Unilateral Carbon Taxes, Border Tax Adjustments and Carbon Leakage

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We examine the impact of a unilateral carbon tax in developed countries, focusing on the expected size of carbon leakage (an increase in emissions in non-taxing regions as a result of the tax) and the effects on leakage of border tax adjustments. We start by analyzing the problem using a simple two-country, three-good general equilibrium model to develop intuitions. We then simulate the expected size of the effects using a new, open-source, computable general equilibrium (CGE) model. We analyze the extent of emissions reductions from a carbon tax in countries that made commitments under the Kyoto Protocol (Annex B countries), the expected carbon leakage, and the effects of border tax adjustments on carbon leakage, all relative to our baseline projections for emissions. We also perform extensive sensitivity tests on the parameters of the CGE model. Finally, we consider the effects of imperfect border tax adjustments on leakage, such as global or regional schedules of border taxes.

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INTRODUCTION

The Framework Convention on Climate Change (UNFCCC) of 1992 envisions a process whereby developed nations commit to reducing their emission of greenhouse gases (GHG) before developing nations take similar steps.[1] Following this vision, the Kyoto Protocol currently only binds thirty-seven nations to targets on their emissions.[2] No fast-growing developing nation faces emission limitations. While recent negotiations in Durban may have softened this strong differentiation, it still appears that developed nations will be asked to reduce emissions prior to developing nations undertaking similar commitments.[3]

While there are a number of important motivations for this approach, there are two central concerns. The first is whether carbon controls that exempt developing nations can sufficiently reduce global emissions. The developing world is expected to be a major source of emissions in the future. Even if the developed world were to cut its emissions drastically, atmospheric carbon dioxide would not be stabilized by this action alone.

The second concern is that if only developed nations impose carbon controls, emissions in the developing world might go up, offsetting reductions, in a phenomenon known as carbon leakage. Carbon leakage is thought to arise for two reasons. First, if only a subset of nations impose controls on emissions of carbon dioxide, energy-intensive production may flee to regions without controls. Second, if nations with carbon controls use fewer fossil fuels, the price of fossil fuels may go down, resulting in more use in other regions. Carbon leakage has the potential to defeat the purpose of having carbon controls, inefficiently shift the location of production and energy use, and create domestic political challenges.

Carbon leakage has been a central worry in negotiations regarding an international climate change treaty and in the design of existing emissions control systems. For example, the United States has maintained that the possibility of carbon leakage makes it undesirable and possibly futile for

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1   United Nations Framework Convention on Climate Change, May 9, 1992, S. Treaty Doc. No. 102-38, 1771 U.N.T.S. 107, *available at* http://unfccc.int/resource/docs/convkp/conveng.pdf.

2   Kyoto Protocol to the United Nations Framework Convention on Climate Change, Dec. 11, 1997, 2303 U.N.T.S. 162, *available at* http://unfccc.int/resource/docs/convkp/kpeng.pdf.

3   For a discussion of the recent negotiations, see Lavanya Rajamani, *Differentiation in the Emerging Climate Regime*, 14 Theoretical Inquiries L. 151 (2013).

it to impose carbon controls while major developing countries do not.[4] The major developing countries, however, insist that the United States (and other developed countries) must act first to reduce emissions, in accordance with their agreement under the UNFCCC. The result has been an impasse. The European Union on the other hand has imposed a unilateral carbon price, but constructed the system to prevent leakage by providing subsidies to trade-exposed industry.[5] The result is a less efficient pricing system.

We analyze the effects of a tax on carbon dioxide emissions (a carbon tax) as a method of controlling emissions. We focus on the effects of such a tax if it is imposed only in the developed world and the resulting carbon leakage. Our focus is on the legal and institutional design choices that affect carbon leakage, with the goal of understanding how to design an administrable and legal regional carbon tax that most effectively reduces carbon emissions. For example, we consider whether the location of the collection of the tax in the production cycle (i.e., upstream or downstream) can affect leakage, how much border tax adjustments change leakage, and whether administrative or legal restrictions on the types of border tax adjustments that can be used will change these conclusions.

Our analysis relies on two different, although related, tools. We use an analytic general equilibrium model of trade to develop an understanding of the problem and the likely effects. We then use a new, computable general equilibrium model of the global economy, CIM-EARTH, to assess the likely size of the effects and their sensitivity to assumptions.[6]

Our emphasis is on understanding the structure of the problem and the sensitivity of the effects to modeling assumptions and parameters. Simulations of the sort produced here will always have substantial uncertainties. For those who want bottom-line results, however, we can report the following, with

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4   *See* Byrd-Hagel Resolution, S. Res. 98, 105th Cong. (1997) (enacted) ("[T]he Senate strongly believes that the proposals under negotiation, because of the disparity of treatment between Annex I Parties and Developing Countries and the level of required emission reductions, could result in serious harm to the United States economy").

5   For discussions of the design of the E.U. system, see PRICING CARBON: THE EUROPEAN UNION EMISSIONS TRADING SCHEME (A. Denny Ellerman, Frank J. Converty & Christian De. Perthuis eds., 2010); David A. Weisbach, *Carbon Taxation in the EU: Expanding the EU Carbon Price*, 24 ENVTL. L. REV. 183 (2012).

6   There is a substantial prior literature analyzing carbon leakage, most of it using CGE models. Other literature analyzes special cases using analytic general (or sometimes partial) equilibrium models. Part II contains an extensive attempt at replicating the results of prior CGE models; the relevant work is cited there.

appropriate caveats. In our simulations, a carbon tax in the Kyoto Protocol Annex B nations (which roughly make up the developed world) will produce only about one-third of the reductions achieved by a global tax. Leakage, however, is only a modest part of the story. Our central measures for leakage under a carbon tax in Annex B, defined as the increase in emissions in the non-taxing region as a fraction of emissions reductions in the taxing region, are in the range of fifteen to twenty-five percent. Most of the reduced emissions in switching from an Annex B tax to a global tax arise because a global tax will help control the increase in non-Annex B countries, which is expected to occur even without leakage.

We also simulate the effects of border tax adjustments, taxes on the emissions from the production of an imported good, and rebates of domestic carbon taxes on the export of goods. Border tax adjustments are thought to reduce leakage because they reduce the incentive to shift production abroad. In our simulations, border tax adjustments reduce leakage substantially. They result in an increase in emissions in the taxing region and a reduction in the non-taxing region, relative to a production tax. This finding is consistent with our understanding of the reasons why leakage occurs, which we discuss below.

Finally, we simulate the effects of an imperfect border tax system. Border tax adjustments are complex to administer because they require the importing country to determine the emissions from the production of a good produced abroad. Knowledge of the particular and constantly changing production processes and energy sources in other countries may not be available. Moreover, there may be legal concerns with some types of border taxes because of the relevant World Trade Organization (WTO) rules. Therefore, we consider presumptive border tax adjustments under which there are schedules of the appropriate border tax adjustments for different types of goods. We compare presumptive schedules of this sort to perfect border tax adjustments. In our simulations, presumptive schedules are not as effective as perfect border taxes. The imperfect systems we simulate result in roughly double the leakage arising from perfect border taxes, although the size of the differences varies based on the type of system and the tax rate. We do not attempt to measure the savings in administrative costs; presumptive schedules may be superior, all things considered.

Before turning to the analysis, it is worth a brief detour to discuss our methodology. Large computational models, particularly computable general equilibrium models such as the one used here, are not commonly found in the legal literature. Even the most advanced computational models are thought to be too crude to capture legal reasoning, which is a mixture of analogical reasoning, the close reading of statutes, knowledge of history,

and an understanding of how legal rules fit within a given social, legal, and institutional structure.

We view computation as an extension of traditional law and economics analysis, which seeks to understand the effects of legal rules through the use of economic methodology. It is a forward-looking, pragmatic quest for solutions to legal problems. In this sense, computation can serve as a potential tool for law and economics to gain insights into the likely effects of legal rules and the design of institutions. In the present case, for example, analytic models and econometric techniques, both widely used in law and economics, are unlikely to be able to give a sense of the magnitude of carbon leakage, to analyze the size of the effects of border tax adjustments, or to compare perfect border taxes with imperfect border taxes. We can study all of these issues with a computational model. For example, by comparing perfect and imperfect border taxes, we are able to consider the effect of a possible WTO ruling on the issue in ways that cannot easily be accomplished through more traditional methods.

Use of large scale computation to study economic problems often raises concerns about whether the models are sufficiently transparent and whether the results are dependent on model structure rather than being general. We address these criticisms in four ways. First, we use an analytic model to generate economic intuitions and hypotheses, much like studies that rely solely on analytic models. We think of the analytic model as a "model of the model." If the results produced by the computational model are not consistent with the predictions of the analytic model, we can then go back to try to understand the underlying economic forces. Combining analytic and computational models allows us to gain insights into the problem that might be less accessible if we considered only numerical simulations. Computation becomes an addition to rather than a substitute for conventional legal and economic reasoning. It becomes a way of estimating the likely magnitude of the effects that we expect to see from the analytic model and a way of testing the robustness of the analytic model to more complex specifications.[7]

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7   Kenneth Judd discusses the complementarity between computational and analytic models as follows: Analytic models must make strong simplifying assumptions, but are able to establish proofs of results within their limited domain. Computational models are able to sample from a much larger space, but can only show results from the particular points that are sampled. The two together help get a fuller understanding of an issue than either could alone. Kenneth L. Judd, *Computationally Intensive Analyses in Economics*, *in* 2 HANDBOOK OF COMPUTATIONAL ECONOMICS 881 (Leigh Tesfatsion & Kenneth L. Judd eds., 2006); Leigh Tesfatsion & Kenneth L. Judd, *Preface to* 2 HANDBOOK OF COMPUTATIONAL ECONOMICS, *supra*, at xi.

Second, we make our code open source, downloadable from our website.[8] All of our code and model assumptions can be examined by anyone.[9] We encourage replication of our results and testing them for robustness to alternative specifications. Third, we test the robustness of the model results to our parameter choices. We consider how the results change when central parameters change, both alone and in combination. We present some of these results here and document additional tests on our website. Finally, we attempt to replicate prior studies of the problem within our model. While we cannot replicate the precise model structures used in prior studies, we can use their parameter choices in our model. Doing so helps show whether differences in model results are due to different parameter choices, model structures, or other unspecified factors.

The result, we hope, shows the potential for using computation to address legal problems. While computation is not suited to all legal problems, in many cases it can be valuable in understanding the expected effects of a legal rule as an addition to the usual ways of gaining understanding.

This Article comes in two parts. Part I discusses the analytic model. We present the basic assumptions of the model and then describe the intuitions behind the solution. The mathematical statement of the model and derivation of the solution is available on our website. We also provide a numerical simulation of the results using parameters derived from the data we use in our CGE model. The simulation allows us to show the solutions graphically and to see the sensitivity of the results to the central parameters. Part II focuses on CIM-EARTH. The documentation for CIM-EARTH is provided on our website and we do not cover the details here. After giving a brief background on the model structure, we describe several elements of CIM-EARTH that are central to this study: the treatment of trade, our data sources, and our parameter estimates. We then present our results from CIM-EARTH, show their sensitivity to central parameter choices, and attempt to replicate the results from prior studies of carbon leakage.

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8   Ctr. for Robust Decision Making on Climate & Energy Pol'y (RDCEP), www. rdcep.org (last visited July 6, 2012).

9   Our model is currently implemented in the AMPL programming language, which requires a license. In addition, we use Global Trade Analysis Project (GTAP) data, which must be purchased (at modest cost). Therefore, unfortunately, actually running our code is not free, although anyone may obtain the necessary licenses. While we plan to switch to an open-source software system, GTAP data is by far the most comprehensive data, and there does not appear to be a viable alternative. Nevertheless, the underlying code and all of its assumptions can be freely examined.

I. ANALYTIC MODEL OF CARBON TAXATION

As noted, the standard view is that there are two causes of leakage.[10] First, when only one part of the world taxes emissions, energy-intensive production shifts from the taxing region to the non-taxing region in an attempt to avoid the tax. Second, because the tax reduces energy use in the taxing regions, overall energy prices may fall, creating an incentive for greater energy use (and emissions) in the non-taxing region. In this Part, we use a simple model to consider how these effects arise under different types of taxes.

A. Model Structure and Assumptions

Consider a world with only two regions or countries: Home, which imposes a tax on emissions, and Foreign, which does not. Each country has a pool of labor, L and L*, and fossil fuel deposits, E and E* (where variables with asterisks denote Foreign). Assume that these factors cannot be traded: there is no migration and fossil fuel deposits are in the ground.[11] Some goods, such as services, can be produced solely with labor. We call these goods collectively the labor-good or *l*-good. The production of other goods, which we call the energy-intensive-good or *ei*-good, needs energy. To create energy, the deposits have to be extracted.[12] The resulting energy, such as coal or gas, is then used in production, in combination with labor, to produce the *ei*-good. Emissions are created when the energy is used, and we assume that emissions are proportional to energy use. We do not model damages from emissions.

Our goal is to understand how trade affects emissions. (If there were no trade at all, Foreign activity would not be affected by a Home carbon tax.) To this end, assume that all goods — energy, the *l*-good and the *ei*-good — are traded costlessly. This means that there is a single global price of energy, a single global price of the *l*-good, and a single global wage rate.[13] To differentiate foreign and domestic production, we assume that Home and Foreign varieties of the *ei*-good are different and that consumers buy more of their local variety;

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10   *See, e.g.*, Niven Winchester, Sergey Paltsev & John M. Reilly, *Will Border Carbon Adjustments Work?*, 11 B.E. J. ECON. ANALYSIS & POL'Y, art. 7 (2011).

11   This means that we assume deposits cannot be purchased, *see* Bård Harstad, *Buy Coal? Deposit Markets and Environmental Policy*, J. POL. ECON. (forthcoming 2012) (considering the effects of a market for deposits).

12   Extraction, in our model, has increasing marginal costs. Marginal costs will increase if, for example, the deposits with the lowest extraction cost are used first, then more expensive deposits, and so forth.

13   We consider only equilibria in which each country produces some of the *l*-good, a condition that is easily checked given the parameters of the model.

there is a home bias. (The *l*-good and energy, however, are homogenous.[14]) Therefore, there is an *ei*-good and an *ei**-good each of which can be traded.

   We will consider three tax systems in Home, as well as a global tax. The first, which we call a production tax, is imposed on Home use of energy in production. The second, which we call a BTA tax, is a production tax with border tax adjustments. The border tax adjustments are (1) a tax on embedded carbon in imports of the *ei**-good; and (2) a rebate of production taxes previously paid on the *ei*-good when it is exported.[15] Together, these two aspects of border tax adjustments mean that there is a tax on home consumption of *ei*-type goods and no tax on foreign consumption of *ei*-type goods. We can, therefore, think of a BTA tax as a tax on the carbon content of consumption in Home (as compared to a tax on production in Home under a production tax). The final tax is a tax on home extraction of fossil fuels.[16] We can think of the extraction tax as an upstream tax, the production tax as a mid-stream tax, and the BTA tax as a fully downstream tax. Figure 1 presents a picture of the model structure. (The core model equations are presented in the Appendix.)

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14   To keep the model simple, we use Cobb-Douglas production functions and utility functions. These take the form $Q = X^{\gamma} Y^{(1-\gamma)}$, where γ is the share spent on X in production or consumption (depending on what the function is representing) and $(1-\gamma)$ is the share of Y. Because we use Cobb-Douglas functions, the relative spending shares of goods, both in production and consumption, are fixed. This limits the analysis somewhat. Note that the model we used in an earlier version of this Article is a special case of the current model, *see* Joshua Elliott, Ian Foster, Sam Kortum, Todd Munson, Fernando Cervantes Perez & David Weisbach, *Trade and Carbon Taxes*, 100 Am. Econ. Rev. 465 (2010). The key differences are that in our prior work, there was no home bias in consumption and there was no separate production process to convert energy into a consumption good. Setting the relevant parameters correctly converts the model used here into that model.

15   The rebate in our model is based on the aggregate energy use in production of the *ei*-good. If there were individual firms, they would take this rebate (per unit produced) as given. This approach avoids the problem of firms using dirty technology for export and clean technology for domestic use.

16   We need not separately consider an extraction tax with border adjustments, as this is equivalent to a production tax.

Figure 1: Structure of the Analytic Model
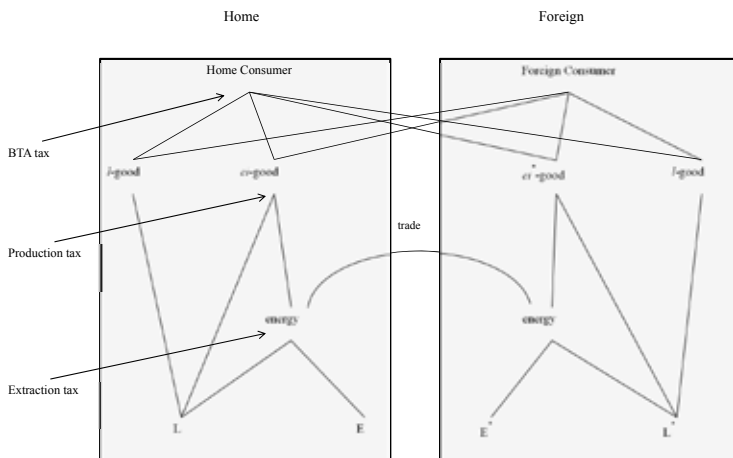
B. No-Tax Case

If there are no taxes, the analysis is straightforward. The countries produce energy in proportion to their relative endowments; the country with the greater endowment will extract more, up to the point at which marginal extraction costs are equated across countries. This efficiency condition arises because extraction has increasing marginal costs, energy is traded so there is a single global price, and labor costs are the same in both countries. The location of energy use, however, is not related to extraction. Instead, because energy is traded, its use depends on the relative demand for each country's variety of the *ei*-good. The country facing higher demand for its energy-intensive products will use more energy. The direction of net trade in energy can go either way, as the country with greater deposits could have even greater relative energy demand.

C. Production Tax

A production tax in Home creates a wedge between the world energy price and the cost of energy as an input to produce the *ei*-good. To some extent, the tax can be absorbed by using less energy in the production of the *ei*-good. But after this, the price of the *ei*-good has to go up. As a result, consumers in both countries will substitute away from the Home variety of the *ei*-good. Overall, emissions in Home (which come from the production of the *ei*-good) fall both because of less energy use in production and because of fewer global purchases of the Home variety of the *ei*-good.

The effects in Foreign are essentially the reverse of the effects in Home. Less energy is used in Home due to the tax, which means that the price of energy falls. The use of energy in the production of the ei^*-good, therefore, is cheaper. To some extent, production of the ei^*-good will be more energy-intensive and to some extent the price of the ei^*-good will fall. As a result, consumers around the world demand more of the ei^*-good, resulting in greater production and emissions in the foreign country. There is a production-location effect and an energy-price effect, corresponding to the two types of leakage noted in the literature.

A key parameter in determining the extent of leakage is the amount by which the supply of energy falls due to the decline in the price of energy resulting from the tax: the price elasticity of energy supply.[17] If the supply is completely insensitive to price, total energy production remains the same even with a carbon tax. We get one hundred percent leakage. This might be a world where the marginal source of energy is Saudi Arabia (i.e., with oil that can be extracted at a low cost) and Saudi Arabia simply pumps out the same amount of oil regardless of the price.[18] A carbon tax has no effect on emissions; it just reduces the rents received by energy producers. At the other extreme, if the quantity of energy produced is highly sensitive to the price, leakage will be low. We might think of this world as one where the marginal source of energy is Canadian tar sands (i.e., the energy is difficult and expensive to produce, so small decreases in the price of energy can lead to large reductions in production). Leakage can approach zero because the tax reduces energy supply with little reduction in the energy price.

D. BTA Tax

Consider how the results change if we add border tax adjustments. We can think of a production tax with border tax adjustments as falling on Home consumption of ei-type goods (i.e., both the ei-good and the ei^*-good). As a result, Home consumption of ei-type goods of both varieties goes down. The reduction in demand in Home means that overall less energy is used to satisfy Home demand, resulting in a lower price of energy. The price of both ei-type goods goes down in Foreign, which raises demand for them there. Finally,

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17   This approach is consistent with other analytic models of leakage, *see* Hans-Werner Sinn, *Public Policies Against Global Warming: A Supply Side Approach*, 15 Int'l Tax & Pub. Fin. 360 (2008); Harstad, *supra* note 11.

18   It is not easy to characterize Saudi Arabia's strategy and we just use it as a placeholder example, without making specific claims about its actual production choices.

production of the *ei*-good becomes less energy-intensive, while production of the *ei**-good becomes more energy-intensive.

The net effects are driven to a large extent by the degree of home bias. Consumers in Home prefer their variety of the *ei*-good, so when they decrease their demand for all *ei*-type goods, the effect falls more heavily on Home production. Similarly, Foreign consumers prefer their variety of the good, so when they increase their demand, more of the additional production takes place in Foreign. The result is emissions reductions in Home, and emissions increases in Foreign. Globally, there is a net reduction in emissions, but there is still leakage under the BTA tax.[19]

The source of leakage in the production tax case and the border tax case is different. In the production tax case, leakage arises because of the increased global demand for the *ei**-good and because of the increased energy-intensity in Foreign production to meet that demand. In the BTA tax case, leakage arises from increased Foreign demand for both varieties of the *ei*-good and the fact that much of that demand will be met by Foreign production (and because production there becomes more energy-intensive).

The effect of the elasticity of energy supply is similar in both the production tax and BTA tax cases, however: Low elasticity increases leakage. The reason is that in both cases, low elasticity of energy supply means that supply does not go down much in response to the tax; instead the tax is absorbed into the pre-tax world energy price. The lower world energy price (and relatively fixed supply of energy) results in increased production of *ei*-type goods in Foreign.

E. Extraction Tax

The final unilateral tax we consider is an extraction tax in Home. The extraction tax lowers the after-tax price received by Home energy producers. The resulting decrease in Home energy supply raises the global price of energy, creating an incentive for more extraction abroad. Because of the unified global price of energy, *ei*-type production in the two countries faces the same change: an overall higher price of energy. Production will become more labor-intensive and global demand for *ei*-type goods of both varieties will go down. The location of the production declines could be in either country.

To illustrate the effects, imagine that all of the energy deposits were in Home. Then all energy producers will bear the extraction tax, resulting in

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19   We know there is a global reduction in emissions because the tax directly hits
      Home consumption, while foreign consumption goes up only through the
      indirect effect of the tax on energy prices, which is tempered by shifts in the
      energy-intensity of production.

reduced supply and a decline in its use in production of *ei*-type goods. The decline will be in both countries, with the share of the decline depending on the relative global demand for each variety of the *ei*-good. If there are energy deposits in Foreign as well, then an increase in extraction there offsets the reduction in extraction in Home, but does not affect where the *ei*-type good production declines occur. If all deposits are in Foreign, of course the extraction tax has no effect. The effectiveness of an extraction tax depends on having a substantial portion of fuel deposits being covered.

In a strict sense, an extraction tax generates no leakage, in that foreign energy use does not go up. It will, in fact, go down because of the global increase in energy costs. Nevertheless, we can think of there being leakage in the sense that foreign activity — here extraction of additional deposits — partially offsets the effects of the tax in Home. Leakage in this sense goes up with the supply elasticity, which is in contrast to the effects of the supply elasticity on leakage (in the production sense) under production and BTA taxes.

We can, therefore, think of an extraction tax as an alternative and quite different type of tax than a production or BTA tax. It works by raising the price of energy, which is a global phenomenon if energy is traded. In contrast, a production tax raises the price of energy use in a particular location and a production tax with border tax adjustments raises the price of consumption in a particular location. If leakage is a serious concern, an extraction tax might be attractive. The downside is that an extraction tax is only effective if a substantial portion of global deposits are covered or if the supply in non-taxed regions is inelastic.[20]

F. Global Tax

The most desirable policy would be one that harmonizes carbon policy around the world. If both countries impose a tax (of the same kind and at the same rate), the distinctions between the different types of taxes largely disappears. Production and extraction taxes create the same wedge between the cost of energy as an input and the price received by those who extract energy. There is, as a result, a shift toward more labor-intensive production of *ei*-type goods and an increase in the price of those goods. Similarly, a BTA tax and a

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20 Many deposits are located outside of Annex B countries, possibly making an extraction tax less effective than other taxes, at least if non-Annex B countries are not to be subject to emissions restrictions and supply is price-elastic. Harstad, *supra* note 11, suggests that the taxing countries can make the supply in non-taxing countries price-inelastic by purchasing marginal reserves held by non-taxing countries.

production tax have the same effects on prices, production, and consumption.

The key difference between the three types of taxes under a global tax system is the allocation of the tax revenue. Under an extraction tax, the country where the extraction takes place gets the revenue; under a production tax, the country where production takes place gets the revenue; and under the BTA tax, the country where consumption takes place gets the revenue. As a result, the choice of taxes may have distributional effects. Note that these effects can be offset through transfer payments between the countries.

G. Simulations

To get a sense of the predictions of our analytic model, we parameterized it to roughly coincide with the data we use for our CGE model. We then ran simulations to test the sensitivity of results to changes in the central variables. Figure 2 shows effects of the three taxes we study on emissions. The global tax reduces global emissions around twice as much as a production tax (i.e., a tax only on Home). This result can be seen by comparing the top and bottom lines. We can get a visual sense of leakage by comparing Home reductions under a production tax and global reductions under the same tax. The higher global emissions (smaller reductions) are due to the increase in Foreign emissions because of the tax, which is leakage. Finally, if we add border taxes, global emissions go down relative to a production tax; leakage appears to be smaller.

Figure 2: Effects of Various Taxes on Emissions in Analytic Model
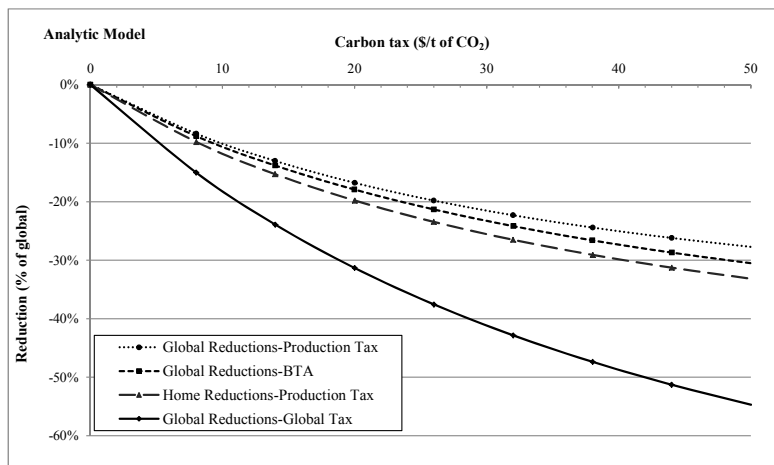

Figure 3 focuses on the effects of border taxes. Like Figure 2, it shows the global emissions reductions under a Home production tax, Home reductions

under that tax, and global reductions under a border tax system. It adds a line showing Home reductions when there are border taxes. Home emissions go up when we add a border tax (comparing the bottom two lines). If climate treaties are based on emissions targets for different regions, border taxes will actually make the target more difficult to reach in Home.

Border taxes reduce leakage in this model. We define the leakage rate as the increase in global emissions relative to reduction in emissions in the taxing region under a given tax.[21] With border taxes, it is based on the difference between the middle two lines in Figure 3. Relative to a production tax, border taxes increase Home emissions and reduce global emissions, and both effects contribute to a reduction in the leakage rate.

Figure 3: Emissions Under Production and BTA Taxes
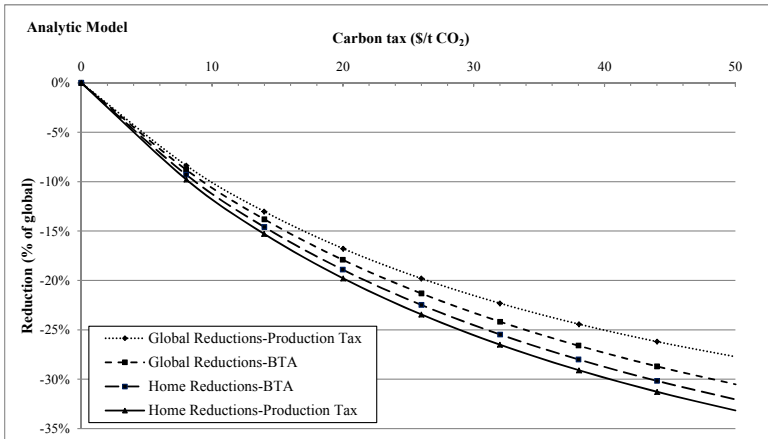
Figure 4 shows the effect of the elasticity of energy supply on leakage for the production and BTA taxes with a tax rate of about twenty-nine dollar/ton of CO_2. The upper line is the production tax; the lower line is the BTA tax. As we can see, leakage is lower under the BTA tax. Both taxes, however, respond similarly to the supply elasticity, and as the elasticity approaches zero, leakage becomes high in both cases. As the elasticity goes up, leakage goes down, and in fact becomes slightly negative with border taxes.[22]

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21 Formally, if a region x imposes a tax, leakage is ($\Delta emisisons_{World}$ -$\Delta emissions_x$)/ $\Delta emissions_x$. This means that leakage under a global tax is defined to be zero (because the numerator is always zero). This does not mean, however, that there are no changes in the location of production or consumption under a global tax, which may be of interest to policymakers.

22 Negative leakage appears to arise because Home is the dominant consumer of

Figure 4: Leakage as a Function of Energy Supply Elasticity
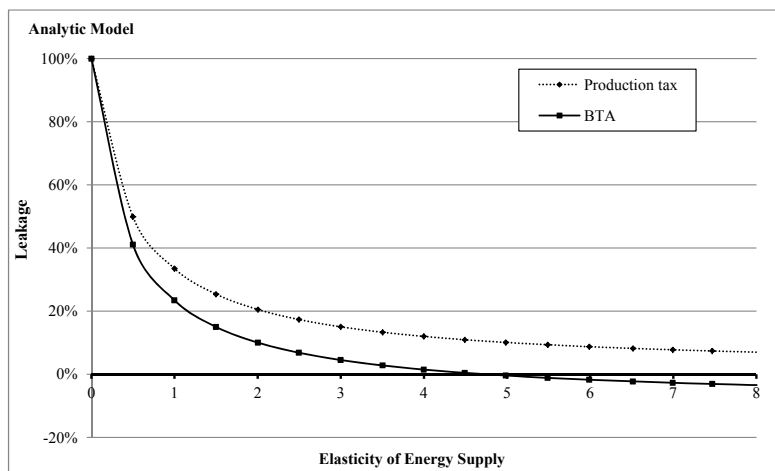
We can examine changes in production and consumption in more detail through what we call carbon matrices. We present these results in Table 1, which shows changes from the no-tax case for an eleven dollar/ton tax on CO_2. The rows represent production. For example, the top row is Home energy use in production. The columns represent consumption. The first column in the first row is the energy use for Home production of goods consumed domestically. The second column in the first row is the energy use for goods produced in Home and exported to (and consumed in) Foreign. The last column is total production in each country. The bottom row is total consumption in each region.

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the ei^*-good, and its demand goes down. If the elasticity of energy supply is large enough, this effect dominates the energy price decline (which stimulates Foreign production). A recent paper shows that leakage can be negative if (1) the output of the untaxed sector or region is not a perfect substitute for the output of the taxed sector or region, (2) the taxed sector or region can reduce carbon per unit of output, and (3) capital or labor are mobile between sectors or regions. *See* Don Fullerton, Daniel Karney & Kathy Baylis, *Negative Leakage* (Working Paper, 2011), *available at* http://works.bepress.com/don_fullerton/61. Under those conditions, they show that the sector or region facing the carbon tax might reduce carbon per unit of output by using resources drawn away from the other sector or region, shrinking that other sector's output and emissions. That mechanism is not operational here, however, because we have assumed that the tax on carbon applies to all Home sectors, while neither labor nor capital are mobile internationally. If our model were to satisfy those three conditions, then leakage might be lower.

We can see in the case of the production tax that Home energy use in production goes down more than Home consumption, while Foreign energy use in production goes up, illustrating carbon leakage. Foreign consumption actually goes down because of the substantial decrease in imports of the *ei*-good. If we add border tax adjustments, there is a large drop in Foreign production (relative to the production tax case) for export to Home. Total Foreign production goes up less.

Table 1: Carbon Matrices in Analytic Model

	Production tax				BTA tax		
	Home	**Foreign**	**Prod.**		**Home**	**Foreign**	**Prod.**
Home	-42.9%	-44.2%	-43.1%	**Home**	-42.9%	-36.0%	-41.4%
Foreign	10.3%	7.9%	9.2%	**Foreign**	-2.1%	8.7%	2.9%
Cons.	-26.0%	-8.7%	-21.0%	**Cons.**	-29.6%	-5.6%	-22.6%

One surprising result from the analytic model is the comparison of the global welfare effects of the production and BTA taxes. We can compare these effects by setting the tax rate so that emissions are the same under the two policies. If emissions are the same, we can ignore the damages from emissions (as they will be the same under either policy) and simply consider welfare from consumption.

With emissions the same under a production tax system and a BTA tax and consider each country's income. There are only two sources of income: labor and returns from exploiting energy deposits. The total labor is fixed and its wage is always 1 in the model, so to measure income, we need only consider the returns from exploiting energy deposits. If emissions are the same under the two tax systems, the total deposits extracted must be the same. If the same deposits are extracted in the two scenarios, the price of energy is also the same. That is, if we set the tax rates so that emissions are the same under a production tax and a BTA tax, the returns from exploiting deposits will be the same. Overall income is unchanged (except for the tax revenues received by Home).

Foreign's income is the same under the production tax and the BTA tax. Climate damages are the same. This means that we can analyze its welfare solely by reference to how much individuals there can consume. With the production tax, foreign consumption of the Home-variety of the *ei*-good includes the tax, whereas under the BTA tax, it does not. Consumers in Foreign can consume more under the BTA tax. Therefore, they are *better* off with border taxes.

Analysis of Home is more complex. If we leave aside tax revenue, it is clear that Home is worse off with border taxes for the same reasons that Foreign is better off. Tax revenue, however, means that Home's income may not be the same in the two cases. If tax revenues are lower when there are border taxes, then Home is worse off. If tax revenues are higher, we have to weigh the additional income against the higher cost of goods, so whether Home is better or worse off will depend on the parameters.

These results regarding welfare are contrary to standard intuitions, which hold that the taxing regions will want to impose border taxes and the non-taxing regions will oppose them. U.S. climate change legislation regularly includes measures to protect domestic industries, while developing countries strenuously object to these measures. The simple model is not capturing something going on in the world that motivates political preferences over these policies.

We have three hypotheses about what these motivations are. The first is that views about border taxes are informed by flawed mercantilist thinking, and that if analysts focused on consumer welfare they would agree with the results of our model. Second, our model abstracts from considerations of good or bad jobs or unemployment. The wage is always 1 regardless of where individuals work. There are also no producer profits. If for some reason wages vary across industries (in ways not related to worker productivity), there could be reasons for preferring one system or the other. Finally, our model does not have adjustment costs. It might be the case that in the long run the results of our model would obtain, but it is not easy to take a steelworker and turn him into a nurse. To the extent there are efficiency wages (or similar effects) or transition costs, these effects should temper our result, but we would still eventually expect the effects we see in the model to occur in the real world.

II. CGE Modeling of Leakage

Given the understanding of the issue from the analytic model, we can test the results in our CGE model and also assess the likely size of the effects. We present the results from this effort here beginning with background on the model.

A. CIM-EARTH Structure

The detailed structure of CIM-EARTH is described in its documentation, and we refer interested readers there.[23] We describe here the basic structure

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23   RDCEP, *supra* note 8; Joshua Elliott, Ian Foster, Kenneth Judd, Elisabeth Moyer

of the model, how trade is treated, and our data sources. While the model is detailed and complex, in many ways it remains greatly simplified. Some, and perhaps many, of the simplifications can be justified as removing unnecessary complexity, but because some may affect the results, it is important to be aware of the major simplifications we make. We highlight them here.

As in all CGE models, individuals own labor and capital, which they provide to industry in exchange for wages and rents. They use this income to purchase goods and to save so as to maximize their utility. In the current version of the model, labor supply is fixed — consumers do not respond to carbon taxes by working less. In addition, individuals are not forward looking, in that they do not anticipate the future; they save because it brings them utility.

Industry hires labor, rents capital, and buys intermediate inputs, which it combines to create goods. The industry structure is designed to mimic how goods actually flow in the economy. For example, the energy sector uses labor, energy, capital, and deposits to extract energy, which is then sold to industries (including the energy industry itself) and households. That is, industry output can be intermediate goods used by other industries or final goods used by consumers. The intermediate goods are used by industries to similarly produce a mix of final and intermediate goods. Eventually, all output is in the form of final goods consumed by individuals or accumulated into stocks of capital.

Industry production functions use a common flexible functional form, which allows us to set input shares based on data and allows industries to substitute across inputs based on specified elasticities of substitution. Industries choose the mix of inputs and outputs to maximize profit. The solution to the model involves a set of prices and outputs, which makes markets clear in each time period.

The version of the model used for this study has sixteen regions and sixteen sectors. Each sector has a single representative consumer (we do not study distributional effects). We present the results of our simulations with fewer regions simply for ease of reading; the underlying model is always run with sixteen regions and sixteen sectors. The current version of the model has only a single type of capital within each region; there are no vintages and capital is perfectly mobile across sectors, but immobile across regions.[24] Labor supply is also completely mobile across sectors within each region and completely immobile across regions. As noted, we do not model the effects

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& Todd Munson, *CIM-EARTH: Framework and Case Study*, 10 B.E. J. Econ. Analysis & Pol'y, art. 11 (2010).

24   An important implication of this assumption is that there is no foreign direct investment in our model. Foreign direct investment may be an important channel of leakage.

of taxes on labor supply: Labor supply is determined by population growth, which is exogenous.

Many of the central variables are exogenous. In particular, labor productivity, energy efficiency, land endowment and yield, and resource availability are all modeled based on estimates of exogenous trends. As we discuss below, we analyze the sensitivity of our results to changes in these estimates. We do not, however, attempt to make them endogenous. One justification for using exogenous trends is that we view the model as producing results for the medium-term, so the tax may not have large effects on business-as-usual trends. The effects of a regional carbon tax may be much different in the long term, as it is both easier to shift production abroad in the long term and, offsetting this effect, the taxes may substantially influence energy efficiency. It is important, in future studies, to make energy efficiency endogenous, particularly for studies of longer-term effects.

A central component of any study of the effects of trade on carbon taxation is how trade is represented in the model. The standard approach in CGE models, which we follow, is to treat each region as producing a slightly different variety of each good. We treat steel from South Korea as a different commodity from steel produced in the United States. Purchasers of the goods have preferences over the varieties and will substitute across the varieties depending on their prices. These elasticities of substitution are known as the Armington elasticities after the inventor of this representation of trade. If the two goods are similar — the origin of steel of a given type might not matter — the Armington elasticity will be high.[25]

The Armington elasticity approach to trade is not based on modern theories of trade, but can be consistent with them.[26] It is highly flexible, and we believe it is a reasonable aggregate representation of trade for purposes of modeling. As discussed below, we test the sensitivity of our results to differing assumptions about the central Armington elasticities.

To complement the Armington representation of trade, we include detail on the transport sector. Steel produced in South Korea has to be shipped to the United States if it is to be used in the United States. Shipping and other

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25   We use Armington elasticities to measure substitution across imported goods, producing what we call an import bundle. The substitution elasticity of this bundle with domestic goods is the import elasticity. The import elasticity measures the competitiveness of domestic production against imports. In this Article, we generically refer to this entire representation as an Armington representation of trade, and to the overall set of elasticities as the Armington elasticities.

26   *See* Costas Arkolakis, Arnaud Costinot & Andres Rodriguez-Clare, *New Trade Models, Same Old Gains?*, 102 Am. Econ. Rev. 94 (2012).

means of transport are included in our industry structure as a necessary input into traded goods. The transport industry uses energy, so taxes on energy affect transport costs.

We use data from the Global Trade Analysis Project (GTAP).[27] GTAP is a global database with individual country input-output data and bilateral trade and transport data. It covers 113 regions and fifty-seven different commodities. We aggregate the data into sixteen regions and sixteen commodities. GTAP collects the data through a global network of governments and researchers. We ran our study using GTAP 7, covering the year 2004, which was the most recent version available at the time.

The more difficult and problematic estimation requirement is determining the parameters of the model, primarily the substitution elasticities. These elasticities determine how firms and individuals respond to changes in prices. For example, we want to know how industries will respond if the price of energy goes up, and this depends on firms' ability to substitute away from energy inputs. These elasticities cannot be directly observed. They should be estimated. We base our elasticities on those used in the MIT CGE model used to evaluate climate policies (known as EPPA). MIT obtained these from a literature search and, where the literature was not available, by elicitation from experts in the relevant industry.[28] We do not have a high level of confidence in these elasticities and, therefore, test the sensitivity of our results to alternative specifications.

Before turning to our simulations, we highlight the key differences between CIM-EARTH and our analytic model. The core models are designed to be similar: The analytic model is essentially a simplified model of CIM-EARTH with far less detail, fewer sectors, and so forth. Nevertheless, there are some important differences. One is that the analytic model uses Cobb-Douglas production and consumption functions, which impose an elasticity of 1 (because spending shares on inputs or consumption are fixed). The CGE model uses a more flexible functional form that allows input shares to vary. A second is that the analytic model ignores the cost of trading goods so that, absent taxes, the law of one price holds internationally. An implication is that factor rewards are also equated across countries. By contrast, CIM-EARTH is calibrated to actual bilateral trade flows by sector, with costs of trade in part accounting

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27   For documentation, see Global Trade Analysis Project, www.gtap.org (last visited July 6, 2012).

28   *See* Mort Webster, Sergey Paltsev, John Parsons, John Reilly & Henry Jacoby, Uncertainty in Greenhouse Gas Emissions and Costs of Atmospheric Stabilization (2008) (Report No. 165 of M.I.T Joint Program on the Science and Policy of Global Change).

for differences in import shares across countries. A third is that, while the analytic model has only one factor of production (labor) that is mobile across sectors, CIM-EARTH also incorporates physical capital used in production. Finally, energy is a homogeneous good in the analytic model, while CIM-EARTH incorporates the different carbon content, transport costs, prices, and imperfect substitutability between coal, natural gas, and petroleum. This last distinction is particularly important, as substitution away from coal is one of the main effects of instituting a moderate price of carbon.

B. Current Trade Patterns

Before turning to our simulations, it is helpful to examine existing trade patterns. Figure 5 shows the relationship between exposure to trade and the energy intensity of production for Annex B.[29] Trade exposure is the percentage of local consumption in Annex B coming from imports from non-Annex B countries. Energy intensity is energy use per dollar of revenues for the industry. The size of the bubbles represents the magnitude of CO_2 emissions.

Figure 5: Trade Exposure v. Energy Intensity for Annex B

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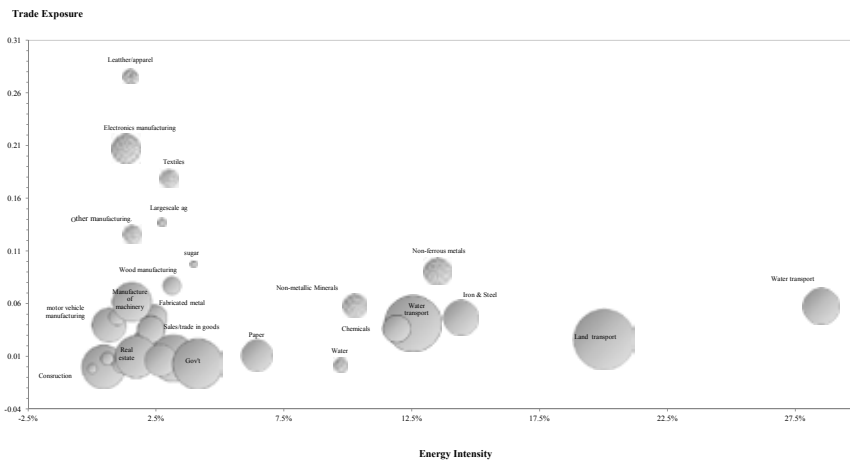
29 This figure is similar to Trevor Houser et al., Leveling the Carbon Playing Field: International Competition and U.S. Climate Policy Design 9 fig. 1.3 (2008), *available at* http://pdf.wri.org/leveling_the_carbon_playing_field.pdf. We use GTAP 7 data and analyze it for Annex B, while Houser looks at the United States. Houser shows notably larger import shares than we do. We suspect this is because he looks at the United States, while we look at Annex B (so that trade within Annex B does not show up as imports).

None of the products with the highest trade exposure are energy-intensive: Apparel, electronics, and textiles have high trade exposures, but require little energy to produce. There are no product categories in the upper-right part of the figure. Services, which occupy the bottom-left corner, take little energy to produce and are not substantially exposed to trade. The product categories that are most likely to be affected by a tax on emissions are in the lower-right quadrant of the graph: nonferrous metals (e.g., aluminum, copper, and titanium), iron and steel, chemicals, nonmetallic minerals and, perhaps, paper. Nonferrous metals in particular stand out as both energy-intensive and moderately exposed to trade. The transport sectors — air, water, and land — are also energy-intensive and somewhat exposed to trade. It is not clear, however, whether production in these sectors can shift abroad in response to a tax on emissions, as their output may be tied to a particular locality.

We can get a better sense of how energy-intensive goods are being traded around the globe by considering where imports come from. Table 2 provides the share of imports into the United States for five energy-intensive goods by origin. Non-Annex-B countries are in gray. Canada dominates the imports of these goods and other Annex-B countries also have large shares. The major exception to these patterns is cement, where China is the largest source of U.S. imports.

Table 2: Country of Origin for Imports to Annex B of Energy-Intensive Goods

U.S. Imports by Origin, 2004									
	Iron & Steel		Non-ferrous metals		Chemicals		Paper		Cement	
Rank	Source	Share	Source	Share	Source	Share	Source	Share	Source	Share
1	Canada	14.9	Canada	35.9	Canada	16.0	Canada	55.1	China	15.6
2	Mexico	9.6	Russia	9.8	Japan	9.4	China	6.4	Italy	12.9
3	Brazil	9.3	Peru	6.2	China	9.1	Finland	4.4	Canada	11.0
4	China	7.2	Mexico	5.2	Ireland	8.0	Germany	4.0	Mexico	10.5
5	Russia	5.7	Brazil	4.8	Germany	7.5	Mexico	3.7	Brazil	6.2

Finally, we can measure trade in what we call embedded carbon.[30] By embedded carbon we mean the carbon emitted in the production of a good,

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30   We follow a prior literature that uses a similar methodology, known as multi-region input-output analysis. For a summary of this literature, see Thomas Wiedmann, *A Review of Recent Multi-Region Input-Output Models Used for*

not carbon that is physically in the good. To do this, we start with the standard measure of emissions, which is based on the physical location of the combustion of fossil fuels. We trace how the resulting goods move through the economy and attribute the emissions to the places where goods are consumed. The result is a matrix that is essentially the same as the matrices we used for the analytic model, except it covers many regions and is based on actual trade patterns.

In particular, standard measures of emissions, including the UNFCCC's mandatory carbon inventories, attribute emissions to the location where the GHG is actually released into the atmosphere. For example, if fossil fuels are burned in South Korea to produce steel, which is subsequently made into an automobile in Japan, and which is shipped to and driven in the United States, the Framework Convention attributes the emissions from the steel production to South Korea, emissions from the automobile fabrication to Japan, and emissions from gasoline combustion to the United States. By knowing the inputs to steel production, how steel is traded, the inputs to automobile production, and how automobiles are traded, we can attribute the emissions to the ultimate consumers in the United States.

The GTAP 7 database provides us with input-output tables, which tell us the inputs into each industry and where the outputs go. Many of the outputs from an industry will go to other industries, while some will be consumed. The input-output tables allow us to trace the flow of goods through the economy to their final consumption. By tracing fossil fuels through these tables, we can determine where goods produced from the combustion of fossil fuels are eventually consumed. In the automobile example, we can see that the fossil fuels burned in South Korea produce steel, which is an input into automobile production in Japan, whose output is sold in the United States. Performing this analysis systematically on a global basis allows us to convert production measures of emissions into consumption measures and to see the extent of trade in embedded carbon.

Table 3 presents our calculations for 2004. Each entry represents emissions from production in the region in that row, which is then consumed in the region in that column, measured in million metric tons of CO_2. For example, the United States emitted 280,000,000 tons of CO_2 to produce goods ultimately consumed in the European Union. The sum across a row is the total emissions from production in a given region. The sum down a column is the total emissions from consumption in a given region.[31]

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Consumption-Base Emissions and Resource Accounting, 69 Ecological Econ. 211 (2009).

31 The region labeled JAZ is an aggregate of Japan, Australia, and New Zealand. CHK is China and South Korea. LAM is all of Latin America, including Mexico,

Table 3: Carbon Matrix for 2004, in Mt of CO_2

2004 Mt CO_2	Annex B					Non-Annex B			
	US	EU	RUS	JAZ	CAN	CHK	LAM	ROW	Prod.
US	5,012	280	7	95	177	109	209	112	6,002
EU	303	3,928	63	72	28	96	66	306	4,863
RUS	71	408	1,468	22	3	83	22	100	2,178
JAZ	84	82	3	1,146	8	160	12	98	1,593
CAN	248	33	1	9	223	12	8	10	543
CHK	577	587	32	390	50	3,679	103	478	5,897
LAM	293	122	6	18	16	36	956	40	1,487
ROW	300	657	31	289	20	376	55	3,199	4,928
Cons.	6,888	6,096	1,610	2,043	526	4,551	1,432	4,344	27,491
Net	877	1,235	-566	488	-19	-1,345	-56	-584	

The standard approach to attributing emissions can be seen by reading down the rightmost column, which gives emissions from production in each region. In 2004, the United States was the largest emitter, followed closely by China/South Korea (CHK in the table). The European Union and ROW (the rest of the world) are next. Global emissions were around 27,500 megatons of CO_2.[32]

Consumption figures are in the row labeled Cons. The United States consumed 6888 megatons of CO_2 compared to its production of 6002 megatons. This means that the United States was a net importer of 877 megatons CO_2: The goods that it imported had 877 more megatons of embedded CO_2 than the goods that it exported. The bottom row shows the net imports. The European Union was the largest net importer of embedded CO_2, with net imports of 1235 megatons. China and South Korea (CHK) are large exporters of CO_2,

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the Caribbean, and South and Central America, and ROW includes all other non-Annex B regions: Africa, the Middle East, and South and Southeast Asia.

32   Note that we use 2004 data because this is the most recent year for the database used in our computational model. More recent emissions data are available and can be readily accessed in the CAIT database, found at CLIMATE ANALYSIS INDICATORS TOOL (CAIT), http://www.wri.org/project/cait/ (last visited July 6, 2012). In 2007, total global emissions were around 33,500 megatons and China was the largest emitter, producing 6703 megatons compared to 5827 megatons for the United States. The CAIT data is aggregated from IPCC data and other sources.

together exporting 1345 megatons. Therefore, when we examine emissions on a consumption basis rather than a production basis, the developed world has comparatively more emissions; the choice by the UNFCCC to allocate emissions based on a production measure favors the developed world.

C. Business as Usual Emissions and Sensitivity

Using CIM-EARTH, we project these current patterns to the future under a business as usual (BAU) policy — i.e., assuming no change in carbon policy from that already in place. Figure 6 gives our overall simulations of BAU emissions and shows how the estimates vary when we vary our assumptions about the growth of labor productivity and energy efficiency. The thin gray lines show how our estimates change when we change our assumptions about the growth of energy efficiency. The grayed groups show how changes in assumptions about labor productivity change our results.

Figure 6: Ensemble of Model Output for a BAU Policy Scenario and a Range of Energy Efficiency and Labor Productivity Assumptions

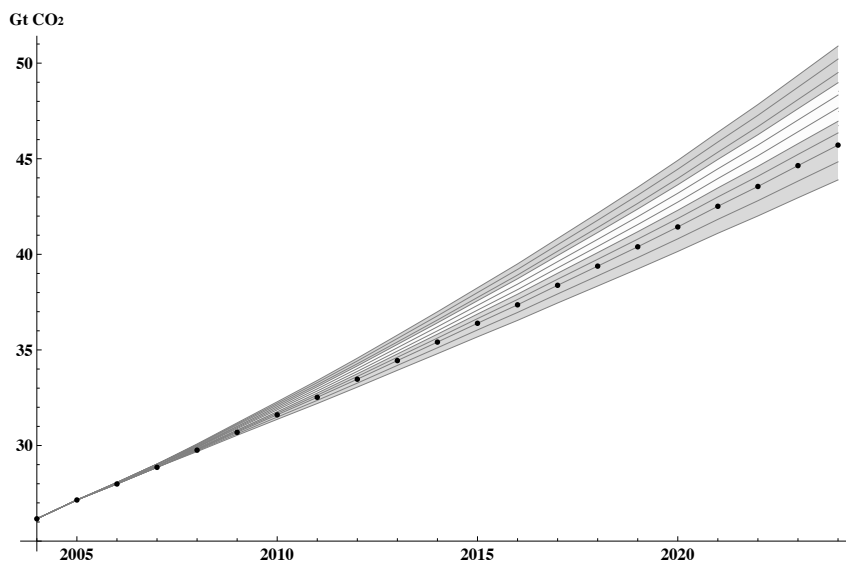Figure 7 shows how our results compare to the results of other simulations. Our results are higher than the EIA estimates (dots), but in the central range for the IPCC estimates (light gray lines).

Finally, for each simulation, we can determine which regions are producing and consuming CO_2, using the same matrix format we used above to present the 2004 data. Table 4 provides the breakdown for our central assessment

of emissions in 2020. Comparing it to Table 3, we can see that emissions go up by fifty-nine percent to 43,800,000,000 tons. By far the largest expected growth is in emissions from China, which we expect to go up by 130%. Russian emissions are expected to go up by eighty-five percent.

Figure 7: Comparison of Historical Data (dashed), 2005-2009 EIA Forecasts (dots), IPCC Scenarios (Gray), and Baseline for Ranges of Labor Productivity and Energy Efficiency (Black Lines).
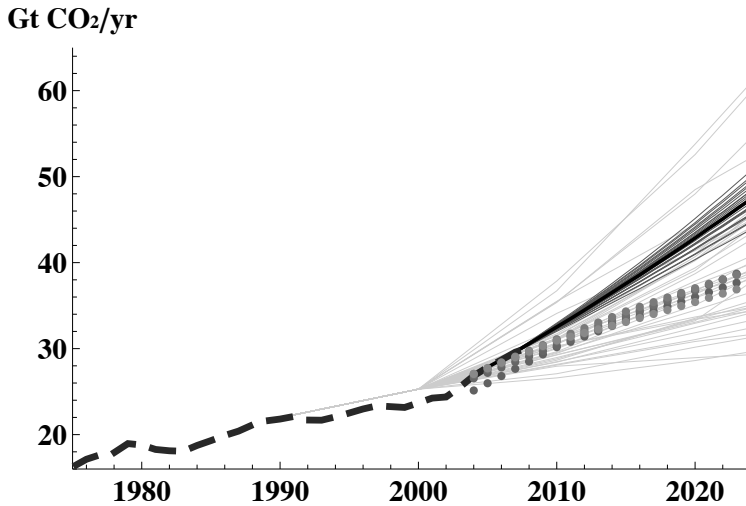
Table 4: Carbon Matrix for 2020 BAU Scenario, Central Case, in Megatons of CO_2

2020 Mt CO_2	Annex B					Non-Annex B				
	US	EU	RUS	JAZ	CAN	CHK	LAM	ROW	Prod.	2004
US	6,583	335	12	117	224	244	268	165	7,951	6,002
EU	377	4,347	102	80	35	195	81	429	5,648	4,863
RUS	138	671	2,644	37	6	282	40	215	4,035	2,178
JAZ	89	85	4	1,266	8	290	14	125	1,852	1,593
CAN	331	40	1	10	296	29	12	16	738	543
CHK	1,338	1,298	99	697	121	8,673	228	1,129	13,586	5,897
LAM	391	148	11	21	20	91	1,273	61	2,020	1,487
ROW	447	867	59	345	31	930	78	5,198	7,960	4,928
Cons.	9,697	7,796	2,935	2,543	746	10,736	1,998	7,338	43,791	27,491

D. Simulations

We consider a number of different tax simulations. We start by comparing global emissions reductions under three different taxes: a global carbon tax, a production tax in Annex B countries, and a BTA tax in Annex B countries, all under various tax rates. Figure 8 presents our results. (Note that we keep the axes the same as in Figure 2 to allow comparison of the analytic model and CIM-EARTH.)

Figure 8: Simulation of Global Emissions Reductions Under Various Taxes
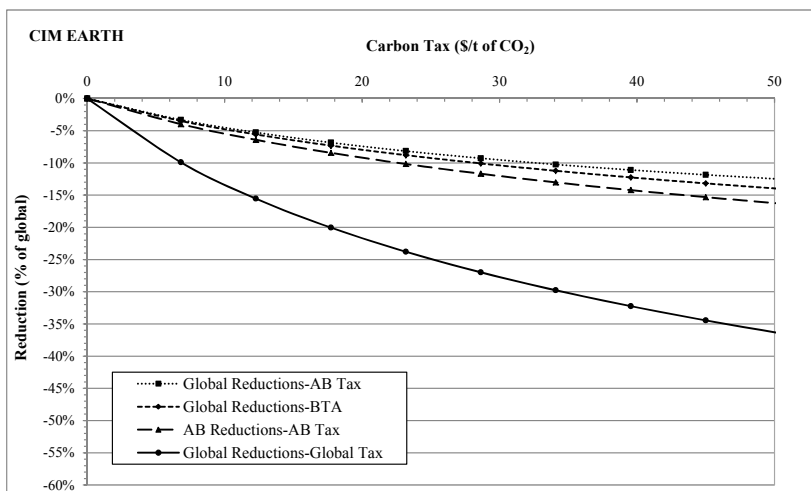
The figure illustrates three results from the model. The first is that a carbon tax only in Annex B, regardless of whether or not it includes BTAs, has limited potential to reduce global emissions. Under our simulations, an Annex B tax will reduce emissions by only about a third as much as a global tax. The reason is straightforward: Most of the growth in emissions is expected to come from non-Annex B countries. The limited effectiveness of an Annex B tax is not by-and-large a result of leakage; it is because major sources of emissions are omitted.

The second result is that leakage rates are between fifteen and twenty-five percent. We can get a visual sense of leakage by comparing the Annex B reductions under the Annex B tax to the global reductions under the Annex B tax. The higher global emissions are a result of an increase in energy use in non-Annex B countries.

Finally, emissions in CIM-EARTH are far less sensitive to carbon taxes than are emissions in the analytic model. This difference can be seen by

comparing Figure 8 and Figure 2, which show the same scenarios in the two models. The analytic model shows reductions of fifty-five percent for a global carbon tax of around fifty dollar/ton of CO_2, while CIM-EARTH produces only thirty-six percent reductions. The analytic model produces reductions of twenty-eight percent for the production tax in Home, while CIM-EARTH produces reductions of only thirteen percent for the Annex B tax.

We suspect that these differences relate to the ability to substitute away from energy in the two models. The analytic model was parameterized so that the relative shares of various inputs are roughly the same as in CIM-EARTH. For example, relative energy resources in the two regions correspond to the relative energy resources in Annex B and non-Annex B countries. The analytic model, however, uses a substitution elasticity between energy and labor of 1, due to the use of a simplified functional form for which it was possible to obtain a closed-form solution to the model. CIM-EARTH sets the equivalent elasticity at 0.5. This small elasticity makes it more difficult to shift away from energy in CIM-EARTH when we add a carbon tax. As a result, we expect lower reductions in CIM-EARTH than we see in the analytic model.[33]

Figure 9, which is analogue to Figure 3, examines the effects of border taxes. As in the analytic model, emissions in Annex B are higher when there are border taxes. To the extent that Annex B commits to emissions reductions goals, it is easier to meet them with a pure production tax than with BTAs. The reason is that more production shifts to non-taxing regions under a production tax.

A comparison of global and Annex B reductions under a BTA system shows that border taxes reduce leakage substantially. As in the analytic model, this result arises because of a reduction in emissions in non-Annex B countries and an increase in emissions in Annex B. We can see the increase in Annex B emissions by comparing the bottom two lines in Figure 9. The global reductions can be seen by comparing the top two lines. Leakage with BTAs is based on the difference in the middle two lines.

An examination of the carbon matrices provides additional insight. Table 5 gives the carbon matrices for an Annex B production tax at twenty-nine dollars/ton tax on CO_2.[34] The numbers are percentage changes from the BAU scenario (given in Table 4).

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33 Preliminary tests of CIM-EARTH using a substitution elasticity between energy and capital/labor inputs of 1 show sensitivities similar to those in the analytic model.

34 We ran our simulations in carbon rather than CO_2. Table 5 is for a 105 dollar/ton carbon tax, which translates to a 28.64 dollar/ton tax on carbon dioxide.

Figure 9: Reductions in Emissions in Annex B Countries
as a Percent of 2020 BAU Scenario
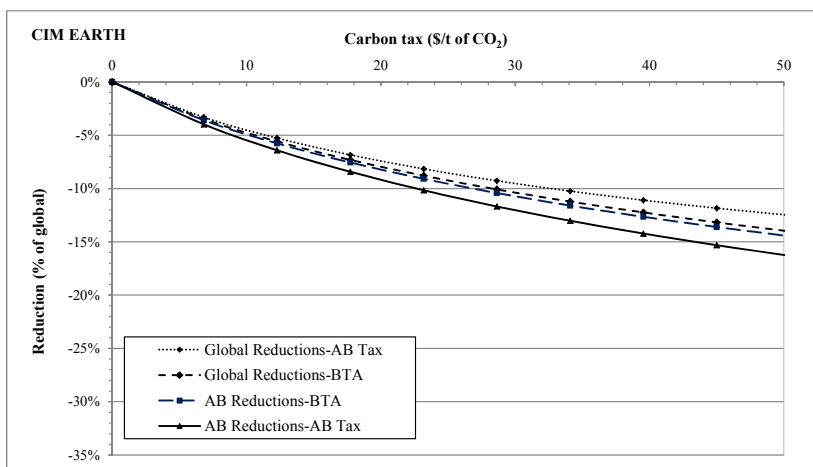
Table 5: Percent Changes from 2020 BAU for a $29/ton CO_2 Tax
in Annex B

AB-29	Annex B					Non-Annex B			
v. ref	US	EU	RUS	JAZ	CAN	CHK	LAM	ROW	Prod.
US	-26.9	-18.9	-21.5	-26.1	-21.3	-24.6	-29.4	-28.7	-26.4
EU	-23.7	-23.3	-19.5	-18.3	-17.8	-21.8	-23.4	-28.1	-23.4
RUS	-38.0	-33.8	-29.3	-34.6	-4.0	-37.5	-39.7	-35.6	-31.4
JAZ	-14.5	-14.5	-17.4	-33.0	-18.8	-22.3	-19.3	-25.0	-28.8
CAN	-21.0	-18.9	-16.4	-19.2	-26.1	-20.4	-20.3	-21.0	-22.9
CHK	1.2	1.7	1.8	2.9	1.9	2.9	2.2	1.2	2.4
LAM	24.8	13.5	46.7	4.0	25.3	2.8	6.5	5.1	10.8
ROW	8.2	12.5	18.2	15.0	8.1	6.2	9.4	4.7	6.6
Cons.	-19.0	-15.0	-26.6	-15.5	-16.8	0.3	-1.2	-0.2	-9.9

The easiest way to read the table is to consider the four large blocks. The upper left-hand block is production taking place in Annex B countries that is consumed in those countries. (The diagonal represents production in a given country consumed there. The off-diagonal entries are trade within Annex B.) This production goes down significantly. The lower left-hand block represents imports into Annex B countries from non-Annex B production.

As we expect, we see an increase in imports: It is relatively less expensive to purchase energy-intensive goods produced abroad because of the carbon tax. Similarly, if we look at the upper right-hand block, we see a decrease in production in Annex B countries for export into non-Annex B countries. It is more difficult for domestic industries to compete in the export market.

The lower right-hand block is production in non-Annex B countries that is consumed locally. We can see that this goes up, uniformly. The reason is the lower price of energy due to decreased use in Annex B. This is the second form of leakage discussed above. We can see the net effect by comparing production in Annex B countries (the right-hand column) to consumption in Annex B countries (the bottom row): production declines by more than consumption, showing production leakage.

Table 6 presents the carbon matrix for the BTA tax, again showing percentage changes from our BAU simulations. The key block is the lower left-hand corner, which shows Annex B imports from non-Annex B countries. This goes from an increase in the production tax case to a decrease in the BTA tax case. Border taxes reduce the incentive to purchase energy-intensive goods from abroad.

Table 6: Carbon Matrix for BTA Tax in Annex B at Twenty-Nine Dollars/Ton CO_2

BTA	Annex B					Non-Annex B			
v. ref.	US	EU	RUS	JAZ	CAN	CHK	LAM	ROW	Prod.
US	-25.3	-18.0	-20.5	-17.9	-20.0	-23.2	-16.6	-21.4	-21.4
EU	-13.5	-20.2	-17.5	-16.0	-15.7	-25.9	-21.8	-23.2	-20.0
RUS	-31.6	-32.5	-30.3	-29.0	-33.5	-16.4	-19.0	-12.4	-28.6
JAZ	-13.6	-16.0	-16.6	-26.3	-18.8	-25.0	-21.0	-22.3	-19.5
CAN	-15.7	-19.2	-13.7	-18.4	-23.2	-25.0	-21.0	-22.6	-19.5
CHK	-8.0	-9.0	-10.0	-9.9	-10.3	3.1	9.3	5.5	0.3
LAM	-9.6	-2.8	15.2	-1.6	-3.0	-1.2	4.1	0.5	0.5
ROW	-4.2	-5.8	-6.4	-7.0	-4.8	1.7	7.6	3.2	1.1
Cons.	-20.5	-17.3	-28.4	-18.3	-18.5	.05	.02	.04	-10.7

Looking at the upper right-hand block, we can also see a smaller reduction in non-Annex B consumption of carbon imports from Annex B countries (relative to the production tax case). This is as expected, because the border tax removes the tax on these exports from Annex B. The upper-left and lower

right-hand blocks represent production and consumption internal to each region. With border taxes, we see slightly lower reductions in emissions in Annex B (for goods consumed in Annex B). Emissions from production in non-Annex B consumed locally show a mixed pattern, with Chinese emissions going up with border taxes and emissions from other regions going down.

E. Robustness/Sensitivity/Replication

A central problem with estimating the size of the effects of a regional carbon tax is that we are unsure of many of the central elasticities. As noted, elasticities cannot be directly observed; they have to be econometrically estimated, and the data that might be used for this estimation is scarce. Because of the uncertainty in these parameters, we check the robustness of our results to changes in the central elasticities. Another problem with CGE modeling of the problem is that it can be difficult to compare CGE results with one another because model structures vary in subtle ways and the underlying data and elasticities may be different. To respond to this problem, we attempt to replicate the findings of other models within ours using their choices of elasticities.

Robustness checks and replication are similar in that in both cases we compute results within our model for alternative choices of the central parameters. We can perform both activities at the same time by making sure that our sensitivity analyses encompass the parameter choices used in other models. We present two of our results here.[35]

The first sensitivity result we present is the sensitivity of leakage to changes in the price elasticity of energy supply, ψ_{ES}, which, as we indicated above for the analytic model, we expect to be a central parameter. A low ψ_{ES} means that the supply of energy does not change much when the price changes, while a high ψ_{ES} indicates that supply is highly sensitive to price. We expect leakage to be higher when ψ_{ES} is low. Figure 10 presents these results.

Figure 10: Sensitivity of Leakage to ψ_{ES} for a Twenty-Nine Dollar/Ton CO_2 Tax in Annex B, No BTAs

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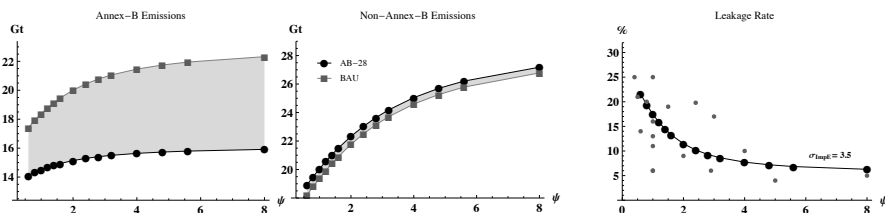
35   For additional robustness checks, see RDCEP, *supra* note 8.

The left-most two graphs show the change in emissions in Annex B and non-Annex B as we change ψ_{ES}. The vertical difference between the two lines — BAU and AB-28 — highlighted in gray is the change in emissions due to the tax for various values of ψ_{ES}. We can see in the left-most graph that the change in emissions is quite sensitive to ψ_{ES} for low values. There is little effect in non-Annex B regions. The net effect is that leakage is highly sensitive to ψ_{ES}, primarily because of its effect in Annex B. The dots represent the leakage rates and value of ψ_{ES} used in prior studies.[36]

The second result we show is an attempt to reproduce the findings of nineteen prior studies using their parameter sets.[37] The parameters that we

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36   For a list of prior studies, see *infra* note 37.

37   Mustafa H. Babiker & Henry D. Jacoby, Developing Country Effects of Kyoto-Type Emissions Restrictions (1999); Paul Veenendall & Ton Manders, CPB Neth. Bureau for Econ. Pol'y Analysis, Border Tax Adjustments and the EU-ETS: A Quantitative Assessment (2008), *available at* http://www.cpb.nl/en/publication/border-tax-adjustment-and-eu-ets-quantitative-assessment; Mustafa H. Babiker, *Climate Change Policy, Market Structure, and Carbon Leakage*, 65 J. Int'l Econ. 421 (2005); Mustafa H. Babiker, *Subglobal Climate-Change Actions and Carbon Leakage: The Implication of International Capital Flows*, 23 Energy Econ. 121 (2001); Alain Bernard & Marc Vielle, *Allocation efficace d'un cout global d'environnement entre pays: permis negociables VS taxes ou permis negociables ET taxes?*, 82 Economie Internationale 103 (2000) (Fr.); Paul M. Bernstein, W. David Montgomery & Thomas F. Rutherford, *Global Impacts of the Kyoto Agreement: Results from the MS-MRT Model*, 21 Resource & Energy Econ. 375 (1999); Steffen Kallbekken, Line S. Flotorp & Nathan Rive, *CDM Baseline Approaches and Carbon Leakage*, 35 Energy Pol'y 4154 (2007); Onno J. Kuik & Reyer Gerlagh, *Trade Liberalization and Carbon Leakage*, 24 Energy J. 97 (2003); Warwick J. McKibbin, Martin T. Ross, Robert Shackleton & Peter J. Wilcoxen, *Emissions Trading, Capital Flows and the Kyoto Protocol*, 20 Energy J. 287 (1999); Warwick J. McKibbin & Peter J. Wilcoxen, *The Economic and Environmental Effects of Border Tax Adjustments for Climate Policy*, 2008/2009 Brookings Trade F. 1 (2009); Sergey V. Paltsev, *The Kyoto Protocol: Regional and Sectoral Contributions to the Carbon Leakage*, 22 Energy J. 53 (2001); Winchester, Palstev & Reilly, *supra* note 10; Jean-Marc Burniaux & Joaquim Oliveira Martins, *Carbon Emission Leakage: A General Equilibrium View* (Org. for Econ. Co-Operation & Dev. (OECD), Econ. Dep., Working Paper No. 242, 2000); Jean-Marc Burniaux & Troung P. Truong, *GTAP-E, and Energy-Environmental Version of GTAP* (Global Trade Analysis Project (GTAP), Technical Paper No. 16, 2002), *available at* https://www.gtap.agecon.purdue.edu/resources/download/1203.pdf; Reyer Gerlagh & Onno Kuik, *Carbon Leakage with International Technology Spillovers* (Fondazione Eni Enrico Mattei, Working Paper No. 2007.33, 2007); Miles

consider include the Armington elasticities, the elasticity of substitution of energy goods, and the price elasticity of energy supply. Figure 11 shows the leakage reported in prior studies compared to the closest parameter fit within our model. We show the full set of estimates in the left-hand graph. In the right-hand graph, we eliminate an outlier study. We can explain much of the variation in leakage estimates as being due to variations in parameters. CIM-EARTH, however, predicts higher leakage than the comparison models when using the same parameter set.

Figure 11: Replication of Parameters in Prior Models

Light, Charles Kolstad & Thomas Rutherford, *Coal Markets and the Kyoto Protocol* (Ctr. for Econ. Analysis, Dep't of Econ., Univ. of Colo. at Boulder, Working Paper No. 99-23, 1999); Andreas Loschel, Victoria Alexeeva-Talebi & Tim Mennel, *Climate Policy and the Problem of Competitiveness: Border Tax Adjustments or Integrated Emission Trading* (Z.E.W., Discussion Paper No. 08-061, 2008), *available at* http://ideas.repec.org/p/zbw/zewdip/7384.html; Aaditya Mattoo, Arvind Subramanian, Dominique Van der Mensbrugghe & Jianwu He, *Reconciling Climate Change and Trade Policy* (World Bank Pol'y Res., Working Paper No. 5123, 2009); Everett B. Peterson & Joachim Schleich, *Economic and Environmental Effects of Border Tax Adjustments* (Sustainability & Innovation, Working Paper No. S1/2007, 2007), *available at* http://econstor.eu/dspace/handle/10419/28514; Johannes Bollen, Ton Manders & Hans Timmers, Decomposing Carbon Leakage, Paper Presented at Third Annual Conference on Global Economic Analysis, Melbourne, Austl. (June 27-30, 2000).

F. Proxy Tax Simulations

Border tax adjustments are likely to be difficult to implement. To determine the tax on imports, a customs agent would have to know the marginal source of energy used for each stage of production for an imported good. A finished good may have elements produced in many countries with many different energy sources, making this task difficult. Worse, to give foreign firms the correct incentive to use low-carbon production methods, the tax has to be sensitive to the particular production choices and energy sources used for each good. For example, if the tax rate is based on national averages, individual firms in a given country will not have an incentive to switch to low-carbon production, as doing so would have no effect on the tax imposed and would increase costs. Border tax adjustments may also be contrary to WTO law. In particular, the tax would be based on production methods and therefore "like" products may face different taxes.[38]

To address these concerns, we consider three imperfect border tax regimes. The first is border tax adjustments based on the average emissions from production of a good in the importing country. There are two intuitions behind this approach: (1) local customs agents may have better information about domestic production methods than about foreign production methods, so it would be easier to implement; and (2) it may appeal to domestic industry because it imposes the same tax on imports as domestic industry faces. The disadvantage of this approach is that the tax is unrelated to the actual emissions from production of a good abroad. Foreign firms have no incentive to alter their production in response to the tax. In Figures 12 and 13, where we show our results, this tax is labeled BTA-Regional.

The second is a global system of border tax adjustments where the border tax and the rebate on export are based on a schedule set by a global entity such as the WTO or the United Nations. The schedule we model is, for each category of goods, equal to the global average emissions from the production of those goods. The intuition here is that border tax adjustments might be part of a global climate agreement. In addition, once negotiated, a schedule would be easy for countries to impose. The disadvantages are similar to the disadvantages of border taxes based on domestic emissions in the production of like goods. In Figures 12 and 13, this policy is labeled BTA-UN.

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38   There is a large literature on the legality of border tax adjustments for carbon taxes and cap-and-trade systems, *e.g.*, Gavin Goh, *The World Trade Organization, Kyoto and Energy Tax Adjustments at the Border*, 38 J. World Trade 395 (2004); Roland Ismer & Karsten Neuhoff, *Border Tax Adjustments: A Feasible Way to Support Stringent Emission Trading*, 24 Eur. J.L. & Econ. 137 (2007).

The final imperfect system we consider is import tariffs. These are perfectly calculated border taxes, but imposed only on imports, without the corresponding rebate on export. These are punitive, and we imagine them being imposed in response to domestic demands by industry fearful of carbon leakage. We label this system Tariff.

Our results are presented in Figures 12 and 13. Figure 12 shows the global emissions reductions under these scenarios, compared to a production tax. Comparing the production tax (the top line) to the other taxes, we can see that all of the border tax systems reduce emissions more than a pure production tax. The reasons are similar to the reasons perfect BTA reduces emissions, as discussed above: Emissions in Annex B will go up, but emissions in non-Annex B regions go down by more.

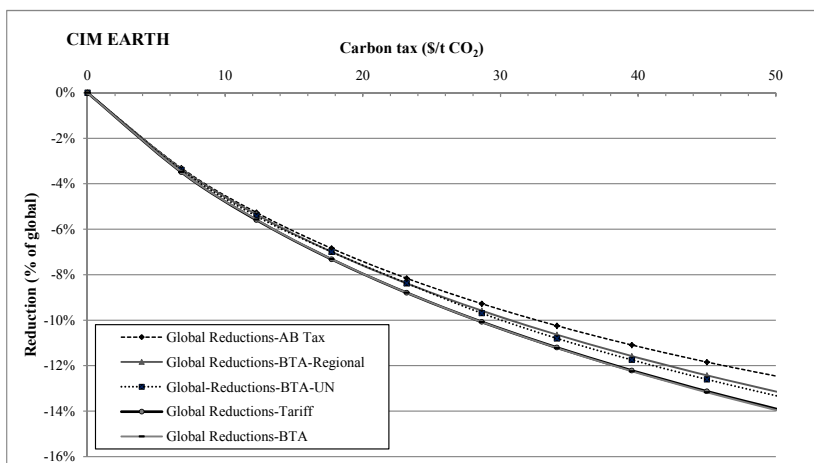**Figure 12: Global Emissions Reductions Under Imperfect BTAs**

Figure 13 shows the leakage rate under each scenario. Perfect border taxes reduce leakage the most. The reason is likely that only perfect border taxes provide the correct incentives to reduce emissions in foreign production.

Comparing the tariff lines in Figures 12 and 13, we can see that tariffs reduce global emissions by almost exactly the same amounts as perfect BTAs, but generate more leakage. The difference between a tariff and border tax adjustments is that border tax adjustments have a rebate on export while tariffs do not. The tariff, by not providing a rebate for exports from Annex B, reduces Annex B emissions by more than perfect border taxes, so the denominator in the leakage measure is bigger (tending to reduce the leakage rate). Offsetting this effect, emissions increases in non-Annex B regions are greater under the tariff than under perfect border taxes because there is

actually a greater incentive to shift production abroad: Annex B production for export to non-Annex B countries is not as competitive as local production in non-Annex B countries (for consumption there). An exporting Annex B industry therefore may shift production to a non-Annex B country. The net result is around double the leakage.

Figure 13: Leakage Rate Under Tax Scenarios
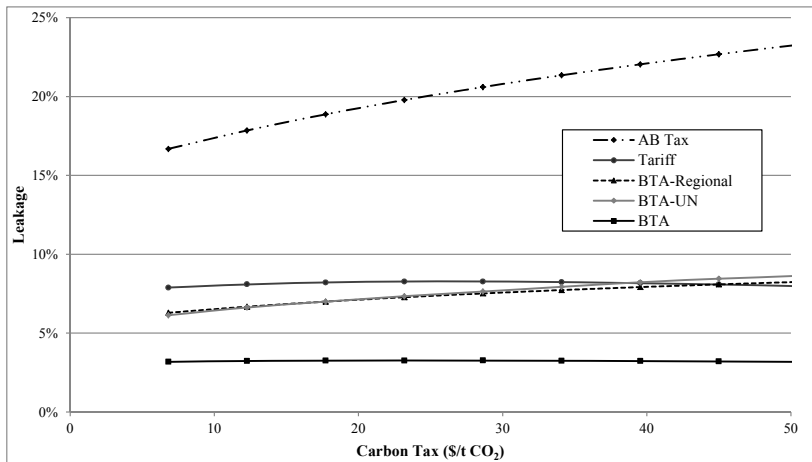
The United Nations and regional border tax systems also do not perform as well as perfect border taxes. These systems have higher overall emissions and higher leakage. The reasons here likely relate to the imperfect incentives these systems provide to non-Annex B production. Because the taxes do not respond to production choices, there is a lower incentive to alter those choices. We do not consider the administrative costs of the alternative systems. If the administrative savings are great enough, it may be worth adopting one of these alternative systems notwithstanding their poorer performance.

Conclusion

We had a number of goals for this study. One was to introduce CGE modeling of a legal problem and to consider ways that it can be made useful and accessible. To do this, we developed a simplified analytic model of the problem with the same core structure as the CGE model. The simplified model provides economic intuitions, which we then simulate in the CGE model. We parameterized the analytic model to match the CGE model so that we could test the sensitivity of the analytic model results to the variables we use in the CGE model. We also made our CGE code open source, provide extensive sensitivity and

robustness checks, and attempt to replicate prior studies within our model. While we suspect that CGE modeling of legal problems will remain difficult to do and difficult to understand for many legal analysts, it may be the best way to study certain classes of problems.

A second goal was to understand the structure of the leakage problem and to understand which parameters drive leakage. One central conclusion in this regard is that a key variable is the price elasticity of energy supply. For both production taxes and border taxes, a low price elasticity of energy supply means that leakage is likely to be high. What really matters for global emissions is the total amount of fossil fuels extracted. If energy supply is inelastic, a regional carbon tax will have little effect on global extraction. These results show up in both our analytic model and in our CGE model. In thinking about the design of regional emissions systems, it might be wise to focus on energy supply as much as on demand.

A third goal was to simulate a variety of tax policies to understand their likely effects. Within our CGE model, we consider perfect border taxes and a number of imperfect taxes, such as a tax based on a global schedule of emissions for different types of goods. Our simulations show that imperfect border taxes may be significantly inferior to perfect border taxes in reducing leakage. The reason appears to relate to the incentives for foreign producers: With imperfect taxes, they gain no benefit from switching to clean production technologies. Our simulations also show the importance of global emissions reductions policies. Carbon taxes only in Annex B have limited potential to reduce emissions, and this is not a result of leakage. Even without leakage, the large expected increases in emissions in the developing world swamp the potential reductions in Annex B.

Appendix

We present below the core equations and parameter values from the analytic model.

Function	Form
Endowments (asterisks indicate the foreign country)	Home: L and E Foreign: L^* and E^*
Production of *l*-good	$Q_l = L_l$ $Q_l^* = L_l^*$
Energy production in each country	$Q_{energy} = \left(\dfrac{L_{energy}}{\beta}\right)^{\beta} E^{1-\beta}$ $Q_{energy}^* \left(\dfrac{L_{energy}^*}{\beta}\right)^{\beta} E^{*(1-\beta)}$
Trade in energy (*M* is demand)	$Q_{energy} + Q_{energy}^* = M_e + M_e^*$
Production of *ei*-good	$Q_{ei} = \left(\dfrac{L_{ei}}{\delta}\right)^{\delta} M_e^{1-\delta}$ $Q_{ei^*}^* = \left(\dfrac{L_{ei}^*}{\delta}\right)^{\delta} M_e^{*(1-\delta)}$
Utility	$U = \left(C_{ei}\right)^{\alpha_H} \left(C_{ei^*}\right)^{\alpha_F} \left(C_l\right)^{1-\alpha_H-\alpha_F}$ $U^* = \left(C_{ei^*}^*\right)^{\alpha_H} \left(C_{ei}^*\right)^{\alpha_F} \left(C_l^*\right)^{1-\alpha_H-\alpha_F}$
Market clearing	$L = L_{ei} + L_{energy} + L_l$ $L^* = L_{ei^*}^* + L_{energy}^* + L_l^*$ $Q_{ei} = C_{ei}^* + C_{ei}$ $Q_{ei^*} = C_{ei^*}^* + C_{ei^*}$ $Q_l + Q_l^* = C_l + C_l^*$

Parameter	Calibrated Value
Share of income spent on own variety, α_H	0.15
Share of income spent on imported variety, α_F	0.07
Labor share in e-good production, β	0.74
Labor share in ei/ei*-good production, δ	0.80
Share of labor in H, $\frac{L}{L^*}$	0.71
Share of resource in H, $\frac{E}{E^*}$	0.40