeding that from the EPA by less than one tenth of a percent. Since the ESA used emissions reported by the EIA and the EPA as basis for their calculations, the discrepancies should have been relatively small. One possible explanation for the ESA figures being larger could be that the ESA assigns some of the emissions from the transportation sector, namely those from light-duty vehicles, to the industrial sector (as well as households and public sectors). In this case, the

similarity of the 2006 numbers is puzzling. However, this could be explained by the fact that the ESA used the initial release of the MECS for 2006, while the EPA figures have been revised later on. Fortunately, for the main analysis based on the Laspeyres index, only the emissions intensities of the base year and relative changes in emissions are needed, with units being irrelevant. Any mismatches between the ESA and the EPA figures will not be a problem as long as the ratio of the true industrial emissions to the EPA estimates remains constant over time.

A third data issue arises from the need to choose an appropriate price index to deflate the nominal measures of economic activity. In certain emissions-intensive industries, prices may have changed faster than the overall producer price index (PPI) due to factors unrelated to the nature of the products. Therefore, using the PPI can exaggerate changes in predicted emissions based on the scale and composition of the industrial sector as revenues rather than actual quantities are used to measure output. For instance, since energy-intensive industries are also carbon-intensive, when energy prices rise faster than the PPI, using the PPI will exaggerate the role of technology in the clean-up. This is indeed a problem, because the period from 1998 to 2006 has witnessed fast increases in fossil fuel prices. Therefore, industry-specific price indices are used in the analysis. However, by doing so, the composition of the industries is sensitive to the choice of base year. Fortunately, this does not have any significant effect on the results.

3.4 Technology: An Indirect Assessment of the Technique Effect

In environmental economics, it is now conventional to think about changes in total pollution as coming from three sources, the overall size of the economy ("scale"), the mix of sectors and industries comprising the economy ("composition"), and the

technologies employed in production and abatement ("technique"). Mathematically, total industrial CO_2 emissions, V, can be written as the sum of emissions from each of its component industries, V_i. This in turn can be written as the gross output of industry, Y, multiplied by the sum of each industry's share of total output, $\theta_i = Y_i/Y$, times an emissions coefficient that reflects the amount of emissions per dollar of real gross output in that industry $z_i = V_i/Y_i$,

$$V = \sum_i V_i = \sum_i Y_i z_i = Y \sum_i \theta_i z_i \tag{3.1}$$

or, in vector notation,

$$V = Y\boldsymbol{\theta}'\mathbf{z} \tag{3.2}$$

where $\boldsymbol{\theta}$ and $\mathbf{z}$ are $n \times 1$ vectors comprising the market shares of each of the n industries and their emissions intensities, respectively.

Totally differentiating equation (3.2) yields

$$dV = \boldsymbol{\theta}'\mathbf{z}dY + Y\mathbf{z}'d\boldsymbol{\theta} + Y\boldsymbol{\theta}'d\mathbf{z} \tag{3.3}$$

The first term in equation (3.3) is the scale effect, which explains what happens to total emissions as the overall size of the industrial sector increases, holding fixed the composition of disaggregated industries and their emissions intensities; the second term is the composition effect, which accounts for the changing mix of industries, holding constant the overall scale and the emissions intensities; and the third term is the technique effect, which captures changes in emissions levels resulting from varying the emissions intensities, holding fixed scale and composition.[14]

[14]This formulation in total differentials is based on infinitesimal changes. As pointed out by Levinson (2009), using it for decomposition of discrete-time changes assumes that there are no interaction terms. For instance, changing the scale of industry does not affect the industry composition or the emissions intensities. Alternatively, we can think of equation (3.3) as assuming that all of those interaction terms are combined into the third term, the technique effect, which will be a remainder

Estimating how much of the historical emissions reduction can be attributed to each of the three effects in equation (3.3) requires time series data on total emissions V, total output Y, and each industry's share of total output $\boldsymbol{\theta}$. The one variable in equation (3.3) that is not available by year is $\mathbf{z}$, each industry's emissions intensity. Therefore, I calculate the first term and a modified version of the second term in equation (3.3), and construct the third term as the remainder. In discrete-time notation,

$$\begin{aligned} \Delta V &= V^t - V^0 \\ &= \Delta V_Y + \Delta V_{\boldsymbol{\theta}} + \Delta V_{\mathbf{z}} \qquad (3.4) \\ \Delta V_Y &= Y^t \boldsymbol{\theta}^{0\prime} \mathbf{z}^0 - V^0 \\ \Delta V_{\boldsymbol{\theta}} &= Y^t \boldsymbol{\theta}^{t\prime} \mathbf{z}^0 - Y^t \boldsymbol{\theta}^{0\prime} \mathbf{z}^0 \\ \Delta V_{\mathbf{z}} &= V^t - Y^t \boldsymbol{\theta}^{t\prime} \mathbf{z}^0 \end{aligned}$$

where the superscripts 0 and t denote the base and the current periods respectively, and ΔV_Y, $\Delta V_{\boldsymbol{\theta}}$ and $\Delta V_{\mathbf{z}}$ are the scale, composition and technique effects. This is effectively a modified Laspeyres index decomposition in additive form with the following interpretation. ΔV_Y is the change in overall emissions resulting from a scaling of the economy, holding composition and the emissions intensities fixed; $\Delta V_Y + \Delta V_{\boldsymbol{\theta}}$ gives the changes in emissions resulting from changes in economic activities including both the scale and composition aspects, holding emission intensities fixed; $\Delta V_{\mathbf{z}}$ captures the residual changes, resulting from changes in the emissions intensities and their interactions with scale and compositional changes. Compared to a conventional

of changes after accounting for the first and second terms. This is equivalent to a Laspereys index decomposition with the residual term added to the third term.

Laspeyres index decomposition,[15] the scale effect remains the same, while the residual term in the Laspeyres decomposition is spread over the composition and technique effects in equation (3.4). The changes in percentage terms relative to the base-year emissions are then reported. This formulation uses the base-year, or start-year, emissions intensities, $\mathbf{z}^0$. The results may differ from what they would be if end-year intensities, $\mathbf{z}^T$, were used.[16] In particular, if over this time period the dirty industries were cleaned up more, proportionally, than the clean industries, then using the base-year emissions intensities will underestimate the technique effect (in percentage terms). Hence, by using the base-year intensities, it gives a conservative estimate of the role of technology. On the contrary, if over this time period the emissions-intensive industries cleaned up less relatively, the role of technology will be overstated. Based on the available data on the emissions intensities in years 1998, 2002 and 2006, it appears that neither scenario is a concern, as the correlations between the initial-period intensities and the percentage changes in the four or eight years afterwards are very weak.

Figure 3.3 illustrates the analysis for industrial CO_2 emissions. Line (1) plots the trend for CO_2 emissions from U.S. industry, as reported by the EPA and scaled

[15] See the method (a) in the appendix for a description of the Laspeyres index methods. A Laspeyres index decomposition of equation (3.2) in the additive form is

$$\begin{aligned} \Delta V &= \Delta V_Y + \Delta V_{\boldsymbol{\theta}} + \Delta V_{\mathbf{z}} + \Delta V_{\mathbf{R}} \\ \Delta V_Y &= Y^t \boldsymbol{\theta}^{0\prime} \mathbf{z}^0 - V^0 \\ \Delta V_{\boldsymbol{\theta}} &= Y^0 \boldsymbol{\theta}^{t\prime} \mathbf{z}^0 - V^0 \\ \Delta V_{\mathbf{z}} &= Y^0 \boldsymbol{\theta}^{0\prime} \mathbf{z}^t - V^0 \end{aligned}$$

and $\Delta V_{\mathbf{R}}$ is a residual term consisting of the interaction terms of the scale (ΔV_Y), composition ($\Delta V_{\boldsymbol{\theta}}$) and technique ($\Delta V_{\mathbf{z}}$) effects.

[16] In this case, the scale, composition and technique effects are formulated as follows.

$$\begin{aligned} \Delta V_Y &= V^T - Y^t \boldsymbol{\theta}^{T\prime} \mathbf{z}^T \\ \Delta V_{\boldsymbol{\theta}} &= Y^t \boldsymbol{\theta}^{T\prime} \mathbf{z}^T - Y^t \boldsymbol{\theta}^{t\prime} \mathbf{z}^T \\ \Delta V_{\mathbf{z}} &= Y^t \boldsymbol{\theta}^{t\prime} \mathbf{z}^T - V^t \end{aligned}$$

Compared to a conventional Paasche index decomposition (See the method (b) in the appendix), the technique effect remains the same, with the residual term spread over the other two terms.

so that the 1998 emissions equal 100. The emissions in 2007 are 4.6% below the 1998 level. This represents the combined scale, composition, and technique effects, or ΔV in equation (3.4), relative to base-year emissions, V^0. Line (2) depicts the total real gross output of the U.S. industrial sector, deflated using sectoral price indices and scaled so that the 1998 value equals 100. If the mix of industries making up the industrial sector had remained constant, i.e., $d\boldsymbol{\theta} = 0$, and the technology of production and abatement had remained constant, i.e., $d\mathbf{z} = 0$, line (2) represents how emissions would have changed over time. This 7.9% increase from 1998 to 2007 is the scale effect, or ΔV_Y. Line (3) in the figure is the result of multiplying each industry's real gross output in each year (Y_i^t) by the CO_2 emissions coefficient in 1998 ($\mathbf{z}_i^0$) and aggregating across industries to obtain $Y^t\boldsymbol{\theta}^{t\prime}\mathbf{z}^0$. It represents what CO_2 emissions would have been in each year if each industry had produced its concurrent output, but used the production and abatement technology from 1998. This combines the scale and composition effects, $\Delta V_Y + \Delta V_{\boldsymbol{\theta}}$, which added up to 8.5% from 1998 to 2007. Line (3) lies slightly above line (2), indicating that the composition of the U.S. industrial sector had shifted slightly toward industries that emit CO_2 more heavily. The difference between line (3) and line (2) suggests that the composition effect, $\Delta V_{\boldsymbol{\theta}}$, had led to an increase in emissions of about 0.6%. This effect is small and not consistent over time. As can be seen in the figure, in 2006, the composition effect suggests a slight move toward cleaner industries relative to 1998. Lastly, the technique effect, $\Delta V_{\mathbf{z}}$, is the difference between lines (1) and (3). From 1998 to 2007, the scale, composition, and technique effects together accounted for a reduction of CO_2 emissions by 4.6%, while the scale and composition effects alone would have implied an increase in emissions of 8.5%. Therefore, the technique effect must account residually for a 13.1% decline in emissions, offsetting the opposite forces of the scale and composition effects.

It is not surprising that improvements in technology turn out to be the most important factor contributing to the clean-up. What is interesting, however, is that changes in industry composition had little effect. If anything, U.S. industry seems to have shifted toward more emissions-intensive industries over the period. Previous studies have generally found the composition effect to be of the other direction, i.e., toward a cleaner mixture of industries, and of a large magnitude (Weber, 2009; Huntington, 2010). There are two plausible explanations for the different findings here. First, this study covers only the industrial sector, while the other studies apply to the overall economy. Therefore, broader structural changes between aggregate sectors, such as a shift from manufacturing to service, will not be captured in the current analysis. Rather, this will be reflected as a smaller scale effect, i.e., the industrial output had grown more slowly than it would have had it maintained the same share of GDP. Second, this may indeed be a new pattern revealed by more recent data. Looking closely at lines (2) and (3) in Figure 3.3, one can see that indeed the composition shift was toward cleaner industries in the late 1990s. However, the trend has been reversed in the 2000s, generating a net composition effect that is negligible. This can potentially be attributed to the lack of a national climate change policy in the United States. While other industrialized countries committed to quantitative GHG emissions targets under the Kyoto Protocol, the United States had not and did not plan to ratify the protocol which went into effect in mid-2000s. This unique position, absent of carbon taxes or cap-and-trade systems, has contributed a U.S. comparative advantage in producing more carbon-intensive goods. Though these compositional shifts are small and could be affected by a number of factors

As mentioned in Section 3.2, there have been a multitude of decomposition methods proposed and utilized in empirical research. Each index has its advantages and shortcomings. Generally, alternative decomposition methods provide similar results, though differences could be significant at times. To provide a robustness check for

the analysis, I calculate a variety of decomposition indices for comparison and present the results in the appendix. In all cases, the results are qualitatively similar to those presented above.

3.5 Energy Demand and Fuel Switching: Decomposing the Technique Effect

The previous section shows that the technique effect is responsible for the clean-up of the U.S. industrial sector. This section takes a closer look at this effect and attempts to allocate credit to different types of technique changes, using a different set of data. Two main technological advances are directly related to energy use, which is the largest source of CO_2 and of overall GHG emissions. One of these is the improvement in energy efficiency or energy productivity. If an industry uses less energy to produce the same amount of goods, the industrial CO_2 emissions need not grow as the economy expands. The other is the change in the fuel mix that the industries employ. Since the different types of fossil fuels have substantially different conversion factors between their energy content and carbon content, switching from using a dirtier fossil fuel, such as coal, to a cleaner one, like natural gas, may significantly reduce CO_2 emissions.

Potentially, the conversion factors may also vary over time. Nonetheless, in the case of primary energy sources such as coal, oil and natural gas, the conversion factors are mainly determined by the chemical makeup of the fuel. Hence, such variations, while they do exist across location and time, are very small in magnitude. The lone exception is electricity, whose conversion factor is in turn largely affected the mix of primary energy sources used for its generation. Therefore, changing conversion factors is not considered a major explanation for the technique effect.

This section focuses on energy-related CO_2 emissions and leaves out process emissions from the analysis. CO_2 emissions from fossil fuels and biomass use, including

those directly by the industrial sector and those indirectly through the use of retail electricity, account for more than 80% of all industrial CO_2 emissions. Similar to equation (3.1), total energy-related emissions from industry, V^E, can be written as the sum of emissions from each of its energy sources, V_j^E. This in turn can be written as total energy demand from industry, E, multiplied by the sum of each fuel's share of total energy, $\sigma_j = E_j/E$, times a conversion factor that reflects the amount of emissions per unit of energy content for that energy source, $c_j = V_j^E/E_j$. Further, the total energy demand, E, can be expressed by the real gross output of the industrial sector, Y, times the average energy intensity of the sector, e.

$$V^E = \sum_j V_j^E = \sum_j V_j^E c_j = E \sum_j \sigma_j c_j = eY \sum_j \sigma_j c_j \tag{3.5}$$

or in vector notation,

$$V^E = E\boldsymbol{\sigma}'\mathbf{c} = eY\boldsymbol{\sigma}'\mathbf{c} \tag{3.6}$$

where $\boldsymbol{\sigma}$ and $\mathbf{c}$ are $m \times 1$ vectors comprising the shares of each of the m fuels and their emissions conversion factors, respectively.

Totally differentiating equation (3.6) yields

$$dV^E = \boldsymbol{\sigma}'\mathbf{c}dE + E\mathbf{c}'d\boldsymbol{\sigma} + E\boldsymbol{\sigma}'d\mathbf{c} \tag{3.7}$$

$$= e\boldsymbol{\sigma}'\mathbf{c}dY + Y\boldsymbol{\sigma}'\mathbf{c}de + eY\mathbf{c}'d\boldsymbol{\sigma} + eY\boldsymbol{\sigma}'d\mathbf{c} \tag{3.8}$$

Equation (3.7) closely mirrors equation (3.3). The first term is the scale effect, relating to the level of total energy use. The second term is the composition effect, which accounts for the effect of the changing mix of energy sources. The third term is the technique effect, which captures the effect of the changes in the carbon intensity of various fuel sources. As discussed earlier, the only major energy source whose carbon intensity may have substantial moves in the time frame of the analysis is electricity. If

the mixture of the primary sources used in electricity generation changes significantly, electricity can become more or less emissions intensive. Additionally, if the power stations and the electric grid become more efficient, hence requiring less raw energy to provide a unit of retail electricity, the conversion factor for electricity will also become smaller.

Equation (3.8) further decomposes the energy scale effect into contributions from the size of the industrial sector and its energy intensity. One may be tempted to label the change in energy intensity as purely technological; however, it does include the compositional effects resulting from a restructuring of the industries with varying energy intensities within the industrial sector.

Figure 3.4 shows the result of the decomposition following equation (3.7) in a similar way to equation (3.4). From 1998 to 2007, CO_2 emissions from energy use by the industrial sector were reduced by about 7.6%, as shown by line (1). The main contributing factor is a reduction in energy use, represented by line (2), which dropped by about seven percent during the period. The composition effect, i.e., the difference between line (3) and line (2), is small and has actually contributed to more emissions, by 0.4%, over the same period, as much of the shift was from relatively less carbon intensive natural gas to more carbon intensive petroleum prior to the shale gas boom in the late 2000s. In the meantime, reduced carbon intensities of the energy sources contributed to a reduction of CO_2 emissions of about one percent. In fact, this technique effect comes predominantly from a reduced carbon conversion factor for retail electricity. This in turn comes from two sources. The first is the improved efficiency in the power sector and its delivery system, resulting in less primary energy use for the same amount of electricity provided for retail use. The second factor is the mix of primary energy sources for the power sector. In more recent years, the technique effect has become more pronounced as the emissions intensity of electricity

drops further with gas-powered plants replacing coal generation, with the shale gas boom providing cheap natural gas on the U.S. market.

The observation that most of the energy-related CO_2 emissions reduction comes from lower energy demand despite output growth supports the idea that improved energy efficiency is an important factor in the greening of U.S. industry. However, there remains to be determined what exactly drives this reduced energy intensity of the industrial sector. It can come from adopting new technologies or practice innovations that saves energy, or from substitution of the energy input with other factors in production, such as labor or raw materials. After all, the period of 1998-2007 was one that saw crude oil prices rise from $20 to $80. The increasingly expensive fossil fuels could have potentially induced firms to engage in more energy-saving arrangements in one way or another. From a policy perspective, the two possibilities have different implications. If the change was driven by improved energy efficiency or technological breakthroughs, a policy aiming to replicate the clean-up may emphasize innovation and technology diffusion. On the other hand, if most of the changes are a result of input substitution, then market based policies that affect the relative prices of inputs might be more effective. This is the idea of directed technological change in the framework of Acemoglu, Aghion, Bursztyn & Hemous. (2012). Of course, the two aspects are not independent of one another. Both could be responses to increasing energy prices and both serve to optimize production. The substitution of production factors is in fact an important component of production technology.

A number of studies have attempted to further pin down the potential causes of the aforementioned improvement in energy productivity. Casler and Rose (1998) uses SDA to show that substitution within the energy sector and between energy and other inputs was the leading cause of the decline in carbon dioxide emissions in the United States over the period from 1972 to 1982. Sue Wing (2008) uses econometric methods to show that price-induced substitution of variable inputs generated transitory energy

savings, while innovation induced by energy prices had only a minor impact. Due to data limitations further analysis is beyond the scope of the current paper.

3.6 International Trade: Measuring Displaced Emissions

The previous sections have documented the declining trends in the carbon emissions and energy use of U.S. industry. In recent years, one focal point of the discussion on climate change policies has been carbon leakage, i.e., such clean-ups by the developed economies have simply come from shifting the production of emissions-intensive goods elsewhere. To analyze whether the experience of U.S. industry in the late 1990s to the mid-2000s is subject to the same concern, I apply a similar approach to analyze emissions related to goods traded internationally. Let V^M be the extra CO_2 that would have been emitted in the United States had imported goods been produced domestically. This can be written as the sum of the extra emissions from each imported industry, Y_i^M, which in turn can be expressed as the total value of imports, Y^M, multiplied by the sum of each industry's share in that total imports, $\theta_i^M = Y_i^M/Y^M$, times each industry's emissions per dollar of shipments in the United States, $z_i = V_i/Y_i$,

$$V^M = \sum_i V_i^M = \sum_i Y_i^M z_i = Y^M \sum_i \theta_i^M z_i \tag{3.9}$$

or, in vector notation,

$$V^M = Y^M \boldsymbol{\theta}^{M\prime} \mathbf{z} \tag{3.10}$$

where $\boldsymbol{\theta}^M$ and $\mathbf{z}$ are $n \times 1$ vectors comprising the import shares of each of the n industries and their emissions intensities, respectively.

Note that V^M does not measure the emissions occurring overseas as a consequence of producing the goods for the United States, because other countries could have different emissions intensities from the United States. In addition, neither does it measure the exact additional U.S. industrial emissions had those imported goods been produced domestically, because producing all imports domestically would almost surely alter the relative prices and affect the domestic emission intensities. Rather, V^M estimates the amount of CO_2 emissions "displaced" by imports, assuming that domestic emissions intensities were not affected.

Another important issue that needs to be addressed before proceeding with the analysis is to choose the appropriate measure of emissions intensities. In the previous analysis of domestic emissions, direct emissions intensities have been used, accounting for only emissions that are generated directly by the industry making the output.[17] The fact that the emissions generated by intermediate products are not separately calculated does not matter. The intermediate input of one industry must be the output of another. Therefore, the emissions embodied in intermediate products are accounted for as long as they are produced domestically. In the case of international trade, however, ignoring the emissions embodied in intermediate inputs can significantly underestimate the emissions embodied in the entire production process of traded goods (Levinson, 2009). To address this issue, I use total emissions intensities derived through an input-output framework, which takes into account emissions throughout the production chain. Analysis using direct emissions intensities is also presented for comparison.

A similar decomposition analysis to equation (3.4) can be performed on the displaced emissions. Totally differentiating equation (3.10) yields

$$dV^M = \boldsymbol{\theta}^{M\prime}\mathbf{z}dY^M + Y\mathbf{z}'d\boldsymbol{\theta} + Y\boldsymbol{\theta}'d\mathbf{z} \tag{3.11}$$

[17]Except for emissions in the electricity generating industry, which are distributed to end-use industries.

where the three terms in the decomposition are the scale, composition and technique effects respectively. Unlike in previous sections, since the displaced emissions are not directly measured, but only estimated using current-period trade data and base-year emissions intensities data, only the scale and composition effects can be estimated.

Figure 3.5 shows the evolution of emissions embodied in U.S. imports from 1998 to 2010. Total value of U.S. imports, represented by line (1), grew by more than 75% in real terms from 1998 to 2007. This is the scale effect in equation (3.11). Line (2) plots the displaced emissions calculated following equation (3.10), taking into account emissions from intermediate inputs while assuming that the emissions intensities stayed constant as in 1998. It closely tracks the path of the volume growth. This suggests that overall the mix of U.S. imports did not become more emissions intensive since the late 1990s, as the difference between line (2) and line (1) represents the composition effect. In fact, the average imports appeared to have become slightly less emissions intensive in recent years. Note that an analysis using the direct emissions intensities would suggest a much stronger clean-up trend in the composition of U.S. imports. The emissions embodied in U.S. exports are also calculated in a similar fashion, and are presented in Figure 3.6. The U.S. exports also grew rapidly, up by 60% from 1998 to 2007. Unlike the imports, the embodied emissions of the U.S. exports seem to have slightly outpaced their volume growth. Using the direct emissions intensities would again lower the emissions path, but not by much this time.

It is also interesting to further disaggregate trade with different partner countries. U.S. trade was traditionally dominated by its exchange with other industrialized countries, but imports from emerging markets have been rising rapidly during the time period under consideration. In 1998, imports from high-income OECD countries represented 52% of all U.S. imports; exports to these countries accounted for 57% of total U.S. exports. By 2007, the shares had dropped to 41% and 51% respectively, and further to 35% and 45% by the end of the decade as the developed economies

were slow to recover from the global financial crisis. Concerns about carbon leakage and competitiveness often surface in debates about domestic regulations of carbon emissions. Such worries, similar to the pollution haven theories, focus on trade with the developing nations. Figure 3.7 shows the decomposition of the trade-embodied emissions disaggregated to trade with Annex I countries,[18] or the industrialized countries, and the others. Indeed, different patterns can be observed for the two groups. Apart from the striking difference in growth rates, it is notable that the composition of the U.S. imports from Annex I countries have become cleaner over time, while that from non-Annex I economies have become more carbon-intensive. The average U.S. exports to non-Annex I countries have also become more emissions intensive, though the exports to Annex I countries have not shown much change in terms of emissions intensity. These facts are consistent with the findings of Wang (2012) that the United States is importing more emissions-intensive products from countries with less stringent climate change policies. The differential paths in the trading patterns suggest that such concerns about carbon leakage are not completely off base.

The strong growth in international trade, particularly in imports, led to more than a doubling of net imports for the United States, as shown by line (1) in Figure 3.8. Though the net imports do not appear to have become more emissions intensive, the rise in its scale has sizable implication for the emissions picture of U.S. industry. Figure 3.3 illustrates the last step in the analysis, estimating the fraction of the U.S. emissions reduction that can be explained by changes in the combined scale and compositional variations of international trade. Using emission intensities of 1998 and replacing the imports in equation (3.10) with the changes in net imports from 1998, I obtain an estimate of CO_2 emissions displaced by the changes in net trade from 1998

[18] Annex I countries are those that are parties to the Annex I of the Kyoto Protocol. These include high-income OECD countries, which are traditionally important trade partners of US, and Eastern European and some former Soviet states, whose share in US trade is small (less than two percent of imports or exports throughout the analysis period). Annex I countries committed to quantitative GHG emissions caps under the Kyoto Protocol.

had technology remained unchanged since then. By 2007, this would imply a four percent increase in emission relative to the 1998 level. Line (4) in Figure 3.3 uses this series. Holding technology fixed as of 1998, line (4) plots what U.S. industrial CO_2 emissions would have been if the all increased net imports since 1998 had instead been produced domestically in the United States. The difference between line (3) and line (4) therefore represents the contribution of net trade changes to the clean-up of U.S. industry. From 1998 to 2007, this net trade change effect of negative four percent amounts to about one third of the scale effect and a little less than one fourth of the total clean-up from the combined scale, composition effects and no-net-trade-change scenario, i.e., the difference between line (1) and line (4). The remaining three quarters are attributed to the technique effect.

It should be noted that this no-net-trade-change scenario, similar to all the displaced emissions calculations, represents a purely partial-equilibrium analysis. In no sense does line (4) in Figure 3.3 represent what the level of U.S. industrial emissions would actually have been absent trade growth even if technology stayed constant. It is merely an accounting exercise, asking what fraction of the clean-up of U.S. industry can be matched to increased imports. In fact, if the United States imports the carbon-intensive goods because they are less expensive when produced abroad, then in the absence of trade growth the U.S. economy would likely produce and consume fewer such carbon-intensive goods.

3.7 Conclusion

The analysis suggests that recently most of the carbon emissions reduction in the U.S. industrial sector has come from changes in technology, rather than from increases in net imports or changes in the types of goods produced domestically. From 1998 to 2007, industrial CO_2 emissions decreased by 4.6%. The technique effect is by far

the most important driving force, which accounts for almost all of the reduction in emissions. With respect to international trade, the effect of increased net imports amounts to less than one third of the technique effect, or less than one fourth of the total clean-up of U.S. industry. Furthermore, most of the technique effect can be attributed to improved energy efficiency in the industrial sector, with fuel switching playing a minor role.

The decomposition exercises are rather mechanical, and they are meant to serve as a first step in identifying the forces driving carbon emissions as well as opportunities for further environmental improvement. A useful accompanying exercise would be to decompose the changes in carbon emissions of the aggregate economy and find out if the findings on the industrial sector generalize to the wider economy. An interesting follow-up study would be to assess the drivers behind the downward trend in energy demand, as mentioned in section 3.5. Despite a lack of CO_2 emissions regulations at the federal level, there have been plenty of state and regional policies attempting to address climate change in the United States. Did any of these or other environmental regulations have an impact on energy uses? Was it caused by innovation and improvements in technology or do energy prices play a more important role? Further analysis should provide more insight into the evolution of U.S. GHG emissions as well as the impacts of potential policies.

Bibliography

Acemoglu, D., Aghion, P., Bursztyn, L., & Hemous, D. (2012). "The environment and directed technical change," *American Economic Review*, *102*, 131-166.

Ang, B.W. (2004) "Decomposition analysis for policymaking in energy: Which is the preferred method?" *Energy Policy*, *32*, 1131–1139.

Ang, B.W., Liu, F.L., & Chew, E.P. (2003). "Perfect decomposition techniques in energy and environmental analysis,". *Energy Policy*, *31*, 1561-1566.

Ang, B.W., Liu, F.L., & Chung, H.S. (2004). "A generalized Fisher index approach to energy decomposition analysis,". *Energy Economics*, *26*, 757-763.

Ang, B.W. & Zhang, F.Q. (2000). "A survey of index decomposition analysis in energy and environmental studies," *Energy*, *25*, 1149–1176.

Boyd, G.A., Hanson, D.A., & Sterner, T. (1988). "Decomposition of changes in energy intensity: A comparison of the Divisia index and other methods," *Energy Economics*, *10*, 309-312.

Casler, S.D., & Rose, A. (1998). "Carbon dioxide emissions in the US economy: A structural decomposition analysis," *Environmental and Resource Economics*, *11*, 349-363.

de Boer, P. (2009). "Generalized Fisher index or Siegel-Shapley decomposition?". *Energy Economics*, *31*, 810-814.

Dietzenbacher, E. & Los, B. (1998). "Structural decomposition techniques: Sense and sensitivity," *Economic Systems Research*, *10*, 307-324.

Economics and Statistics Administration (ESA), U.S. Department of Commerce (DOC). (2010). "US carbon dioxide emissions and intensities over time: A detailed accounting of industries, government and households." Available at: http://www.esa.doc.gov/Reports/u.s.-carbon-dioxide.

Fortin, N., Lemieux, T., & Firpo, S. 2011. "Decomposition methods in economics," in Card, D., & Ashenfelter, O., eds., *Handbook of Labor Economics*, 4th Edition, Elsevier North Holland, 1-102.

Golove, W.H. & Schipper, L.J. (1996). "Long-term trends in US manufacturing energy consumption and carbon dioxide emissions," *Energy*, *21*, 683-692.

Golove, W.H., & Schipper, L.J. (1997). "Restraining carbon emissions: Measuring energy use and efficiency in the USA," *Energy Policy*, *25*, 803-812.

Greening, L.A., Davis, W.B., & Schipper, L. (1998). "Decomposition of aggregate carbon intensity for the manufacturing sector: Comparison of declining trends from 10 OECD countries for the period 1971-1991," *Energy Economics*, *20*, 43-65.

Greening, L.A., Ting, M., & Davis, W.L. (1999). "Decomposition of aggregate carbon intensity for freight: Trends from 10 OECD countries for the period 1991-1993," *Energy Economics*, *21*, 331-361.

Greening, L.A., Ting, M., & Krackler, T.J. (2001). "Effects of changes in residential end-uses and behavior on aggregate carbon intensity: Comparison of 10 OECD countries for the period 1970 through 1993. Energy Economics, 23(2), 153-178.

Hamilton, C. & Turton, H. (2002). "Determinants of emissions growth in OECD countries," *Energy Policy*, *30*, 63-71.

Hoekstra, R. & Van den Bergh, J.C. (2003). "Comparing structural decomposition analysis and index," *Energy Economics*, *25*, 39-64.

Huntington, H.G. (1989). "The impact of sectoral shifts in industry on US energy demands," *Energy*, *14*, 363-372.

Huntington, H.G. (2010). "Structural change and US energy use: Recent patterns," *Energy Journal*, *31*, 25-39.

Intergovernmental Panel on Climate Change (IPCC). (2007). "Summary for policymakers," in Metz, B., Davidson, O.R., Bosch, P.R., Dave, R., & Meyer, L.A. (eds.), *Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press.

Kim, Y. & Worrell, E. (2002). "International comparison of CO_2 emission trends in the iron and steel industry," *Energy policy*, *30*, 827-838.

Leontief, W. (1970). "Environmental repercussions and the economic structure: An input-output approach," *Review of Economics and Statistics*, *52*, 262–271.

Lescaroux, F. (2008). "Decomposition of US manufacturing energy intensity and elasticities of components with respect to energy prices," *Energy Economics*, *30*, 1068-1080.

Levinson, A. (2009). "Technology, international trade, and pollution from US manufacturing," *American Economic Review*, *99*, 2177-2192.

Liu, F. (2004). "Decomposition analysis applied to energy: Some methodological issues," Dissertation. Available at http://scholarbank.nus.sg/handle/10635/14741.

Liu, H., Polenske, K.R., Guilhoto, J.J.M., & Xi, Y. (2011). "Direct and indirect energy consumption in China and the United States," MRPA Paper No. 37960. Available at http://mpra.ub.uni-muenchen.de/37960/.

Liu, N. & Ang, B.W. (2007). "Factors shaping aggregate energy intensity trend for industry: Energy intensity versus product mix," *Energy Economics*, *29*, 609-635.

Malla, S. & Im, E.I. (2011) "Assessment of factors affecting carbon dioxide emission from power generation in the united states: A decomposition analysis," *Asia-Pacific Journal of Social Sciences*, *Special Issue No. 2*, 97-113.

Metcalf, G.E. (2008), "An empirical analysis of energy intensity and its determinants at the state level," *Energy Journal*, *29*, 1-26.

Mulder, P. & de Groot, H.L.F. (2012). "Structural change and convergence of energy intensity across OECD countries, 1970-2005," *Energy Economics*, *34*, 1910-1921.

Office of Energy Efficiency and Renewable Energy, U.S. Department of Energy. (2012). "Energy intensity indicators." Available at http://www1.eere.energy.gov/analysis/eii_index.html.

Onder, H. (2012). "Trade and climate change: An analytical review of key issues," *Economic Premise*, *86*, the World Bank, Washington, DC.

Peters, G.P. & Hertwich, E.G. (2008). "CO_2 embodied in international trade with implications for global climate," *Environmental Science and Technology*, *42*, 1401-1407.

Pierce, J.R. & Schott, P.K. (2010). "Concording US Harmonized System codes over time." Available at: http://faculty.som.yale.edu/peterschott/sub_international.htm.

Rose, A. (1999). "Input-output structural decomposition analysis of the energy and environment," *Handbook of Environmental and Resource Economics*, Cheltenham: Elgar, 1104-1179.

Schipper, L.J., Haas, R., & Sheinbaum, C. (1996). "Recent trends in residential energy use in OECD countries and their impact on carbon dioxide emissions: A comparative analysis of the period 1973–1992," *Mitigation and Adaptation Strategies for Global Change*, *1*, 167-196.

Schipper, L., Murtishaw, S., Khrushch, M., Ting, M., Karbuz, S., & Unander, F. (2001). Carbon emissions from manufacturing energy use in 13 IEA countries: long-term trends through 1995. Energy Policy, 29(9), 667-688.

Schipper, L., Ting, M., Khrushch, M., & Golove, W. (1997). "The evolution of carbon dioxide emissions from energy use in industrialized countries: An end-use analysis," *Energy Policy*, *25*, 651-672.

Scholl, L., Schipper, L., & Kiang, N. (1996). "CO_2 emissions from passenger transport: A comparison of international trends from 1973 to 1992," *Energy Policy*, *24*, 17-30.

Schott, P.K. (2008). "The relative sophistication of Chinese exports," *Economic Policy*, *23*, 5-49.

Su, B. (2011). "Environmental input-output analysis: Emissions embodied in trade and structural decomposition analysis," Dissertation. Available at http://scholarbank.nus.sg/handle/10635/30258.

Su, B., Huang, H.C., Ang, B.W., and Zhou, P. (2010). "Input–output analysis of CO_2 emissions embodied in trade: The effects of sector aggregation," *Energy Economics*, *32*, 166–175.

Sue Wing, I. (2008). "Explaining the declining energy intensity of the US economy," *Resource and Energy Economics*, *30*, 21-49.

Sun, J.W. (1998). "Changes in energy consumption and energy intensity: A complete decomposition model," *Energy Economics*, *20*, 85-100.

Sun, J.W. and Malaska, P. (1998). "CO_2 emission intensity in developed countries 1980-1994," *Energy*, *23*, 105-112.

Torvanger, A. (1991) "Manufacturing sector carbon dioxide emissions in nine OECD countries, 1973-87: A Divisia index decomposition to changes in fuel mix, emission coefficients, industry structure, energy intensities and international structure," *Energy Economics*, *13*, 168-186.

U.S. Bureau of Economic Analysis (BEA) (2012). *GDP by Industry Data*. Available at http://www.bea.gov/industry/gdpbyind_data.htm.

U.S. Census Bureau. (2007-2011). *US Imports Merchandise Trade, 2006-2010*, Washington, DC: U.S. Census Bureau.

U.S. Census Bureau. (2007, 2009-2010). *Annual Survey of Manufactures (ASM), 2006, 2008-2009*. Available at: http://factfinder.census.gov/servlet/DatasetMainPageServlet?_program=EAS.

U.S. Census Bureau. (2008). *2007 Economic Census and Surveys*. Available at: http://factfinder.census.gov/servlet/DatasetMainPageServlet?_program=ECN.

U.S. Energy Information Administration (EIA). (2012). *Annual Energy Review*. Available at http://www.eia.gov/totalenergy/data/annual/index.cfm.

U.S. Environmental Protection Agency (EPA). (2012). *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2010*. Available at http://www.epa.gov/climatechange/ghgemissions/usinventoryreport.html.

Vinuya, F., DiFurio, F., & Sandoval, E. (2010). "A decomposition analysis of CO_2 emissions in the United States," *Applied Economics Letters*, *17*, 925-931.

Weber, C.L. (2009). "Measuring structural change and energy use: Decomposition of the US economy from 1997 to 2002," *Energy Policy*, *37*, 1561-1570.

Wiedmann, T. (2009) "A review of recent multi-region input–output models used for consumption-based emission and resource accounting," *Ecological Economics, 69*, 211-222.

Wiedmann, T., Lenzen, M., Turner, K. & Barrett, J. (2007). "Examining the global environmental impact of regional consumption activities – Part 2: Review of input-output models for the assessment of environmental impacts embodied in trade," *Ecological Economics*, *61*, 15-26.

Appendix: Alternative Decomposition Analysis

As explained previously, the decomposition analysis featured in the main text largely amounts to an additive version of the Laspeyres index. To provide a robustness check for the analysis, I present in this appendix alternative IDA results for comparison.

A couple of data related issues are noted here. First, since calculating the indices, other than the modified Laspeyres used in the main text, requires detailed emissions coefficients at both the start and end periods, the indices reported are for changes between years 1998, 2002 and 2006, the years for which data are available. Second, the overall industrial emissions data utilized in the indices are also different from the series used in the main analysis. While the yearly emissions levels used before come from EIA, the emissions data in the IDA are from ESA, which conform with the emissions intensities data available. This results in different estimates of the changes in industrial CO_2 emissions over the years.

The indices are presented in Tables 3.1 through 3.2. The methods included are some of the widely adopted and recommended in decomposition analysis and related research (Ang, 2004). The traditional Laspeyres and Paasche methods produce sizable residues, sometimes larger than certain component effects. This can be attributed to weighting solely based on the starting or ending period. When the analyzed period is longer and changes are larger, the interaction effects of the different main components can become more pronounced and it results in large residue changes unaccounted. Nonetheless, these two methods still yield decomposition results in line with the other methods. The results suggest a similar story to the analysis in the main text. The technique effect has been the main driving force behind the reduction in the U.S. industrial CO_2 emission since late 1990s. It accounts for about four fifths of the clean-up (after accounting for the increase in scale), which the rest one fifth coming from the composition effect. The composition effect appears to be larger than claimed

in the main text. This is partly due to the difference in end year. It can be seen in Figure 3.3 that by 2006, the composition effect does give a small contribution to the clean-up, but it vanishes after that.

Table 3.4 provides a similar presentation of IDA of industrial CO_2 emissions from energy use, offering a comparison to section 3.5. Since the emissions intensities data by fuel is available for all years, I provide the result for the period between 1998 and 2007, the focal period in the main text. This time, all methods provide remarkably similar decomposition results. They confirm the story that reduced energy use, or the scale effect, is by far the most important factor in the decline of energy-related CO_2 emissions from U.S. industry, accounting for more than 88% of the changes. The composition effect, or the changing energy mix, has a very small impact increasing emissions. The magnitude of the technique effect, mainly due to improved efficiency in the electricity sector, accounts for about one seventh of the decline of industrial energy intensity.

A summary of the decomposition methods used follows.

Summary of Index Decomposition Formulae

Assume that V is an aggregate, there are n factors, $V = \sum_i x_{1,i}x_{2,i}...x_{n,i}$ and $V_i = x_{1,i}x_{2,i}...x_{n,i}$, where i denotes an attribute of the aggregate such as an industry or fuel type. Further assume that from period 0 to period T the aggregate changes from $V^0 = \sum_i x^0_{1,i}x^0_{2,i}...x^0_{n,i}$ to $V^T = \sum_i x^T_{1,i}x^T_{2,i}...x^T_{n,i}$. Then a multiplicative decompositions is

$$D_{total} = V^T/V^0 = D_{x_1}D_{x_2}...D_{x_n}D_{residue}$$

and an additive decomposition is

$$\Delta V_{total} = V^T - V^0 = \Delta V_{x_1} + \Delta V_{x_2} + ... + \Delta V_{x_n} + \Delta V_{residue}$$

where $D_{residue}$ and $\Delta V_{residue}$ are residual terms. Some methods do not have a residual term by design and are called perfect decomposition. Hence, calculations following equation (3.4) yield perfect decomposition. Note also that the additive decompositions in the tables are presented as a fraction of base period aggregate.

The relevant formulae for the methods are summarized below.

(a) Laspeyres index methods

The conventional Laspeyres index uses base period weights. The formulae of the effect of the kth factor are:

Multiplicative:

$$D^L_{x_k} = \frac{\sum_i x^0_{1,i}...x^T_{k,i}...x^0_{n,i}}{\sum_i x^0_{1,i}...x^0_{k,i}...x^0_{n,i}}$$

Additive:

$$\Delta V^L_{x_k} = \sum_i x^0_{1,i}...x^T_{k,i}...x^0_{n,i} - \sum_i x^0_{1,i}...x^0_{k,i}...x^0_{n,i}$$

(b) Paasche index methods

The other basic index, Paasche, uses end period weights.

Multiplicative:

$$D^P_{x_k} = \frac{\sum_i x^T_{1,i}...x^T_{k,i}...x^T_{n,i}}{\sum_i x^T_{1,i}...x^0_{k,i}...x^T_{n,i}}$$

Additive:

$$\Delta V^P_{x_k} = \sum_i x^T_{1,i}...x^T_{k,i}...x^T_{n,i} - \sum_i x^T_{1,i}...x^0_{k,i}...x^T_{n,i}$$

(c) Fisher index method

The Fisher "ideal" index is calculated as the geometric mean of the Laspeyres and Paasche indices.

Multiplicative:

$$D^F_{x_k} = \sqrt{D^L_{x_k} D^P_{x_k}}$$

The Fisher index gives perfect decomposition.

(d) Log mean Divisia index methods (LMDI I)

The LMDI I methods take a rather simple form and give perfect decomposition.

Multiplicative:

$$D_{x_k} = \exp\left(\sum_i \frac{L(V_i^T, V_i^0)}{L(V^T, V^0)} \ln\left(\frac{x_{k,i}^T}{x_{k,i}^0}\right)\right)$$

Additive:

$$\Delta V_{x_k} = \sum_i L(V_i^T, V_i^0) \ln\left(\frac{x_{k,i}^T}{x_{k,i}^0}\right)$$

where function $L(a, b)$ is the logrithmic average of two positive numbers a and b given by

$$\begin{aligned} L(a,b) &= \frac{a-b}{\ln a - \ln b} \quad \text{for} \quad a \neq b \\ &= a \qquad\qquad\quad \text{for} \quad a = b. \end{aligned}$$

(e) Arithmetic mean Divisia index methods (AMDI)

The AMDI methods employ an arithmetic mean weight function instead of the log mean weight function used in LMDI I methods. Their formulae are therefore slightly simpler. The decomposition results they give are often close to those from the LMDI I, though they do not give perfect decomposition.

Multiplicative:

$$D_{x_k} = \exp\left(\sum_i \frac{1}{2}\left(\frac{V_i^T}{V^T} + \frac{V_i^0}{V^0}\right) \ln\left(\frac{x_{k,i}^T}{x_{k,i}^0}\right)\right)$$

Additive:

$$\Delta V_{x_k} = \sum_i \frac{1}{2}\left(V_i^T + V_i^0\right) \ln\left(\frac{x_{k,i}^T}{x_{k,i}^0}\right)$$

(f) Generalized Fisher index method

The modified Fisher ideal index method gives a perfect multiplicative decomposition. The general formulae are a little complicated (see Ang et. al. (2004) for detail) When decomposition involves only two factors, it is identical to the Fisher ideal index.

In the case of the analysis performed here, there are three factors and the formulae are given below (subscript i in all variables are omitted for conciseness):

$$
\begin{aligned}
D_{x_1} &= \left[\frac{\sum x_1^T x_2^0 x_3^0}{\sum x_1^0 x_2^0 x_3^0}\left(\frac{\sum x_1^T x_2^T x_3^0}{\sum x_1^0 x_2^T x_3^0}\frac{\sum x_1^T x_2^0 x_3^T}{\sum x_1^0 x_2^0 x_3^T}\right)^{\frac{1}{2}}\frac{\sum x_1^T x_2^T x_3^T}{\sum x_1^0 x_2^T x_3^T}\right]^{\frac{1}{3}} \\
D_{x_2} &= \left[\frac{\sum x_1^0 x_2^T x_3^0}{\sum x_1^0 x_2^0 x_3^0}\left(\frac{\sum x_1^T x_2^T x_3^0}{\sum x_1^T x_2^0 x_3^0}\frac{\sum x_1^0 x_2^T x_3^T}{\sum x_1^0 x_2^0 x_3^T}\right)^{\frac{1}{2}}\frac{\sum x_1^T x_2^T x_3^T}{\sum x_1^T x_2^0 x_3^T}\right]^{\frac{1}{3}} \\
D_{x_3} &= \left[\frac{\sum x_1^0 x_2^0 x_3^T}{\sum x_1^0 x_2^0 x_3^0}\left(\frac{\sum x_1^T x_2^0 x_3^T}{\sum x_1^T x_2^0 x_3^0}\frac{\sum x_1^0 x_2^T x_3^T}{\sum x_1^0 x_2^T x_3^0}\right)^{\frac{1}{2}}\frac{\sum x_1^T x_2^T x_3^T}{\sum x_1^T x_2^T x_3^0}\right]^{\frac{1}{3}}
\end{aligned}
$$

(g) Shapley/Sun method

Sun (1998) proposed an additive decomposition method which is identical to the Shapley decomposition used by researchers in cost allocation problems. This method creates perfect decomposition by distributing the interaction terms in the conventional Laspeyres index method to the main effects. It has therefore been referred to as the refined Laspeyres index method. The formulae for the three factor case are:

$$
\begin{aligned}
\Delta V_{x_1} &= \sum \Delta x_1 x_2^0 x_3^0 + \frac{1}{2}\sum \Delta x_1\left(\Delta x_2 x_3^0 - x_2^0 \Delta x_3\right) + \frac{1}{3}\sum \Delta x_1 \Delta x_2 \Delta x_3 \\
\Delta V_{x_2} &= \sum x_1^0 \Delta x_2 x_3^0 + \frac{1}{2}\sum \Delta x_2\left(\Delta x_1 x_3^0 - x_1^0 \Delta x_3\right) + \frac{1}{3}\sum \Delta x_1 \Delta x_2 \Delta x_3 \\
\Delta V_{x_3} &= \sum x_1^0 x_2^0 \Delta x_3 + \frac{1}{2}\sum \Delta x_3\left(\Delta x_1 x_2^0 - x_1^0 \Delta x_2\right) + \frac{1}{3}\sum \Delta x_1 \Delta x_2 \Delta x_3
\end{aligned}
$$

where $\Delta x_k = x_k^T - x_k^0$.

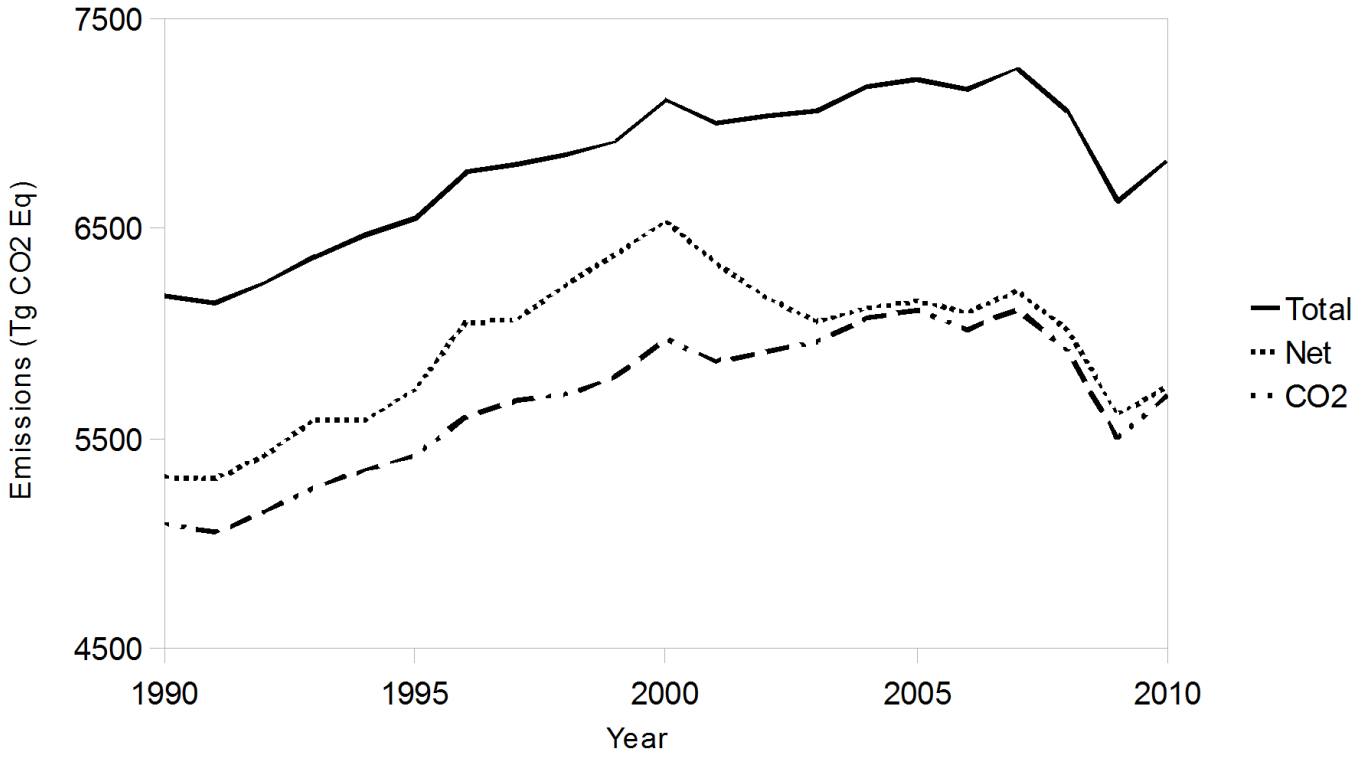


Figure 3.1: U.S. Greenhouse Gas Emissions

Note: Emissions are measured in teragrams (million metric tons) of CO_2-equivalent. Net GHG emissions include emissions from land use, land-use change, and forestry (sinks). Both total GHG and CO_2 emissions exclude emissions from land use, land-use change, and forestry (sinks).

Data Source: EPA (2012).

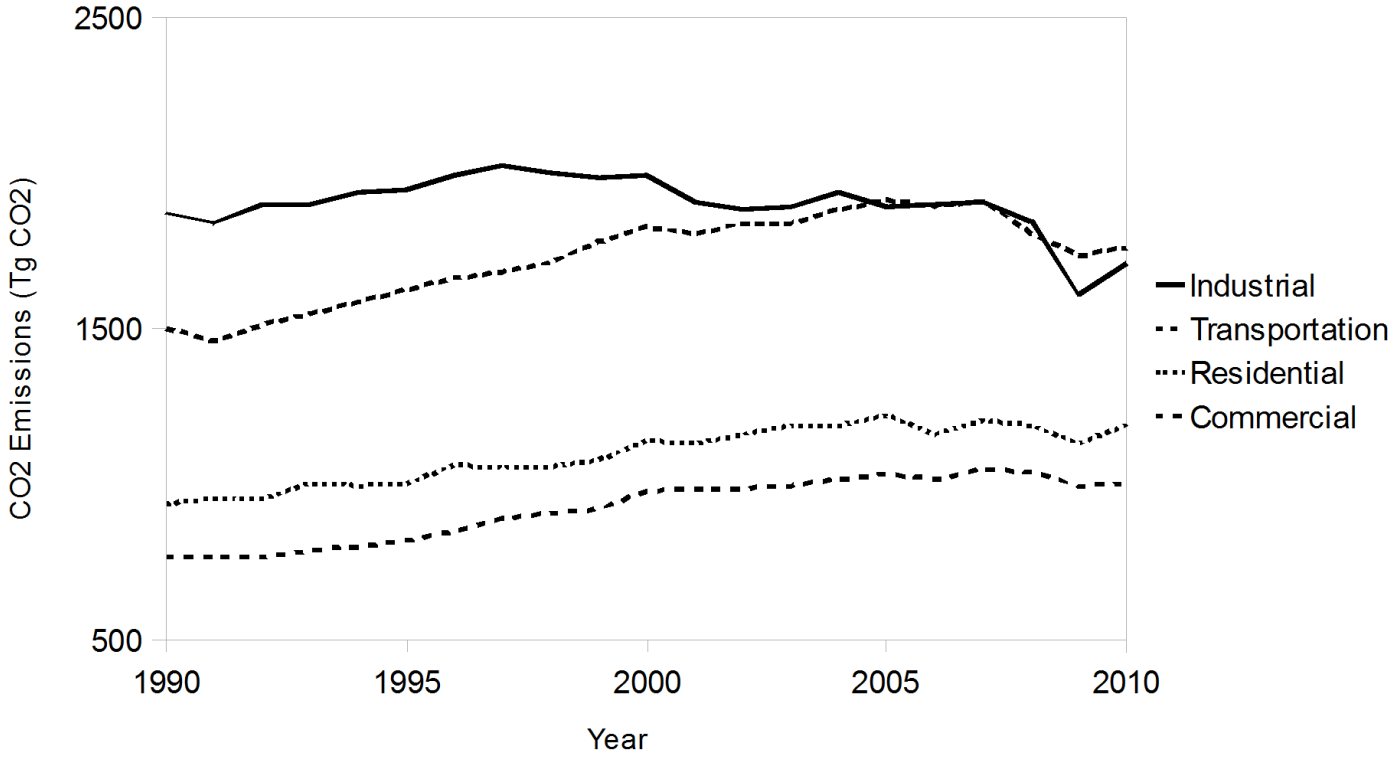


Figure 3.2: U.S. CO_2 Emissions Allocated to Economic Sectors

Note: Emissions are measured in teragrams (million metric tons) of CO_2.
Data Source: EPA (2012).

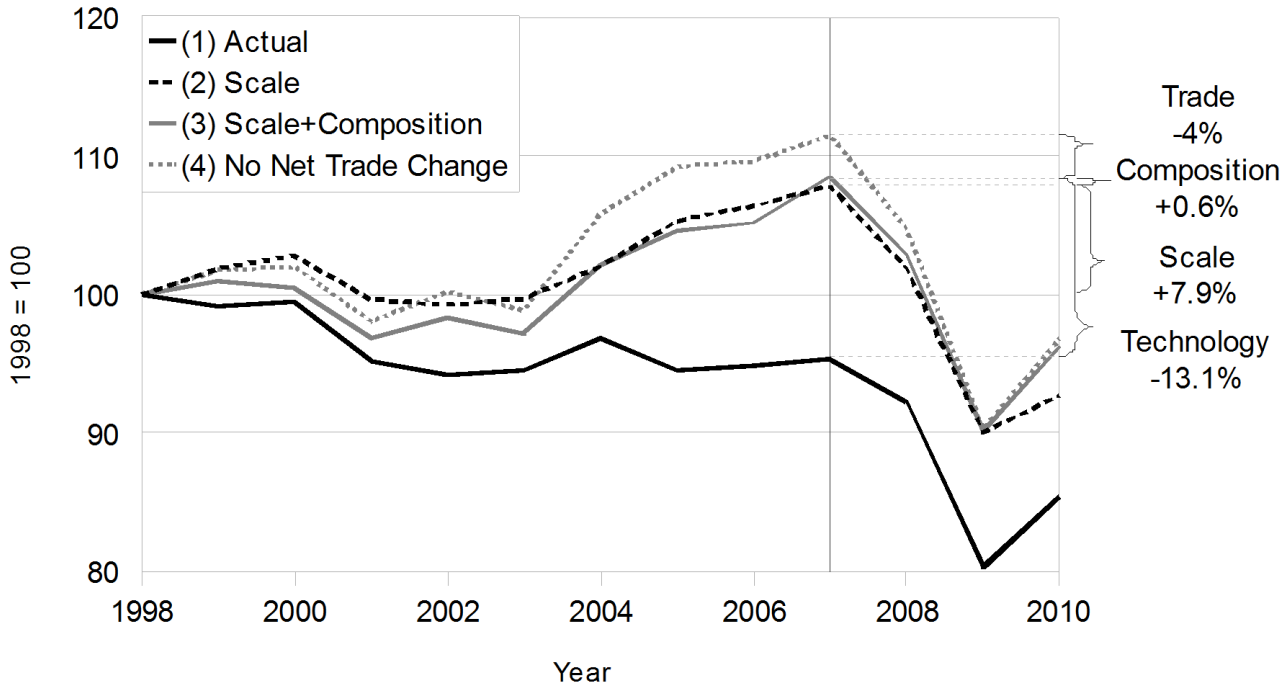


Figure 3.3: CO_2 Emissions from U.S. Industry

Note: CO_2 emissions are shown in relative terms, with industrial CO_2 emissions in 1998 equal to 100. The decomposition follows equation (3.4): scale, line (2) relative to 100; composition, line (3) - line (2); technique, line (1) - line (3).

Taking into account of international trade effect: scale + composition, line (4) relative to 100; net trade change, line (3) - line (4).

Data Source: Author's calculation.

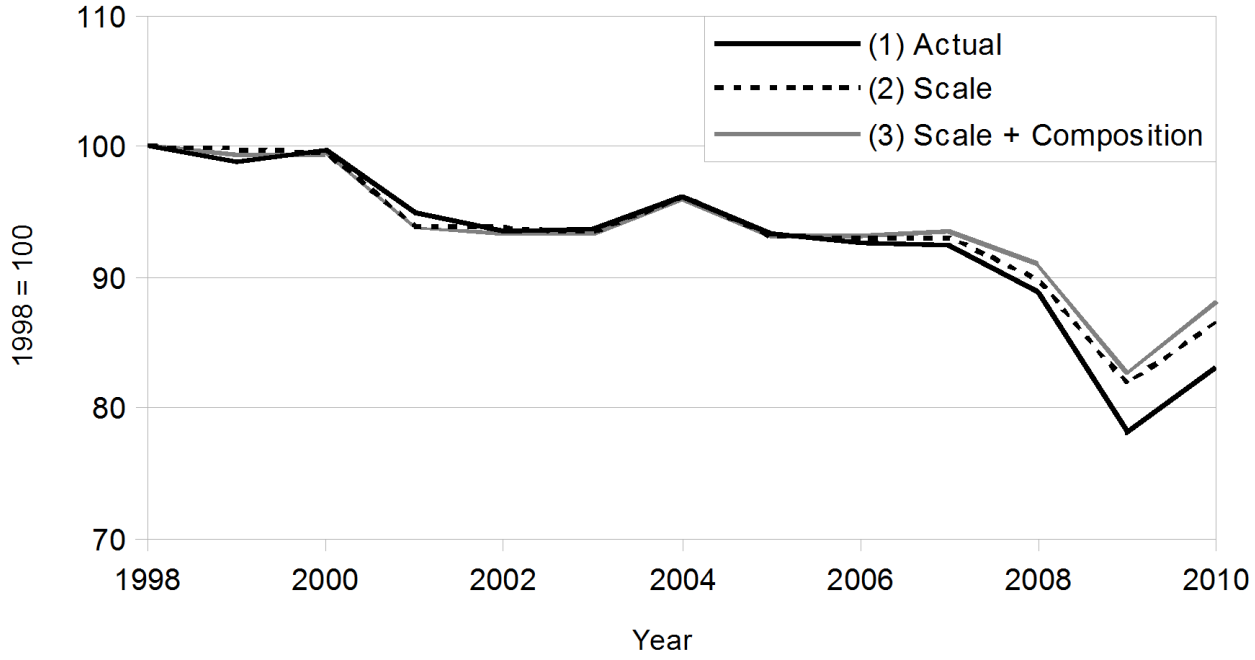


Figure 3.4: U.S. Industrial CO_2 Emissions from Energy Consumption

Note: CO_2 emissions are shown in relative terms, with energy-related industrial CO_2 emissions in 1998 equal to 100. The decomposition follows equation (3.7): scale (energy demand), line (2) relative to 100; composition (fuel mix), line (3) - line (2); technique (conversion factors), line (1) - line (3).

Data Source: Author's calculation.

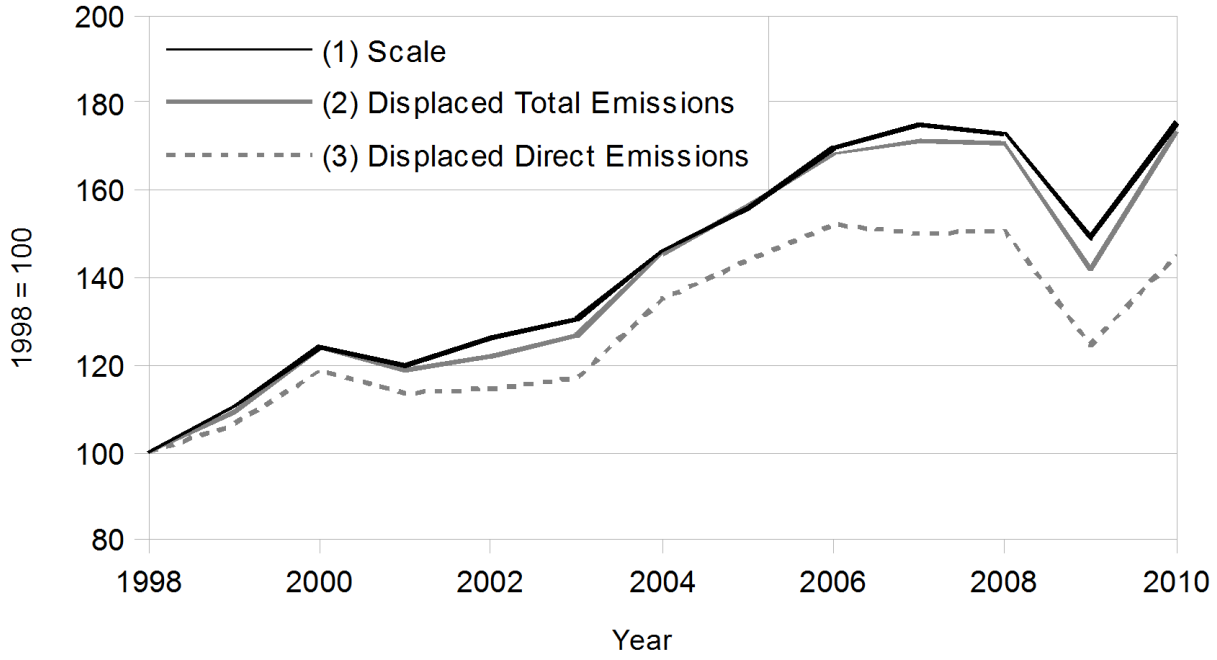


Figure 3.5: "Displaced" CO_2 Emissions by U.S. Imports

Note: CO_2 emissions are shown in relative terms, with CO_2 emissions displaced by the U.S. imports in 1998 equal to 100. The decomposition follows equation (3.11): scale, line (1) relative to 100; composition, line (2) - line (1).

Data Source: Author's calculation.

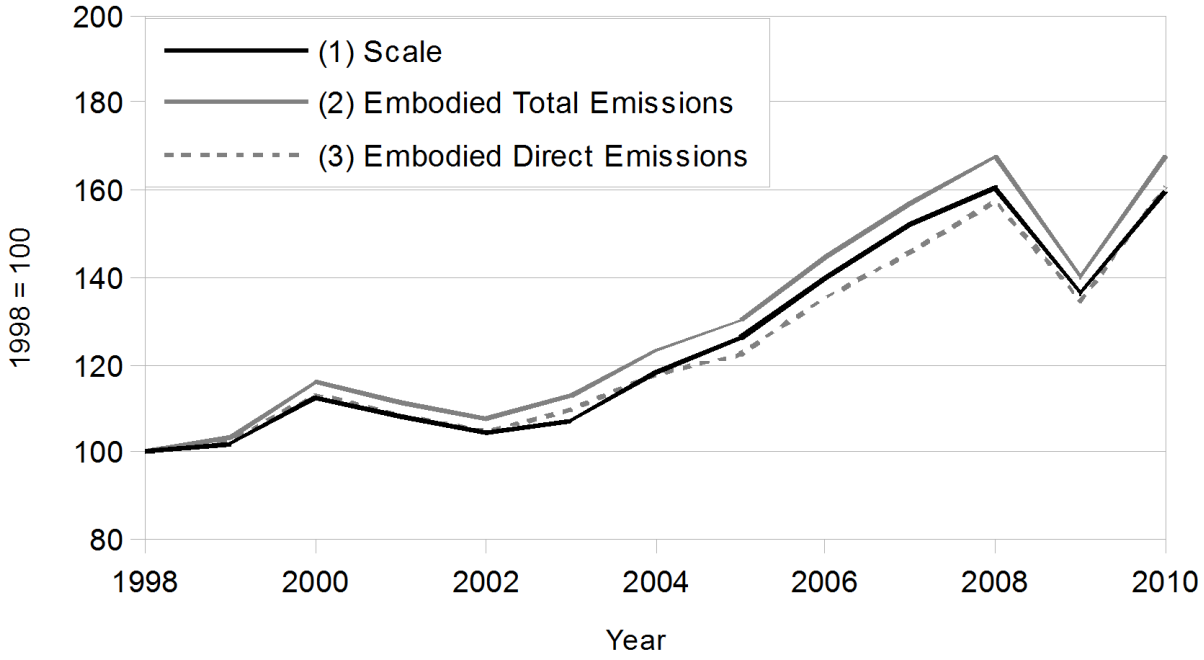


Figure 3.6: Embodied CO_2 Emissions of U.S. Exports

Note: CO_2 emissions are shown in relative terms, with CO_2 emissions embodied in the U.S. exports in 1998 equal to 100. The decomposition follows equation (3.11): scale, line (1) relative to 100; composition, line (2) - line (1).

Data Source: Author's calculation.

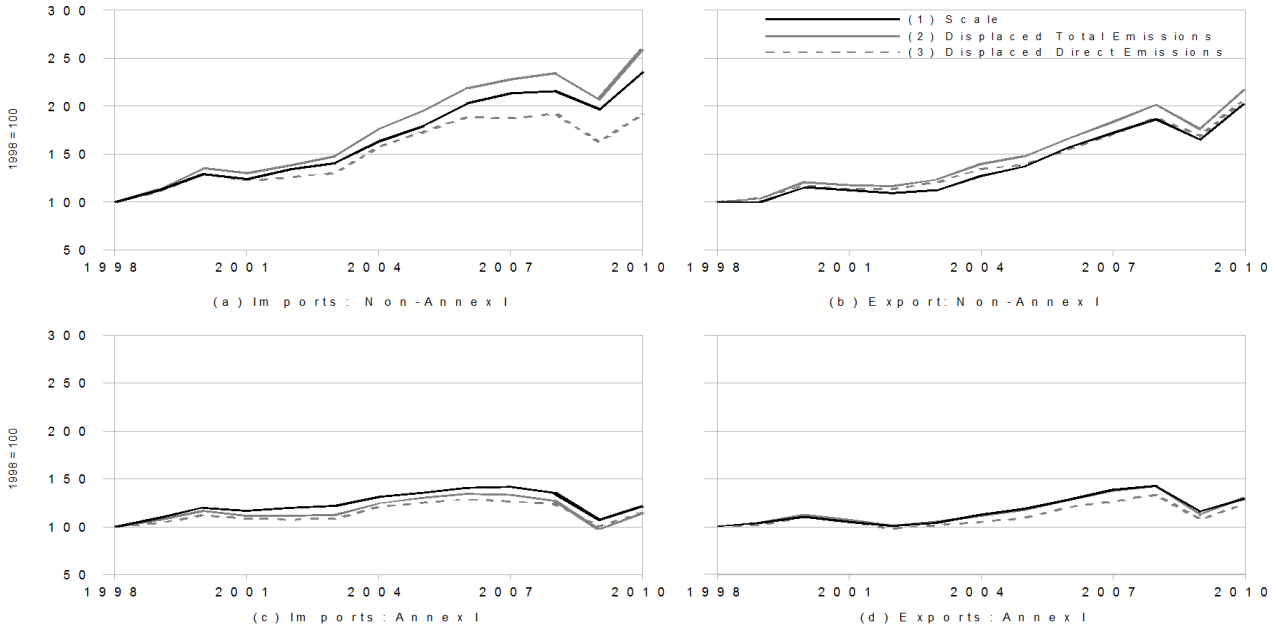


Figure 3.7: CO_2 Emissions Embodied in U.S. Trade by Country Groups

Note: CO_2 emissions are shown in relative terms, with those in 1998 equal to 100. The decomposition follows equation (3.11): scale, line (1) relative to 100; composition, line (2) - line (1).

Data Source: Author's calculation.

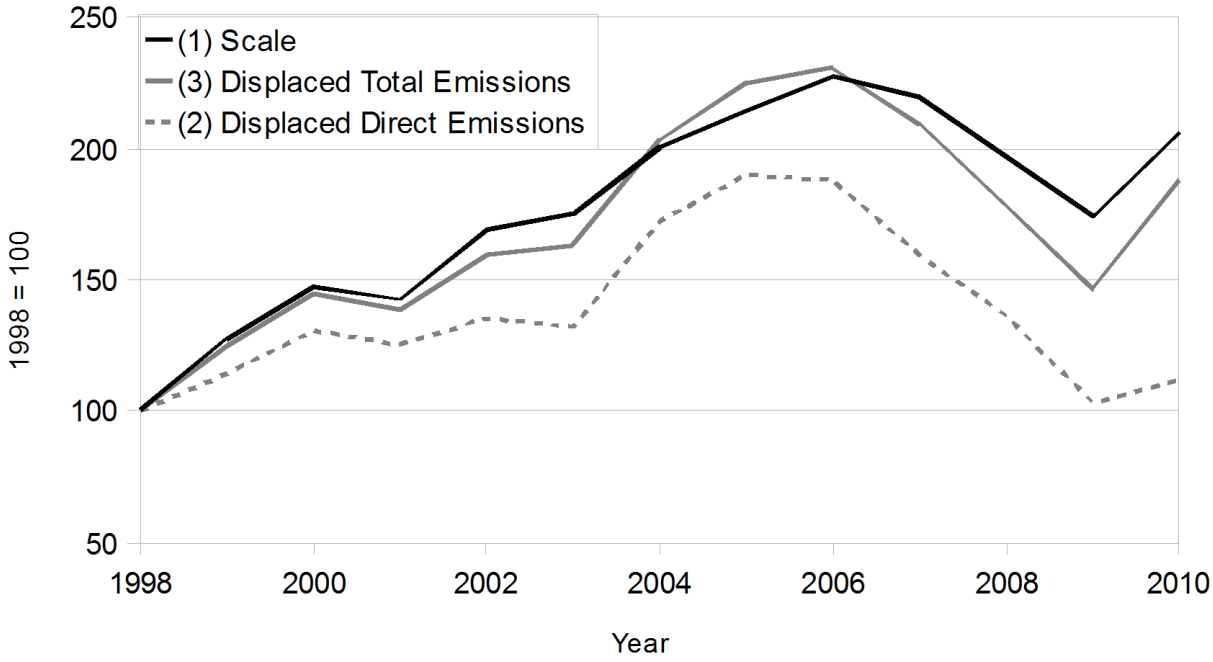


Figure 3.8: "Displaced" CO_2 Emissions by U.S. Net Imports

Note: CO_2 emissions are shown in relative terms, with CO_2 emissions displaced by the U.S. net imports in 1998 equal to 100. The decomposition follows equation (3.11): scale, line (2) relative to 100; composition, line (3) - line (2); technique, line (1) - line (3).

Data Source: Author's calculation.

Table 3.1: Index Decomposition of US Industrial CO2 Emissions: 1998 - 2002

Decomposition	Laspeyres (a)	Paasche (b)	Fisher (c)	LMDI I (d)	AMDI (e)	Gen. Fisher (f)	Shapley/Sun (g)
Multiplicative							
Scale	.9925	.9926	.9926	.9926	.9926	.9926	
Composition	.9914	.9789	.9851	.9843	.9840	.9851	
Technology	.9754	.9631	.9692	.9701	.9710	.9692	
Residue	.9875	1.0127	1	1	.9993	1	
Additive							
Scale	-.0075	-.0071		-.0072	-.0073		-.0073
Composition	-.0086	-.0204		-.0155	-.0158		-.0145
Technology	-.0246	-.0363		-.0296	-.0294		-.0305
Residue	-.0116	.0115		0	.0002		0

Note: Industrial CO2 emissions fell by 5.23% from 1998 to 2002.The components of a multiplicative decomposition multiply to .9477. The components of an additive decomposition add up to -.0523.

Table 3.2: Index Decomposition of US Industrial CO2 Emissions: 2002 - 2006

Decomposition	Laspeyres (a)	Paasche (b)	Fisher (c)	LMDI I (d)	AMDI (e)	Gen. Fisher (f)	Shapley/Sun (g)
Multiplicative							
Scale	1.0721	1.0721	1.0721	1.0697	1.0721	1.0721	
Composition	.9899	.9825	.9862	.9859	.9860	.9862	
Technology	.9302	.9233	.9267	.9274	.9272	.9267	
Residue	.9925	1.0076	1	1	.9997	1	
Additive							
Scale	.0721	.0659		.0685	.0689		.0690
Composition	-.0101	-.0174		-.0141	-.0139		-.0137
Technology	-.0698	-.0814		-.0746	-.0745		-.0755
Residue	-.0124	.0129		0	-.0006		0

Note: Industrial CO2 emissions fell by 2.02% from 2002 to 2006. The components of a multiplicative decomposition multiply to .9798. The components of an additive decomposition add up to -.0202.

Table 3.3: Index Decomposition of US Industrial CO2 Emissions: 1998 - 2006

Decomposition	Laspeyres (a)	Paasche (b)	Fisher (c)	LMDI I (d)	AMDI (e)	Gen. Fisher (f)	Shapley/Sun (g)
Multiplicative							
Scale	1.0641	1.0641	1.0641	1.0635	1.0641	1.0641	
Composition	.9886	.9611	.9747	.9717	.9719	.9747	
Technology	.9080	.8828	.8953	.8986	.8986	.8953	
Residue	.9722	1.0286	1	1	.9992	1	
Additive							
Scale	.0641	.0559		.0594	.0599		.0603
Composition	-.0114	-.0376		-.0277	-.0281		-.0242
Technology	-.0920	-.1233		-.1031	-.1043		-.1074
Residue	-.0321	.0336		0	.0011		0

Note: Industrial CO2 emissions fell by 7.14% from 1998 to 2006. The components of a multiplicative decomposition multiply to .9286. The components of an additive decomposition add up to -.0714.

Table 3.4: Index Decomposition of US Industrial CO2 Emissions from Energy Use: 1998 - 2007

Decomposition	Laspeyres (a)	Paasche (b)	Fisher (c)	LMDI I (d)	AMDI (e)	Gen. Fisher (f)	Shapley/Sun (g)
Multiplicative							
Scale	.9317	.9317	.9317	.9318	.9317	.9317	
Composition	1.0028	1.0031	1.0029	1.0028	1.0028	1.0029	
Technology	.9885	.9888	.9887	.9887	.9887	.9887	
Residue	1.0003	.9997	1	1	1.0001	1	
Additive							
Scale	-.0683	-.0677		-.0679	-.0681		-.0680
Composition	.0028	.0028		.0027	.0024		.0028
Technology	-.0115	-.0105		-.0110	-.0110		-.0110
Residue	.0008	-.0008		0	.0004		0

Note: Industrial CO2 emissions from energy use fell by 7.62% from 1998 to 2007. The components of a multiplicative decomposition multiply to .9238. The components of an additive decomposition add up to -.0762.