Inter-American
Development Bank

Department of Research
and Chief Economist

TECHNICAL NOTE

No. IDB-TN-740

CGE Modeling:

The Relevance of Alternative Structural Specifications for the Evaluation of Carbon Taxes' Impact and for the Integrated Assessment of Climate Change Effects: Simulations for Economies of Latin America and the Caribbean

Omar O. Chisari
Sebastián Miller

February 2015

CGE Modeling:

The Relevance of Alternative Structural Specifications for the Evaluation of Carbon Taxes' Impact and for the Integrated Assessment of Climate Change Effects: Simulations for Economies of Latin America and the Caribbean

Omar O. Chisari
Sebastián Miller

Inter-American Development Bank
2015

Cataloging-in-Publication data provided by the
Inter-American Development Bank
Felipe Herrera Library

Chisari, Omar O.
CGE modeling: the relevance of alternative structural specifications for the evaluation of carbon taxes' impact and for the integrated assessment of climate change effects: simulations for economies of Latin America and the Caribbean / Omar O. Chisari, Sebastián Miller.
p. cm. — (IDB Technical Note ; 740)
Includes bibliographic references.
1. Computable general equilibrium models. 2. Carbon taxes—Latin America.. 3. Climatic changes—Latin America. I. Miller, Sebastián. II. Inter-American Development Bank. Department of Research and Chief Economist. III. Title. IV. Series.
IDB-TN-740

http://www.iadb.org

Abstract[*]

This paper constructs a small CGE model to study the impact of carbon taxes on GDP and emissions under alternative closure rules and hypotheses (about mobility of factors, availability of alternative technologies and labor market disequilibrium). The model is simulated for Argentina, Brazil, Chile, El Salvador, Jamaica and Peru. The paper evaluates the costs of lowering emissions under different scenarios and finds that: i) those costs are lower under full employment and when international mobility of capital is limited and are higher when those taxes are not imitated by the rest of the world; ii) the compensation of carbon taxes with other taxes can help to reverse GDP and welfare losses; iii) alternative technology effective application will be reduced when it is intensive in capital from the rest of the world. The second part uses the assessment of costs of abatement of emissions with carbon taxes in an Integrated Assessment Model.

JEL classifications: C68, D58, H23
Keywords: CGE model, Carbon tax, Alternative technology, Integrated Assessment Model

---

[*] The authors are grateful to L. Mastronardi, J.P. Vila Martínez and J. Maquieyra for their assistance.

1. Introduction

What are the costs of reducing emissions? Do those costs differ in the long run and short run? Could those costs be different for economies with macroeconomic imbalances, unemployment and high international capital mobility? Climate change poses a variety of challenges to researchers and policymakers of Latin America and the Caribbean, and those challenges are particularly great because the current experience of climate change is still relatively new and therefore largely undocumented in terms of both data series and policy lessons.

Computable General Equilibrium (CGE) models can help to overcome those difficulties because, even though they are very demanding in terms of data on composition of GDP or structural parameters, they do not rely on thorough statistical studies or time series. CGE models can thus provide an initial estimate of how the costs and benefits of climate change policies could affect economies, how they will be distributed among different economic agents and how they will influence the allocation of resources and the rate of growth.

Though initially oriented to the study of tax changes, tax reforms and international trade policies (see, for example, Shoven and Whalley, 1992) CGE models have increasingly been used for other aims, including climate change. Analysis with CGE models therefore implies that the workings of the price system are a key determinant of the results. For every counterfactual simulation, a price vector that equals demand to supply is computed, and in turn those prices are at the core of changes in the welfare of agents of the economy, modifications in activity levels of industries and the general performance of the economy. Entry barriers to that methodology have been reduced, and the diffusion of CGE models is at this moment wide and documented, but their use is not necessarily accompanied by tests of reliability of the results under alternative specifications.

Different models of partial and general equilibrium have been in use, e.g., DICE, MERGE, PAGE and FUND (and other like SWOPSIM,[1] IMPACT,[2] PEATSIM,[3] AGLINK,[4] FAPRI-CARD,[5] GTAP,[6] INGEM and RICE). While those models' databases are important for

---

[1] SWOPSIM (Static World Policy Simulation Model), developed by USDA.

[2] IMPACT (International Model for Policy Analysis of Agricultural Commodities and Trade) developed by International Food Policy Research Institute.

[3] PEATSim (Partial Equilibrium Agricultural Trade Simulation) developed by USDA.

[4] AGLINK developed by OECD.

[5] FAPRI-CARD developed by Food and Agricultural Policy Research Institute and the Center for Agricultural and Rural Development.

the results and prescriptions, analysis of those databases and corroboration of their information is insufficient for evaluating and deciding on climate change policy in real time, and a lack of transparency in the data fed into the models is a serious problem. Moreover, policymakers cannot afford to make decisions based on models whose analytical structure and internal causalities are imperfectly known.

With these considerations in mind, in this paper we attempt to highlight what elements and explicit or implicit assumptions of the analytical structure of CGE models are relevant in the short and long run to determine their results for climate change policies, in particular mitigation based on carbon taxes.

As noted above, climate change poses many new questions for the design of policy around the world, especially as many economies are already under macroeconomic stress. Climate change adds new challenges to a list that already includes trade balance constraints, fiscal imbalances[7] and insufficient growth. In addition, unequal income distribution and poor standards of living raise questions regarding the political feasibility of particular policy measures.[8] Consequently, even optimal policies on climate change have to pass the reality check of economic constraints and opportunity costs. As Carraro and Metcalf (2000) note, "*actual policymakers often attach considerably more importance to the distributional impacts of the policy measures that they adopt than they do to issues of efficiency.*" A socially suboptimal black box approach could thus result in abandoning a useful tool or approving prescriptions based on models whose mechanisms are unknown.

The relevance of alternative specifications of CGE models is illustrated in the classic work of Dervis, De Melo and Robinson (1982). That book emphasized the analysis of different closures for the analysis of the implications of development policies. In our case, we consider that the evaluation of the impact of carbon policies can be enriched under a variety of possible states of economy. This is for two reasons: i) because policymakers may face scenarios of uncertainty (in the Knightian sense) with respect to key parameters and causalities in their economies and ii) because the social feasibility of some policies, such as carbon taxes, will

---

[6] GTAP (Global Trade Analysis Project).

[7] According to Goulder (2013), "a major challenge of climate policy is figuring out how to achieve reductions in emissions of greenhouse gases at low cost."

[8] Boccanfuso, Estache and Savard (2008) emphasize the need to use CGE models to estimate the impact on income distribution, and on the identification of winners and losers, especially to take into account the indirect effects (e.g., the change in the cost of energy) of carbon policies.

depend on their costs both in absolute terms and in terms of the distribution of those costs (and benefits) between households and industries.

What, then, are the differences among CGE models?

As noted above, beyond the data which could be obtained from a common pool, models might differ in terms of structure, causalities and assumptions on their closure rules. First of all, the modelling of energy use and of agricultural production and land use (including forests) is critical for estimating emissions of greenhouse gases (GHGs). The main sources of GHG emissions are energy and/or land use, and the treatment given to them is very relevant. However, the relative composition of the GDP in terms of those basic sources of GHG and its change in response to policies and shocks will depend on the assumptions made in relation to other aspects such as the following:

1. Whether the basic sensitivity analysis focuses on elasticities of substitution.
2. The presence or absence of idle resources and therefore of the rules of determination of their prices (for example, the determination of wages in nominal or real terms under unemployment or the Walrasian flexible wages solution).
3. The degree of mobility of resources (labor and capital) between industries and between rural and urban areas.
4. The degree of mobility of capital to and from the rest of the world.
5. The presence of alternative technologies of production.
6. The determination of savings and the allocation of investments (new capital) between industries.
7. The potential different applications of the proceedings of environmental taxes by the public sector.

Items 2, 3 and 4 refer to the fact that there may be fundamental differences between short-run and long-run appraisals of costs and benefits. Most models focus on the allocation of resources assuming that the economies are in a long-run equilibrium and thus underestimate the short-run costs faced by economies and policy makers.

Additionally, changes in the elasticities of substitution could affect the size of the estimated effect of carbon taxes. Though that could be relevant for the appraisal of costs and benefits, the more dramatic case would be a reversal of signs, and that result in general is observed when the structure of the model is modified in more substantial ways.

That reversal will happen, for example, when GDP is expected to increase following the implementation of a policy and instead declines. Could that be observed? In principle yes, if a model assumed that capital were not mobile to and from the rest of the world, and the costs were to fall on factors in inelastic supply. If capital were in fact mobile, it could migrate to reduce the burden of a tax (for example, environmental taxes could reduce the relative remuneration of capital in the domestic country, fostering an exit of firms to the rest of the world and creating a carbon leak problem). This could likewise occur if wages are assumed to be determined in nominal instead of real terms. Were they fixed in real terms, additional taxes would trigger nominal wages increases and in turn reduce employment, with negative consequences for consumption and savings (see Neary, 1985, for a classic discussion of how mobility of capital and the determination of wages can change the results).

Moreover, the presence of unemployment and of rigidities in wages could change the evaluation of the optimal taxes. Optimal taxes on fossil fuels have recently been examined by Golosov et al. (2011) in models of optimal growth inspired by Nordhaus DICE and RICE models; those model assume not only a representative agent with perfect forecasting, but also full employment. However, it is well known that optimal taxes should be modified under unemployment. For example, Ramsey taxes should be corrected, reducing those applied on goods that are labor intensive (see Marchand, Pestieau and Wibaut, 1989, Koskela and Schöb, 2001, and Böhringer, Boeters and Feil, 2005).

The aim of this study is to construct the framework of a small computable general equilibrium model with applications to climate change, and then use that framework to compare the assumptions and expected outcomes of the most important models available in the literature in order to identify what elements they have in common and what are their most important differences.

In the **first part** of the paper we focus on a static model and study how differences in the assumptions can make a difference in estimates of the costs of mitigation when carbon taxes are the instrument. The general equilibrium approach seems appropriate because it will help to estimate costs to economies in terms of distortions, taking into account that expenses in mitigation can be remuneration to factors of production and therefore do not necessarily imply an economic cost.

As previously noted, emphasis will not be placed on the data. Instead, the aim will be to highlight similarities or differences in terms of, for example, capacities of substitution, presence of unemployment and rules of adjustment of wages, implicit mobility of resources, rules of determination and allocation of investments, and closure of external and fiscal balances.

To illustrate the analysis with quantitative estimates, we examine the impact on six economies of Latin America and the Caribbean of the application of taxes on the carbon content of goods and services, using CGE models. The models were constructed for Argentina, Brazil, Chile, El Salvador, Jamaica and Peru, and the content of carbon of their productions was estimated using available information from the Intergovernmental Panel on Climate Change (IPCC).

A discussion of the characteristics of CGE models can be found in Wing (2004), who discusses the use of mixed complementary methods that are applied in our case and in Chisari, Maquieyra and Miller (2012) for the case of Latin American and Caribbean economies. In the latter, there is a full description of the analytical structure of the models used in this paper, as well as a presentation of the corresponding Social Accounting Matrix for every country and of the computational code.

Taxes are one of the main instruments for giving private agents incentives to protect the environment. Though other alternatives have been proposed, it is highly probable that taxes will play a fundamental role in future climate change policies in the future; see Aldy, Levy and Parry (2010). One important reason is that they are more easily administered by the governments of several countries of the region than more sophisticated instruments such as cap-and-trade mechanisms, which could prove highly demanding with respect to the supply of services that their institutions can provide. Moreover, according to Tol (2008), taxes on emissions are the lowest-cost instrument; at the end of this paper, however, we will also discuss also second best possibilities.

To discuss the results, we borrow the useful taxonomy proposed by Brock and Taylor (2004). According to it, emissions can be reduced through three channels: i) the **scale effect**, which takes into account how the scale of activity can change in response to taxes or other incentives; 2) the **composition effect**, which considers modifications in the composition of value added (in terms of share of every activity in the total), reducing the relative share of emission-intensive activities; and finally iii) the **intensity effect**, the reduction of the coefficients of emissions per unit of output as a result of the adoption of alternative technologies.

If a CGE model studies the reduction of emissions following the application of carbon taxes without taking into account the option of introducing new methods of production that are less intensive in emissions, then the reduction of emissions could only be achieved through changes in scale (reduction of GDP keeping the share of every industry constant) or in the composition of value added (changes in the structure of GDP).

The existence of alternative technologies should, at least in principle, be able to aid abatement without changing the economy's industrial structure or changing its scale of operation. It seems unrealistic to assume, however, that alternative technologies can be accessed for free. As will be seen, the presence of sunk capital and the opportunity cost of foreign resources could limit the introduction or the extent of application of a new clean technologies that could change the intensity of emissions per unit of production.[9]

We will explore first the effectiveness of carbon taxes in reducing emissions and their impact on the economy assuming that there is not an alternative technology to those available in the benchmark; in that case, emissions could only be abated via a combination of scale and composition effects. Relative prices will move against the most polluting activities and will induce the substitution of goods and services they produce. The final effect will be a reduction of emissions but also a loss of GDP and of welfare (with factor and personal distributional consequences as well). Secondly, we will compare these results for the economy and for emissions to the case when an alternative technology is present for the most polluting industry in order to appraise the differential emissions and activity levels with respect to the case without technological alternatives. Since the new technology will produce the same good as the old polluting industry, their products are perfect substitutes, and prices therefore will be the same in all markets.

---

[9] The adoption of cleaner technologies can be promoted through market-based incentives such as taxes on older and dirtier technologies, or subsidies. However, those incentives can be costly in terms of performance of the economy or due to the marginal cost of public funds. Moreover, the adoption of new technologies has to be voluntary as a response to market incentives, and it is not clearly established that old methods of production can be replaced rapidly. In fact, installed capacity can be an obstacle to substitution, since old vintage capital can accept reduction of its reward (since it is in inelastic supply). This creates inertial effects that neutralize the expected results of subsidization of new technologies via changes in relative prices.

Thus we shall consider several cases:

- The first will be the application of a tax of 20 dollars per ton of CO2 on every activity depending on its contribution to GHG emissions, and we shall assume that the revenue is collected by governments and spent following the initial distribution of expenses (i.e., we shall assume that every item of expense will keep constant its share in the total of expenditures of the government). The equivalent ad valorem taxes applied are presented in Appendix for each individual country. A 20 dollar tax is not far from the proposal of Hope (2011), who argues that taking into account the cost of damages, the estimate should be of 250 dollars (as of 2012) in the United States and 15 dollars in poorer regions of the world.
- In a second group of simulations we will compare the results of the basic case that assumes unemployment and minimum constant real wages with alternative specifications of the workings of the labor market. We will consider the case of downward nominal rigidity of wages and of full employment and market determination of wages. The results show that under full employment the cost of lower emissions is significantly reduced with respect to the basic case, and this result raises the point that the sensitivity of the results on the conditions specified for the labor market in particular, and of factor markets in general. The presence of distortions and different elasticities of supply of factors plays a relevant role in the quantitative results.
- The third simulation will address the possibility of compensation of the additional revenue with a reduction of other taxes (an equal-yield replacement). In this case, we will explore two cases. The first assumes that all other taxes are reduced proportionally without introducing more “surgical” tax reforms (that could provide greater gains in welfare, for example, when a highly distorting tax is reduced or eliminated). The second case will reduce labor taxes to compensate for additional revenue in order to find evidence of the “double dividend.” Even though this does not represent the pure case, the

idea in this instance is to observe the plausibility of emergence (or not) of a "double dividend"—see, for example, Goulder (1998).[10]

- The fourth case will re-examine our first counterfactual exercise (non-compensated), but it will be assumed that some proportion of total capital of the economy can be more mobile locally and internationally. More domestic capital mobility helps to reduce costs, as expected. On the other hand, when it is assumed that a certain proportion of capital is freely mobile with respect to the rest of the world, costs of abatement are higher for the economy, since capital migrates to regions with higher returns. The simulation is intended to appraise long-run impacts of taxes on the economy, and to obtain some indication of whether the "carbon-intensiveness" of the economy will be reduced when capital migrates. This simulation can be related to the so-called "leakage" problem, though in this case the capital that is allocated to the rest of the world will not necessarily be used in polluting activities.
- The fifth case will consider the possibility that domestic carbon taxes will be accompanied by an increase in the price of exports. That will address, for example, the case when the reform is not made in isolation but in the context of a world program aimed at reducing global emissions. When carbon taxes are applied as the result of an economy's own initiative, the costs of production of domestic goods will grow compared to the rest of the world, exports will lose competitiveness and the external balance will require a reduction of domestic absorption. On the other hand, when prices in the rest of the world are increased because similar taxes are applied in other economies, the negative consequences of domestic cost increases could be compensated. These simulations show the importance of the specification of the behavior of external markets with respect to carbon taxes. It also illustrates the results when the economy is not small with respect to the rest of the world; some Latin American countries, such as Argentina and Brazil, cannot realistically

---

[10] According to Schöb (2003), the weak form of the "double dividend hypothesis" states that tax revenues from a revenue-neutral green tax reform can be used to cut distorting taxes thus lowering the efficiency cost of the green tax reform. The strong form of the double dividend asserts that a green tax reform not only improves the environment but also increases non-environmental welfare.

be considered small economies in terms of agricultural production. Since agriculture is one of their main sources of emissions, taxation of emissions could be to some extent passed through to international prices.

- The last case discussed in this paper will address the problem of substitution of technologies, i.e., the intensity effect. We shall assume that there is an alternative technology for the most polluting sector of production of every economy, one that substitutes domestic capital for capital from the rest of the world, and study under what conditions the new technology will be adopted. The determination of whether the technology will be adopted or not, and to what extent, will be part of the solution of the model.

One relevant finding of the study is that the costs of reducing emissions are not negligible in the majority of cases. There are two main reasons: the state of the labor market and the impact on exports. The costs of carbon taxes are magnified when wages are not determined in the market and when capital is freely mobile with respect to the rest of the world. For example, under a regime of downward inflexibility of real wages, an increase of costs due to taxes also increases nominal wages, which reduces the activity level of firms and total employment. Additionally, domestic goods become less competitive, which diminishes exports (the model assumes that the economies are "small"). Capital flight due to differentials of the rate of return with respect to the rest of the world reinforces the reduction of domestic activity.

Another relevant finding is that the presence of an alternative technology, which competes with the incumbent technology, helps to reduce the costs in a significant way provided it is not too demanding on foreign resources. The probability that a low-emissions technology will be adopted voluntarily will be higher the less stress it puts on the external accounts of the economies.

Thus there are two important fronts on which to appraise the costs of climate change policies. The domestic front involves how wages are determined institutionally or by the market, because additional costs could be passed through to wages and therefore reduce employment (with obvious political consequences). On the external front, well-intended initiatives by individual countries initiatives could be jeopardized by the stress of external accounts, when foreign resources are necessary but costly, by losses of competitiveness when not accompanied by the rest of the world (since a simultaneous move by all countries could help to stabilize relative changes in competitiveness), or by the migration of capital to other regions of the world.

The **second part** of the paper complements this analysis with an intertemporal evaluation using recursive dynamic models that include damage functions. Those functions represent costs for economies in terms of negative shocks to Total Factor Productivity due to climate change. Thus, we include in the model an additional characteristic element of Integrated Assessment Models, and this allows the evaluation of the opportunity costs of inaction.

For these models we consider two alternative cases: i) when emissions of countries are small and therefore their policies are ineffective if the rest of the world continues with business-as-usual, i.e., when their actions to reduce mitigation are ineffective unless they are accompanied by the reduction of emissions from the rest of the world; and ii) when carbon taxes are applied, the country is relevant for total emissions of the world and its policies are imitated by the rest of the world.

The main interesting finding of this second part is that the use of the additional tax revenue becomes relevant. In particular, when investments by the public sector increase the rate of growth, the composition effect will be limited by the scale effect due to the increase of total GDP originating in additional savings by governments. To illustrate this we use a recursive dynamic model applied to Brazil and El Salvador.

The plan of the paper is as follows. The second section will present a synthetic analytical version of the model. Section 2 will be devoted to a discussion of alternative general equilibrium specifications, making reference to models available in the literature. Section 3 will put the analysis in the context of a simplified recursive dynamic model. Section 4 will present the databases and the Social Accounting Matrices for the simulations. Section 5 will present the results for the basic case and for the alternative specifications. Section 6 is devoted to the discussion of the estimated functions of costs of mitigation using taxes as instruments, and Section 7 evaluates the results of two economies (Brazil and El Salvador) in a recursive dynamic model that incorporates costs due to climate shocks and that is closer to an Integrated Assessment Model. Then we shall summarize the main results in Section 8. Complementary information is presented in the Appendix.

2. Simplified Version of Static Model Used to Estimate Mitigation Costs

In this section we present a brief discussion of the basic elements of the model in a simplified version. Let us focus on the basic elements of the model by looking at a simplified version of the computable general equilibrium (CGE) model. Though we have in general two agents in our CGE models, let us assume that there is only one representative household that maximizes utility.

Equation (1) gives the equalization of the subjective rate of substitution with relative prices, corrected by ad valorem taxes, in this case only charged on good 1 (the general model includes several taxes, as well as agents and goods).

(1) $U_1/U_2 = (1+ t_1)P_1/ P_2$

Equation (2) gives the budget constraint. It is assumed that there is only one kind of labor, L_0 (W is the wage rate) but two kinds of capital—fixed and mobile—between industries. There is one unit of specific capital in each industry, and its prices are indicated by π_i (alternatively, this can be interpreted as total profits of the sector with constant returns to scale).

The endowment of internationally mobile capital, owned by the domestic household, is given by K_0 and its remuneration is R^*. At the benchmark the proportion of fixed capital owned by the domestic household with respect to mobile capital is therefore $2/K_0$ (in fact, this parameter can be unobservable and uncertain).

(2) $P_1C_1 (1+ t_1) +P_2C_2 = WL_0 + R^*K_0 +1\ \pi_1 + 1\ \pi_2$

Equations (3) to (6) give the definition of profits for sector 1, the production function, and the optimal benefits first order conditions, respectively. The price received by producers is net of expenses in intermediate inputs, both domestic and imported (given by a, and α). Imported goods are used as the numeraire. Equations (7) to (10) are the analogous equations for sector 2.

(3) $\pi_1 = (P_1 - P_2a - \alpha)Q_1 - WL_1 - R^*K_1$

(4) $Q_1 = F(L_1, 1, K_1)$

(5) $(P_1 - aP_2 - \alpha) F_L = W$

(6) $(P_1 - aP_2 - \alpha) F_K = R^*$

(7) $\pi_2 = (P_2 - P_1b - \beta)Q_2 - WL_2 - R^*K_2$

(8) $Q_2 = G(L_2, 1, K_2)$

(9) $(P_2 - P_1 b - \beta) G_L = W$

(10) $(P_2 - P_1 b - \beta) G_K = R^*$

Equation (11) represents the budget condition for the public sector; in this simplified case it is assumed that all revenue is used to hire labor (the general model includes purchase of goods, transfers to households, investments, and net changes in the financial result).

(11) $WL_g = t_1 P_1 C_1$

Equations (12) to (15) are the equilibrium market conditions. The first includes exports, x; the third determines unemployment, Un, and the last gives the equalization of demand and supply of mobile capital.

(12) $C_1 + bQ_2 + x = Q_1$

(13) $C_2 + aQ_1 = Q_2$

(14) $L_1 + L_2 + L_g + Un = L_0$

(15) $K_1 + K_2 + K_m = K_0$

Equation (16) fixes the price of good 1 at the level given by the rest of the world because it is a tradable good (this is the case of a small economy).

(16) $P_1 = P^*$

Equation (17) represents nominal wages determination as a weighted average of prices of tradable goods, non-tradable goods and imports (it is assumed that the price of imports is 1).

(17) $W = \gamma_1 P_1 (1+t_1) + \gamma_2 P_2 + \gamma_3 1$

In equation (18) we define imports, limited to those for industrial uses, which in this simplified version does not include imports of final goods (the CGE model includes imports of final and intermediate goods).

(18) $\alpha Q_1 + \beta Q_2 = m.$

The 18 unknowns are: P_1 C_1 P_2 C_2 W π_1 π_2 L_1 L_2 Un K_1 K_2 Q_1 Q_2 L_g m x K_m.

The taxes in the computed model are for the year 2015. Even under wage indexation for all countries condition (17) is no longer operative, for capital growth surpasses population growth and all unemployment is absorbed.

The role of carbon taxes in approaching Pareto optimality depends on the initial tax structure of the economy. For example, for the economy presented above, a new ad valorem tax t_2 charged on final demand for the second good could reduce losses due to distortions rather than increase them (when $t_2 = t_1$).[11]

The net result in terms of emissions depends on carbon inter-industrial transactions. For example, let us assume that total emissions can be written as

$$EM = m_1 Q_1 + m_2 Q_2.$$

The coefficient m_i stands for the emissions of GHG per unit of total product. Then there will be three separate effects when we follow the taxonomy provided by Brock and Taylor (2004):

- *The scale effect*, given by movements along a ray defined by $Q_2 = s\, Q_1$, where s is a positive number. Then $dEM/dQ_1 = m_1 + m_2 s$.
- *The intensity effect*, which depends on the emissions per unit of production, for example $dEM/dm_1 = Q_1$. The intensity effect could be the result of the substitution of new technologies for old ones.
- *The composition effect*, which depends on the movement of the economy along the frontier of possibilities of production $Q_2(Q_1)$, and thus $dEM/dQ_1 = m_1 + m_2 Q_2'(Q_1)$.

Our computable models explore all those effects, in general equilibrium, and therefore relative prices will determine the net result in terms of emissions, but taking into account total emissions through input-output relations. For example, per unit of final demand in the simplified model the carbon footprint will be given by:[12]

$$EM(C_1 = 1, C_2 = 0) = (m_1 + am_2)/(1 - ab),$$

$$EM(C_1 = 0, C_2 = 1) = (bm_1 + m_2)/(1 - ab).$$

---

[11] This would be a case of “double dividend” in the weak sense in terms of Zhang and Baranzini (2000).

[12] It is assumed that imports do not contain carbon.

Therefore, the direct coefficients do not necessarily identify the products that are more intensive in the use of carbon.

We explore the consequences of determining domestic taxes given total or partial indexation of wages with parameters γ_i and the relative share of mobile capital in the total. In this example we approximate that proportion by $2/K_0$ (when the initial prices in the benchmark are all equal to one, a hypothesis regularly adopted in computed general equilibrium); this is an uncertain parameter and its actual value can produce differences between the expected impact of policies and its real effect. The degree of capital mobility was calibrated in all models to replicate the rate of growth observed empirically[13] (i.e., the model is validated using the capital mobility parameter).

There is also the potential threat of the application of carbon taxes, based on products' presumed CO2 content. In our simulations, as revenue is collected by the public sector, but if it were collected by the rest of the world there would be significant differences, as those taxes would be equivalent to reductions in the prices of exports.

3. Moving towards an Integrated Assessment Model

Following Dell, Jones and Olken (2014: 782-83), "Integrated assessment models combine information about human behavior and climate systems to make predictions about future climatic change and its consequences. IAMs used for economic policy analysis typically include four broad components: 1) a model projecting the path for greenhouse gas (GHG) emissions, 2) a model mapping GHG emissions into climatic change, 3) a damage function that calculates the economic costs of climatic shocks, and 4) a social welfare function for aggregating damages over time and potentially across space."

Thus, the study of the costs of mitigation has to be complemented with an impact factor that takes into account the effects on the economy of the accumulation of GHG. This will give the economy the necessary trade-off between sacrificing resources in mitigation or accepting loss of productivity due to climate change shocks.

---

[13] Fullerton, Lyon and Rosen (1983) suggest taking into account capital mobility when using tax policy choices to illustrate and investigate the more general problem of uncertain parameter values in models devising to evaluate policy choices. Koskela and Schöb (2000) state that, according to conventional wisdom, internationally mobile capital should not be taxed. Frankel (1992) points out that there are at least four distinct definitions of perfect capital mobility.

To understand how an IAM works, let us consider the following simplified version of a recursive dynamic model. In this case, we assume that there is only one good in the economy produced using the production function $F(K_t)$ where K_t is the stock of capital of the economy. Notice that we are assuming that capital is the only factor of production, while the general model allows substitution with labor and considers different types of capital, and also that the production function stands for total production, not per capita production. This is necessary because what count are total emissions, not per capita emissions. The stock of capital in period t+1 will then be given by:

$$(19)\quad K_{t+1} = s\theta(S_t)\, F(K_t) + (1 - \delta)K_t - cm_t^2$$

where s is the savings propensity of the economy, θ is a function that represents shocks due to climate change (assumed to be one when there is no shock and 0 in an extreme situation). A higher accumulation of GHG in the atmosphere, S_t implies a reduction of TFP (i.e., $\theta'(S_t) < 0$). Parameter δ is the rate of depreciation of capital and cm_t^2 stands for an approximation of the costs of mitigation m_t, as estimated with the static CGE models described in the previous section (it will be seen below that the quadratic approximation is realistic).

The evolution of the climate shock is determined by:

$$(20)\quad S_{t+1} = (e_{RW} - \delta_{GHG})\, S_t + \gamma[F(K_t) - bm_t]$$

where δ_{GHG} is the depreciation of the shock due to natural absorption of the stock of GHG in the atmosphere, e_{RW} represents the rate of growth of emissions due to the rest of the world as a proportion of the stock of GHG, γ stands for emissions per unit of output net of reductions due to mitigation, and b is a parameter that represents the effectiveness of mitigation.

The first part of the paper deals with the construction of the function cm_t^2 using CGE models. The estimate of costs for the economy depends on the instrument used. The instrument chosen for mitigation are taxes in our estimates.

Taxes help to reduce emissions via a reduction in the scale or composition of the economy. This will determine the level of net output $\gamma[F(K_t) - bm_t]$ computed for emissions.

The costs of mitigation could also depend on the presence or absence of alternative technologies of production. The presence of alternative technologies could change the form of the aggregated production function $F(K_t)$ or modify parameter γ. The impact damage parameter

θ_t is estimated using information on the expected evolution of temperature, expected to be approximately 3°C over the next 50 years.

The previous equations do not specify how m_t is determined or through which instrument it becomes operative. One way is to assume that a given \$20 tax per Ton of CO2 emitted is used. In the second part of the paper it will be assumed that the tax is not constant but determined to compensate for negative shocks of climate change; we evaluate then the case of myopic economies that increase taxes when shocks are strong and reduce them when shocks are small. Though the determination of this tax is not optimal, it helps to illustrate how complex political processes could react to climate shocks spontaneously, without a plan, and how that will influence the performance of the economies and total emissions. In a dynamic optimal model, the tax would be determined taking into account the intertemporal alternatives open to the economy, given the rate of discount, and with a forward-looking strategy given the expected evolution of S_t. That is not our case; instead, the recursive dynamic model used for the simulations does not assume the knowledge of equation (20).[14]

4. Strategy for Estimating Cost of Mitigation Using Taxes and Social Accounting Matrices

The country models were disaggregated to capture the workings of the relative prices, but not so much as to lose the big picture of their impact on the economy and its main macroeconomic indicators. One-good macroeconomic models might skip environmental issues as they minimize changes in the structure of the economy[15] due to permanent modifications of relative prices.

---

[14] In a dynamic optimal model, the proportion of GDP that is saved would be determined to take advantage of intertemporal substitution opportunities, of course influenced by the social rate of discount. This is not necessarily the case for the recursive dynamic model. However, representation by a recursive dynamic model helps to highlight the relevance of s for the evolution of emissions, since the chosen instrument of mitigation could modify s. In fact, our results will show that for some economies it is possible that taxes could increase savings and investments, and therefore growth, when the government's propensity to save exceeds the propensity of private agents. Thus, the intended reduction of emissions of one period will be neutralized by increasing growth in subsequent years. An additional interesting distinction is between small and big economies from the point of view of emissions. The first case is one for which γ is relatively small with respect to e_{RW}. In that case the efforts of the small economy will probably be ineffective in reducing total emissions, and hence will not be able to prevent reductions of TFP. The second case is one in which the economy is relatively big and therefore its total emissions could count toward reducing expected climate shocks. This case is more relevant for optimal dynamic models, but could also have some effect for the case of taxes that are passively adjusted to climate shocks.

[15] Brock and Taylor (2004) emphasize the role of changes in the structure of the economy.

On the other hand, large-scale CGE models add up many interactions, making it very difficult to disentangle causalities; moreover, they require a large amount of data. Between these extremes, medium-size models can help to capture the relevance of changes of structure as well as provide a transparent initial appraisal of the main costs and benefits for economies. Of course, one shortcoming is that some specific shocks or policies might require more detail, but that objection can be overcome with appropriate planning of scenarios.

The strategy was then to consider CGE models with six or seven sectors of production and two representative households for every one of the five economies of LAC considered here: Argentina, Brazil, Chile, El Salvador and Jamaica.[16] Those economies have different structural characteristics, face different problems and are in different stages of development.

The demand sides were modeled through two representative households (except for Jamaica), a government, and an external sector. Households buy or sell bonds, invest, and consume in constant proportions (Cobb-Douglas) given the remuneration for the factors they own (and the government transfers they receive). The choice of the optimal proportion of the consumption good is obtained from a nested production function in the utility function through a cost-minimization process.

Government is represented as an agent that participates in markets for investments, consumes, and makes transfers to households and has a Cobb-Douglas utility function; its main source of income is tax collection (though it also makes financial transactions through the bonds account). The rest of goods are taken as complementary, and the elasticity of substitution between them is zero. Therefore we have a Cobb-Douglas utility function attributed to the government; the choice was motivated by the property of the Cobb-Douglas function of leaving constant the share of every kind of expenses in the total, which seemed to be a neutral way of modeling the behavior of the government. Thus it is assumed that each dollar of revenue is spent on different factors and goods in the same proportion as in the benchmark. The use of the utility function helps to take into account the provision of non-rival goods by the government; an alternative method would be to distribute the proceedings of carbon taxes among households.

For private agents, welfare changes are calculated using the Equivalent Variation, and the same measure is used for the public sector. Our interpretation is that this would represent a monetary proxy of changes in society’s welfare resulting from modifications in the availability

---

[16] In the case of Jamaica the information available permitted only one representative agent.

of goods and services provided by the public sector (e.g., education, health and defense). The simple change of revenue would not take into account changes in prices of goods, services and factors, and the Equivalent Variation instead helps to provide an estimate of those changes.

For the basic simulation, the economies were assumed to be small with respect to international markets. The rest of the world buys domestic exports and sells imports, in addition to making transactions of bonds and collecting dividends from investments. All social accounting matrices were modified to assume that the economies were in equilibrium in their *trade balances* (i.e., exports value equalized to imports value, except for payments of dividends to shareholders abroad). This means that it would not be possible for economies to finance through either the emission of bonds or external debts that require the repayment of interest or principal. However, it was assumed that dividends are paid abroad on capital owned by the rest of the world and used in production.

With respect to the supply side, the production function in each sector is a Leontief function between value-added and intermediate inputs: one output unit requires x percent of an aggregate of productive factors (labor, non-mobile capital, mobile capital, and land) and $(1–x)$ percent of intermediate inputs. The intermediate inputs function is a Leontief function of all goods, which are a strict complement in production. Instead, value-added is a Cobb-Douglas function of productive factors. Private savings, public savings and foreign savings are totaled to finance investments.

The CGE models have all the basic properties of the Walrasian perspective, and it is numerically solved using the GAMS/MPSGE program.[17] Prices for every period are computed to clear all markets simultaneously. The models then allow relative prices to have a role in the adjustment and growth of economies; instead of having only a composite good and analyzing macroeconomic performance, the model estimates changes in relative prices that influence the path of growth through reallocation of resources leading to modifications of the structure of the economy, income distribution and total emissions. In other words, total GHG emissions depend on the intensity of emissions of every industry and on its level of activity, and changes in relative prices in turn modify the levels of activity and the total emissions of an economy, providing more detailed information on shocks and on unintended effects of policies.

---

[17] The solution of the model is obtained using the representation of General Equilibrium and using the Mixed Complementarities Approach. The model is developed in the environment of GAMS/MPSGE. At present, it can be used in interface with GAMS.

However, when keeping the dimensionality of the model limited we are able to understand better the causality and to re-engineer the simulation exercises in order to have transparency of data and procedures. It is true that sometimes there are losses in terms of the detailed and specific knowledge that environmental policy many times demands, but there are gains in terms of the appraisal of relevance for the economy (a shock or policy's impact as a share of GDP, for example, and how many scarce resources should be devoted to that shock or policy) and hence utility for the policymaker.

Even though growth is taken into account, the model belongs to the set of dynamic recursive models, and not that of optimal growth with a representative agent. Growth is the result of the savings of agents that make decisions according to current rates of return of capital and do not necessarily take into account future returns.

The basic data for the model were organized in a social accounting matrix (SAM). As is customary in applied general equilibrium analysis, the model is based on economic transactions in a particular benchmark year. Benchmark quantities and prices—together with exogenously determined elasticities—are used to calibrate the functional forms.

One difference between the version presented above and the computed models is that some of the taxes on CO2 were charged directly on use or demand for the good or service, rather than on production of the good; see Davis and Caldeira (2010) for results on total CO2 emissions when this differentiation is used. In terms of these economies it might only make differences for export performance; we also studied the application of taxes on the CO2 content of exports, to be discussed in a following paper

The construction of the data set, mainly the SAMs, and the problems that are addressed, or the policies that are considered here, are examples of what can be done with CGE models and how they can help to orient policy but not necessarily policy recommendations; they are instead intended to be illustrations. The results of the simulations allow us to learn about impacts on GDP, industrial activity, emissions and welfare, an exercise enriched by the variety of countries studied here. In addition, the model and the program used (GAMS/MPSGE) are flexible enough to be used for specific cases. A more detailed discussion of the construction of the country SAMs can be found in Chisari, Maquieyra and Miller and (2012).

5. The Application of Carbon Taxes

In this section we present the results of our simulations, focusing on some synthetic indicators. The cases of Compensated changes in taxes, a Non-Compensated tax on emissions of 20 dollars per Ton of CO2 on every activity depending on its contribution to GHG emissions,[18] and a Compensated tax increase (one that leaves government welfare constant by reducing all other taxes in the same proportion) are indicated by C and NC.

We focus our evaluation in some selected indicators and in the implicit cost of reducing 1 percent of GHG in terms of percentage of GDP (i.e., GDP/GE) and do not present the results in terms of welfare of the rich and the poor, or activity levels of individual industries. This information is available from the authors upon request.

A key variable is the cost of lowering emissions, which estimates how much does it cost to the economy to cut 1 percent of emissions in terms of percentage of GDP. Table 1 below presents the main results of basic simulation that assumes a tax of 20 dollars per Ton of GHG. It can be seen that the basic model assumes unemployment, no mobility of capital with respect to the rest of the world, no compensation of taxes, constant prices for exports and imports and downward inflexible real wages (minimum constraint). Several other simulations are compared to these basic cases; the taxonomy and differences between models are presented in Table 2. Table 1 shows changes in GDP and in exports, the level of the rate of unemployment, the change of CO2 emissions, the revenue obtained with carbon taxes in terms of GDP and the average cost of lowering emissions (the ratio of change in emissions to change in GDP, i.e., the average cost of reducing emissions 1 percent).

Table 1. Basic Simulation

		Argentina	Brazil	Chile	El Salvador	Jamaica	Peru
Model 0	GDP	-2.43	-3.26	-0.49	-1.15	-1.22	-0.11
	Exports	-1.55	-3.50	-2.73	-1.21	-3.65	-1.36
	Unemployment rate (av.)	12.16	12.57	6.34	7.72	11.17	7.29
	CO2 Emissions	-7.23	-8.63	-1.27	-6.01	-4.31	-7.43
	CC Taxes/GDP	1.93	1.30	0.74	0.99	1.38	0.94
	Cost of Lowering Emissions	0.34	0.38	0.39	0.19	0.28	0.01

---

[18] See, for example, Bosetti et al. (2011).

Table 2. Taxonomy of Models

	Wage	Unemployment	Domestic capital mobility	International capital mobility	Compensation
Model 0	Real	Yes	Calibration	No	No
Model 1	X	No	Calibration	No	No
Model 2	Nominal	Yes	Calibration	No	No
Model 3	Real	Yes	90% for all countries	No	No
Model 4	Real	Yes	Calibration	Yes	No
Model 5_0	Real	Yes	Calibration	No	Yes
Model 5_1	X	No	Calibration	No	Yes
Model 5_2	Nominal	Yes	Calibration	No	Yes

In the basic case, MODEL 0, there are important reductions in CO2 emissions. This model assumes that wages are downward inflexible in real terms, that the additional revenue obtained by the government is not compensated with reductions in other taxes, that capital is not mobile to the rest of the world and that there is not an alternative technology to the one in use. Carbon taxes help to reduce CO2 emissions through two channels: a scale effect, i.e., via a reduction of GDP, and a composition effect, i.e., a reallocation of resources within economies (there are reductions of activity levels in certain industries, mainly agriculture or those intensive in the use of energy). Economies thus become less intensive in emissions (as shown by the Kutznets index, not shown here). Thus, even when there are not alternative technologies, the economies tend to become less emission-intensive simply by changing the allocation of resources. However, carbon taxes are costly in terms of GDP: for Argentina, Brazil and Chile the costs of reducing emissions by 1 percent are in the range of 0.34 percent to 0.39 percent. Those costs are lower for El Salvador and Jamaica, and surprisingly still lower for Peru (with a very small GDP loss of 0.01 percent).

5.1 Implicit Cost of Reducing Emissions: The Workings of the Labor Market

Table 3 shows that the effect of carbon taxes is important for GDP and emissions in almost all the countries of the group under analysis, though it is more important for Argentina and Brazil and almost without significance for Peru. Those costs, however, become much smaller under full employment (Model 1).

Table 3. Carbon Taxes and the Labor Market

		Argentina	Brazil	Chile	El Salvador	Jamaica	Peru
Model 0	GDP	-2.43	-3.26	-0.49	-1.15	-1.22	-0.11
	Exports	-1.55	-3.50	-2.73	-1.21	-3.65	-1.36
	Unemployment rate (av.)	12.16	12.57	6.34	7.72	11.17	7.29
	CO2 Emissions	-7.23	-8.63	-1.27	-6.01	-4.31	-7.43
	CC Taxes/GDP	1.93	1.30	0.74	0.99	1.38	0.94
	Cost of Lowering Emissions	0.34	0.38	0.39	0.19	0.28	0.01
Model 1	GDP	-0.10	-0.66	0.19	-0.45	-0.39	0.03
	Exports	1.18	-0.44	-1.88	0.05	-2.29	-1.21
	Unemployment rate (av.)	x	x	x	x	x	x
	CO2 Emissions	-5.83	-6.18	-0.70	-5.48	-3.62	-7.33
	CC Taxes/GDP	1.92	1.31	0.74	0.98	1.38	0.94
	Cost of Lowering Emissions	0.02	0.11	-0.27	0.08	0.11	0.00
Model 2	GDP	-2.84	-4.50	-0.86	-1.02	-1.37	-0.26
	Exports	-2.03	-4.96	-3.17	-0.96	-3.90	-1.53
	Unemployment rate (av.)	12.56	14.80	6.55	7.56	11.46	7.91
	CO2 Emissions	-7.47	-9.79	-1.58	-5.92	-4.43	-7.54
	CC Taxes/GDP	1.93	1.30	0.74	0.99	1.38	0.94
	Cost of Lowering Emissions	0.38	0.46	0.55	0.17	0.31	0.03

The models can be considered as extreme cases of labor supply elasticity to wages. The case of unemployment and real wages could correspond to the perfect elastic case, while the full employment model represents the case of inelastic supply, since the endowment of labor is given and there is no demand for leisure in the counterfactual exercises.

To study how the workings of the labor market influence the result, we conducted a simulation assuming that in Model 1 there is no unemployent and labor supply is inelastic and in Model 2 that wages are downwards inflexible in terms of foreign currency (basically, with respect to tradeable goods). It can be seen that the costs of lowering emissions are smaller when there is full employment and labor supply is inelastic; they even become benefits for Chile.[19]

---

[19] The result for Chile could be due to the implicit correction of a distortionary tax structure. The economy is open to the rest of the world and the introduction of carbon taxes could implicitly tax imported energy, thus reducing the differences with taxes applied to domestic activities.

Costs tend to be higher when wages are nominally fixed (compare Model 0 with Model 2). In this case, fixed wages in nominal terms means that wages are fixed in terms of foreign currency. This is consistent with the fact that the adjustment of exports (reduction) is still higher when domestic costs are downward inflexible.

Under full employment the costs of the carbon taxes is reduced and the cost of lower emissions is very small, and in some cases it becomes a net benefit. In fact, Chile and Peru give some evidence of the strong form of the double dividend, indicating that a green tax reform not only improve the environment but also increases non-environmental welfare. Although though the reduction of emissions is less effective, all the countries exhibit important declines in the share of carbon-intensive activities (again except for the case of Chile). Probably carbon taxes are correcting the distortions determined by other taxes, and that would explain the existence of negative costs (benefits) of application of taxes.

Under full employment, the scale effect is lower and the economy must react to changes in taxes via a reallocation of factors. The table shows that the composition effect is relatively big, and even when the scale effect is limited, there is room for reduction of emissions via a change in the share of industries in the economies. For example, when the economy of Brazil reduces GDP 0.66 percent emissions are reduced 6.18 percent (compared with 8.63 percent under unemployment, the composition effects seems very relevant). A similar pattern is found for the other economies.

Thus, the simulation illustrates the relevance of the modelization of the labor market and of the rule of indexation of wages. In fact, Table 4 shows that when wages are downwards inflexible in terms of tradeable goods the reduction of activity of the economies is still higher and the emissions are also reduced, but the net cost of emissions is increased (except for El Salvador). Of course, it should be expected that different elasticities of supply of labor probably will show some sensitivity of the results in the range of the simulations shown here since we considered inelastic supply under full employment, and the other extreme case, with totally elastic supply, resembles our case of downward inflexible real wages.

One important indicator to be taken into account is the reaction of exports. The simulations assume that prices of exports and imports are constant, but the costs of producing domestically the export goods are increasing after taxes. The negative effect on exports is clearly seen when wages are downwards inflexible.

5.2 *Carbon Taxes Replicated in the Rest of the World: The Competitiveness of Exports Matters for the Results and Relaxation of "Small Economy" Assumption*

As mentioned, the decline in GDP is accompanied by a significant reduction in the level of exports, as the increase in domestic taxes increases costs and there is a loss of competitiveness. This implies that exports have to be reduced. Even though there is substitution of domestic consumption goods for imports (not charged with taxes), most imports are modelled as in fixed coefficients with domestic inputs (Leontieff coefficients) and therefore the fall of exports also makes it necessary to reduce activity levels and consequently imports (affecting the rate of growth, since many Latin American and Caribbean economies are importers of capital goods).

To address this last case, we included in the study some additional simulations to evaluate the result of carbon taxes when the economies do not increase carbon taxes autonomously but are instead accompanied by the rest of the world. Table 4 shows the results of assuming that prices of exports also grow by about 1 percent when the domestic policy of applying carbon taxes is replicated by the rest of the world (Model 3.1), when the application of taxes also increases prices of imports by the same percentage (Model 3.2), and finally when prices of exports fall due to sanctions applied by the rest of world when domestic taxes are applied but considered insufficient.

The benchmark scenario is again Model 0 in Table 1.

Table 4. Carbon Taxes and Prices of Exports and Imports

		Argentina	Brazil	Chile	El Salvador	Jamaica	Peru
Model 3.1 (+ PX 1%)	GDP	-2.13	-3.02	-0.13	-0.74	-0.45	0.04
	Exports	-1.91	-4.03	-2.44	0.64	-3.10	-1.76
	Unemployment rate (av.)	11.96	12.37	6.22	7.79	10.52	7.27
	CO2 Emissions	-7.20	-8.57	-1.17	-6.14	-3.77	-7.40
	CC Taxes/GDP	1.94	1.32	0.75	0.99	1.38	0.94
	Cost of Lowering Emissions	0.30	0.35	0.11	0.12	0.12	-0.01
Model 3.2 (+ pX and PM 1%)	GDP	-2.41	-3.26	-0.51	-1.17	-1.29	-0.12
	Exports	-1.52	-3.30	-2.61	-0.56	-3.06	-1.24
	Unemployment rate (av.)	12.15	12.57	6.34	7.90	11.22	7.38
	CO2 Emissions	-7.23	-8.60	-1.26	-6.04	-4.22	-7.42
	CC Taxes/GDP	1.95	1.32	0.74	0.99	1.39	0.95
	Cost of Lowering Emissions	0.33	0.38	0.40	0.19	0.31	0.02
Model 3.3 (- PX 1%)	GDP	-2.72	-3.51	-0.88	-1.56	-1.98	-0.26
	Exports	-1.19	-2.98	-2.93	-3.01	-4.21	-0.96
	Unemployment rate (av.)	12.37	12.77	6.47	7.65	11.82	7.32
	CO2 Emissions	-7.27	-8.68	-1.42	-5.90	-4.85	-7.46
	CC Taxes/GDP	1.91	1.29	0.73	0.98	1.38	0.93
	Cost of Lowering Emissions	0.37	0.40	0.62	0.26	0.41	0.03

The results show that the replication of the policy is helpful in limiting the cost of the domestic policy, but still insufficient to compensate for the significant reduction in the activity level. In addition, much of the gains are lost when prices of imports are increased.

A second interpretation, however, could be given to this exercise. A very usual assumption adopted in CGE models is that economies are “small.” This means that they do not have influence in the determination of their export and import prices, and therefore that there cannot exist any pass-through (even partial) of the costs of their domestic policies to prices in international markets. This is an assumption adopted, for example, in the United States Environmental Protection Agency’s IGEM and ADAGE models (see Goettle et al., 2009, and Ross, 2009, for the U.S. economy).[20]

Model 3.1 could be one of partial pass-through of domestic costs to international prices. Although it is difficult to maintain this assumption for economies like El Salvador and Jamaica,

---

[20] Aldy and Pizer (2009) conduct a statistical analysis and find that a carbon price of $15 could only significantly affect a narrow segment of U.S. industry, mostly energy-intensive sectors.

the importance of Argentina and Brazil in prices of agricultural products could make their domestic policies more relevant for the rest of the world.

Model 3.3 indicates that when the domestic policies are not enough and prices of exports fall the impact on economic activity is worsened. How could that happen? International sanctions or autonomous taxes imposed by the international community on presumed contents of carbon could imply reduction of export prices.[21] This will be a case in which the revenue of the carbon taxes is appropriated by the foreign countries instead of the domestic government.

5.3 Equal Yield Replacement of Taxes: Evidence of Double Dividend

The model consents the possibility of studying the effects of reducing all existing taxes by the same amount collected under the new environmental carbon taxes. Table 5 shows the results of several simulations under different compensations and assumptions.

As can be seen, there is support for the weak form of the “double dividend hypothesis” states that tax revenues from a revenue-neutral green tax reform can be used to cut distorting taxes thus lowering the efficiency cost of the green tax reform.

Model 4 assumes that the additional revenue (obtained from carbon taxes) will be compensated with a reduction of all taxes in the same proportion; this case has to be compared to Model 0. It can be seen that there are not only reductions of the losses, but effective gains for several of the economies. Model 4 shows that the replacement of distortionary domestic taxes with the carbon taxes reduces the magnitude of the losses, and there is reversal of costs into benefits in the cases of Argentina, Chile and Peru.

The presence of distortions helps to reduce the costs of emissions. However, the final results in terms of reduction of emissions are now limited by the expansion of the activity levels increases.

Model 4.1 assumes full employment, Model 4.2 that wages are downward inflexible in nominal (tradable) terms, and Model 4.3 that the taxes to be compensated are labor taxes.

---

[21] See Giordano and Watanuki (2012).

Table 5. Compensation of Carbon Taxes

		Argentina	Brazil	Chile	El Salvador	Jamaica	Peru
Model 4	GDP	0.71	-1.95	0.34	-0.55	-0.92	0.13
	Exports	2.15	-0.85	-1.48	0.87	-1.46	0.05
	Unemployment rate (av.)	9.34	10.36	5.98	7.11	10.29	6.39
	CO2 Emissions	-5.12	-6.99	-0.54	-5.33	-3.08	-6.88
	CC Taxes/GDP	1.92	1.31	0.74	0.99	1.40	0.94
	Cost of Lowering Emissions	-0.14	0.28	-0.63	0.10	0.30	-0.02
Model 4.1	GDP	0.30	-0.56	0.40	-0.35	-0.56	0.04
	X	1.66	0.80	-1.37	1.18	-0.87	-0.05
	Unemployment rate (av.)(n/a)						
	CO2 Emissions	-5.22	-5.67	-0.51	-5.18	-2.79	-6.95
	CC Taxes/GDP	1.92	1.31	0.74	0.99	1.39	0.94
	Cost of Lowering Emissions	-0.06	0.10	-0.78	0.07	0.20	-0.01
Model 4.2	GDP	-0.63	-3.72	-0.47	-0.78	-1.50	-0.19
	X	0.58	-2.96	-2.44	0.42	-2.42	-0.31
	Unemployment rate (av.)	10.65	13.58	6.44	7.38	11.39	7.68
	CO2 Emissions	-5.88	-8.67	-1.21	-5.50	-3.56	-7.12
	CC Taxes/GDP	1.92	1.31	0.74	0.99	1.40	0.94
	Cost of Lowering Emissions	0.11	0.43	0.38	0.14	0.42	0.03
Model 4.3	GDP	5.11	-0.36	1.38	0.37	1.06	1.03
	X	6.95	0.43	-0.73	2.62	1.22	0.49
	Unemployment rate (av.)	3.03	7.33	5.28	6.25	6.56	2.78
	CO2 Emissions	-2.91	-5.58	0.46	-4.80	-2.24	-6.17
	CC Taxes/GDP	1.89	1.32	0.74	0.98	1.38	0.94
	Cost of Lowering Emissions	-1.76	0.06	3.00	-0.08	-0.48	-0.17

There are clear gains of compensation in all cases, but the gains are more noticeable in the case of labor taxes, because there are net gains in GDP for all economies (except for Brazil, which also has very significant reduction in costs). Notice that Model 4.2 is comparable to Model 2, which explains why there are lower losses for Brazil as well when compensation is used. However, the expansion of the economies shows that the performances in terms of emissions are disappointing and that the net result can turn back the initial reduction (as in the case of Chile) and become positive.

Thus, in general there are gains for the economies with this replacement, and they probably depend on the cost of the initial tax structure due to distortions in the allocation of resources. There are also changes in welfare distribution (not shown in the tables). In the case of compensation, rich households do better than poor households (either they gain welfare or face less reduction of their welfare). In general, compensation helps the rich because they pay more taxes and do not receive transfers. When carbon taxes are imposed, as in the case of this paper, their effective rates are assumed to be equal to legal taxes—something that is not necessarily true for other taxes—and are paid by all consumers. This creates additional revenue that helps to reduce all other taxes such as VAT and taxes on labor and capital, which in turn reduces the tax burden on those who consume more and have more labor and capital, i.e., the rich. Using carbon tax revenue to recycle labor income might not be a better policy from poor households' perspective, although it could be the case from the national perspective (including both poor and rich households' average welfare). Thus, the design of compensation matters if one seeks to use the new taxes to meet several objectives. That is, one can reduce some taxes and not others when the additional revenues from carbon taxation become available, for example by establishing exemptions or reducing taxes charged on goods in the consumption basket of the poor. Alternatively, those revenues could be used to reduce labor taxes to cut unemployment, or to limit the cost of capital in a way that fosters investment and growth. In addition, increased funds could be used to increase transfers to the poor, or to increase social spending. There are additional options, the results of which can be explored with our model, which would require further work. As said, compensation helps to reduce losses. There is support for the presence of a double dividend in terms of GDP.

However, except for the case of Argentina, there are still welfare losses for private agents (both poor and rich). Moreover, there are redistributions of welfare that are not necessarily Pareto gains (though that could be possible with subsequent calculations of potential compensations between private agents). In the case of Argentina the reduction of taxes helps the poor, who increase their welfare, and limits the losses of the rich (because there are reductions in labor taxes and VAT, among others).

5.4 Domestic and International Mobility of Capital

When capital is domestically mobile, emissions are reduced still further when compared to the basic case of Model 0 because the workings of the composition effect are stronger. Resources move to industries that are not reached by carbon taxes. Thus, in the long run higher reductions of emissions could be expected. This can be confirmed with the results shown in Table 6 for Model 5.

However the impact of higher mobility of domestic capital between industries on the GDP is not necessarily positive; resources are reallocated to industries that contribute less to GDP and the reallocation produces changes in prices and wages that increase unemployment, as is the case of Brazil, Chile and Jamaica. Instead, some economies have gains from mobility as illustrated by the cases of Argentina, El Salvador and specially Peru, where emissions and GDP show improvements in performance. Higher mobility of domestic capital could depend on the form of capital, its malleability, as well as to regulations and other types of costs of adjustment.

Table 6. Carbon Taxes and Mobility of Capital

		Argentina	Brazil	Chile	El Salvador	Jamaica	Peru
Model 5	GDP	-2.09	-5.51	-2.81	-1.05	-2.96	0.26
	Exports	0.41	-11.15	-6.94	4.88	-6.08	-3.59
	Unemployment rate (av.)	11.84	15.86	7.54	7.56	13.70	5.42
	CO2 Emissions	-13.14	-21.74	-7.47	-7.62	-6.98	-19.77
	CC Taxes/GDP	1.87	1.19	0.68	0.97	1.35	0.83
	Cost of Lowering Emissions	0.16	0.25	0.38	0.14	0.42	-0.01
Model 5.1	GDP	-4.03	-5.18	-1.46	-1.83	-2.24	-0.96
	Exports	-3.29	-11.02	-4.26	1.64	-6.42	-4.52
	Unemployment rate (av.)	12.85	14.42	6.73	7.81	12.00	7.98
	CO2 Emissions	-11.31	-12.20	-2.94	-8.22	-6.93	-10.19
	CC Taxes/GDP	1.90	1.29	0.72	0.97	1.35	0.92
	Cost of Lowering Emissions	0.36	0.42	0.50	0.22	0.32	0.09
Model 5.2	GDP	-0.72	-1.24	0.00	-0.94	-0.85	-0.60
	Exports	0.50	-4.34	-2.53	4.26	-4.01	-3.94
	Unemployment rate (av.)	x	x	x	x	x	x
	CO2 Emissions	-9.34	-7.97	-1.72	-7.69	-5.84	-9.93
	CC Taxes/GDP	1.88	1.30	0.73	0.97	1.35	0.92
	Cost of Lowering Emissions	0.08	0.16	0.00	0.12	0.14	0.06

Models 5.1 and 5.2 evaluate the sensitivity to mobility of capital to (and from) the rest of the world under unemployment and full employment, respectively. The impact of taxes is higher and the costs are increased with respect to the basic case in both cases. Capital flight as result of relative returns can reduce industrial activity levels and make the economy's adjustment to the new taxes more painful. The cases presented show the relevance of taking into account in the analysis the opportunity costs of capital and to what extent the costs of the carbon taxes could be passed to domestic factors in inelastic supply, ameliorating those costs via a reduction of their remuneration.

5.5 Latent Technologies and the Intensity Effect

The effects of taxes on the performance of the economy and the reduction of emissions might be different when a different technology is available to become operative under favorable conditions. Löschel (2002) presents a survey and discussion of taxes' relevance for abatement at lower costs.[22]

The discussion of the presence or not an alternative technology is also of interest when it is considered the difference between bottom-up and top-down models. According to Peterson (2003), bottom-up models disaggregate the polluting sector (energy in her case) and consider specific technologies with both technical and economic parameters, but they neglect the feedbacks in the economy. Top-down models, instead, are aggegated models without a thorough description of technologies.

What we propose to do in this section is to adopt an intermediate approach. We will consider a new technology, but we will emphasizeits use of resources rather than its engineering characteristics, and we will embed it in the aggregated CGE models.

In a very interesting paper, Kiuila and Rutherford (2012) show that the cost of environmental policies could be greatly overestimated when a bottom-up abatement cost technology is not included in the analysis, and the results would require a reduction in demand. In our case, in the absence of intensity effects, their results require a reduction of scale. What they do not consider in their analysis is the possibility that the new technology could be very costly in terms of some resources and could be unaffordable by the economies. Given the

---

[22] The DICE model assumes the existence of a backstop technology that is able to replace the current technology in the future, and that avoids the doom case for the planet.

recurrent crisis of Latin American and Caribbean economies on the external front, we shall assume that the alternative technology is intensive in foreign resources.

Figures 1 to 3 present the results of assuming that carbon taxes are implemented for all sectors, but that there is a latent technology for the most polluting sector of the economy. That technology does not generate emissions, and the main difference with the technology in use is that the specific capital of incumbent technologies has to be replaced by capital from the rest of the world in some proportion. The proportion of specific capital replaced with rest of the world new capital is left to vary between 0 and 1, but in this last case the share of total value added is the same as for the initial capital stock. All other parameters and taxes or subsidies applied in Model 0 are invariable, and therefore the new capital is not overtaxed or subsidized.

We try to capture in this way one main trade-off for industries, which is opting between paying carbon taxes or instead introducing a new technology that has to be imported from the rest of the world and that is costlier. The reason is that the new technology has a given price, while the price of specific capital in inelastic supply could move downwards.[23]

Whole economies similarly face a choice between accepting additional taxes, probably costly in terms of distortions, and increasing stress on their external accounts. What the results show is that for all the economies there is a clear threshold for the share of new capital beyond which the technology is not operative. Figures show the differential impact with respect to the benchmark case Model 0; thus, for example, Delta GDP and DeltaEm show the differential of GDP with respect to the change of GDP in Model 0, and the differential of emissions again with respect to the results obtained with that model. Under evaluation then are the results of taking into account the intensity effect, since Model 0 was focused on composition and scale effects.

The figures also show the variation of the Cost of Lower Emissions (Delta Cost), of the remuneration of specific capital (Delta RR) and of exports (Delta Exports). Delta RR is explored because the introduction of a new technology could be limited by a reduction in the remuneration of specific capital; in general this is not observed because to some extent the new technology uses specific capital and the change in scale of activity supports the price of specific capital. Delta Exports shows that when the new technology is operative, exports are significantly increased for two reasons: on the one hand, it is necessary to compensate the outflow of

---

[23] An alternative would have been to assume that domestic specific capital could be substituted by domestic mobile capital. The observation by Paltsev et al. (2005: 26) on the relevance of malleable capital would be applicable too.

remuneration of capital of the rest of the world and, on the other, because the use of the new technology reduces to some extent the domestic cost after taxes versus foreign costs, after which the relative costs are reversed and the cost of the new technology becomes higher than the additional expense due to taxes.

As said, it can be seen that for low shares of the new capital in total value added there are gains both in terms of GDP as in terms of emissions. In some cases, like Argentina, Brazil, El Salvador and Peru the reductions are very relevant.[24] However, there is a threshold beyond which economies converge to the initial situation.[25]

One lesson from this exercises is that the description of the technologies have to be very detailed not only in terms of the use of the engineering aspects, but also they have to include a description of which are their intensiveness in scarce factors or resources in general.

---

[24] It is interesting that the reduction of emissions due to improvements in agriculture and use of land are not far from estimates of other models; see Rose et al. (2008) and Hertel, Rose and Tol (2008).

[25] Though there are always remaining slight differences because the composition of the endowments of domestic households had to be modified to simulate the new scenarios.

Figure 1. Argentina and Brazil

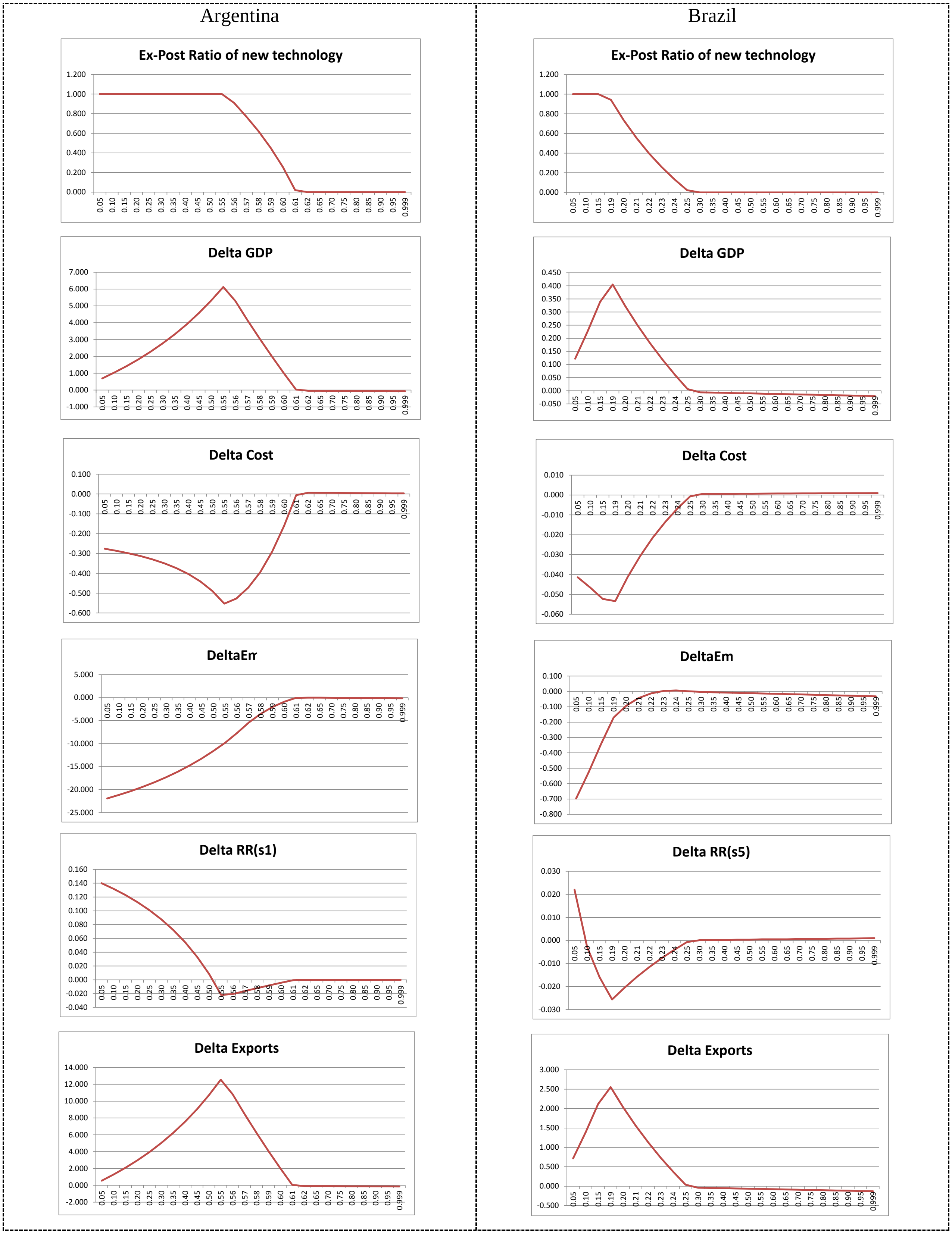


Figure 2. Chile and Jamaica

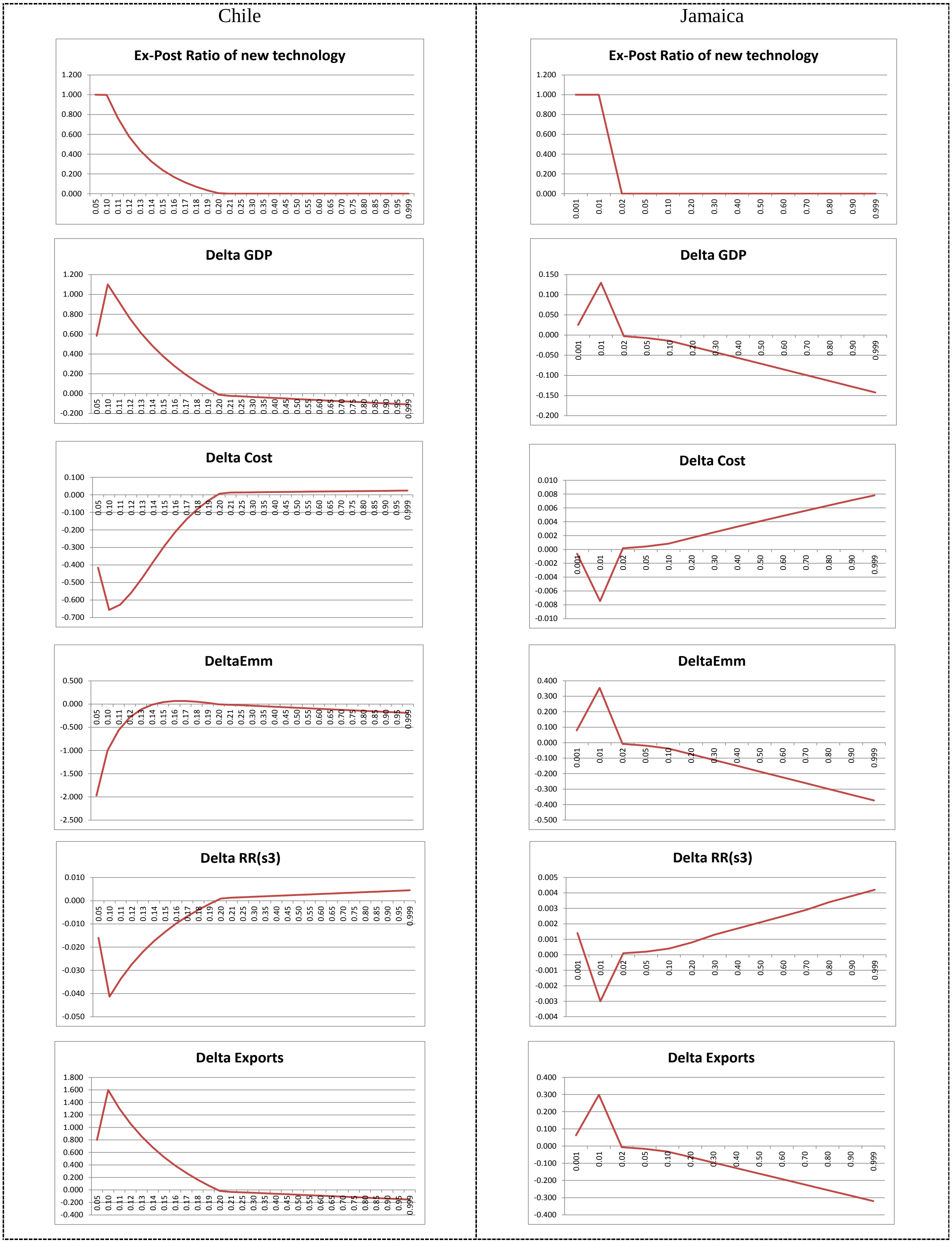
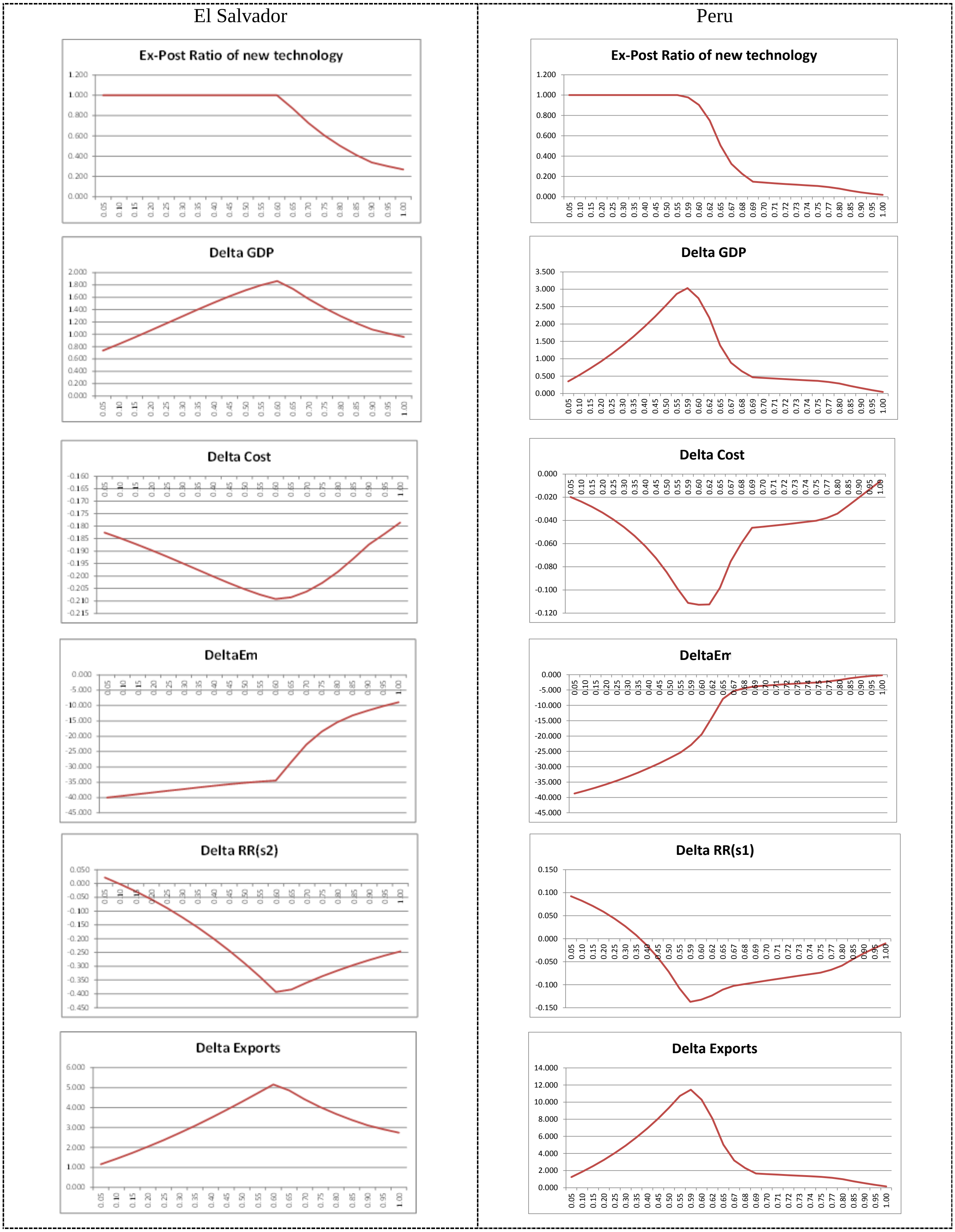


Figure 3. El Salvador and Peru



6. The Cost of Reducing Mitigation Using Carbon Taxes, Second Best Alternative in the Short Run: Idle Capacity and Unemployment

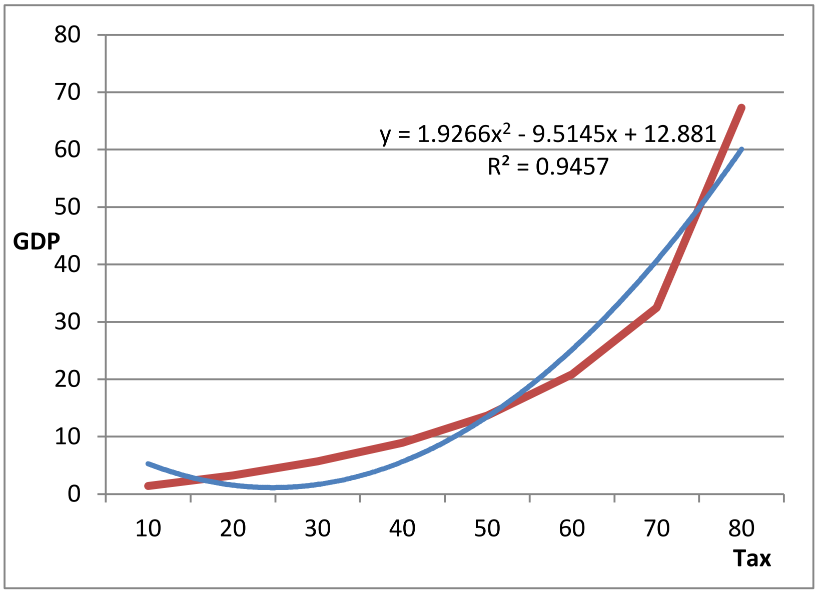
The solutions to the models considered in previous sections assume that carbon taxes are given in ad valorem terms, and that emissions are endogenous. Most of the literature considers carbon taxes as the best instrument to achieve the environmental objectives (see Aldy, Levy and Parry, 2010). One objection to this approach is that under very demanding conditions, it is not possible to be sure that the necessary reductions of emissions could actually be obtained and that the reduction of emissions will be sufficient to prevent climate change shocks.

Most of the approaches also assume conditions of full employment, and we have seen that the short-run costs can be much higher when there is unemployment of resources. This could explain policymakers' reluctance to adopt environmental recommendations based on estimates that assume markets in equilibrium.

Figure 4.1 shows the costs of reducing CO2 emissions in terms of GDP for Brazil, with carbon taxes ranging from US$ 10 per ton to US$ 80 per ton, assuming full employment. The x-axis of Figure 4.2 puts those same costs in terms of percentage of emissions reduction.

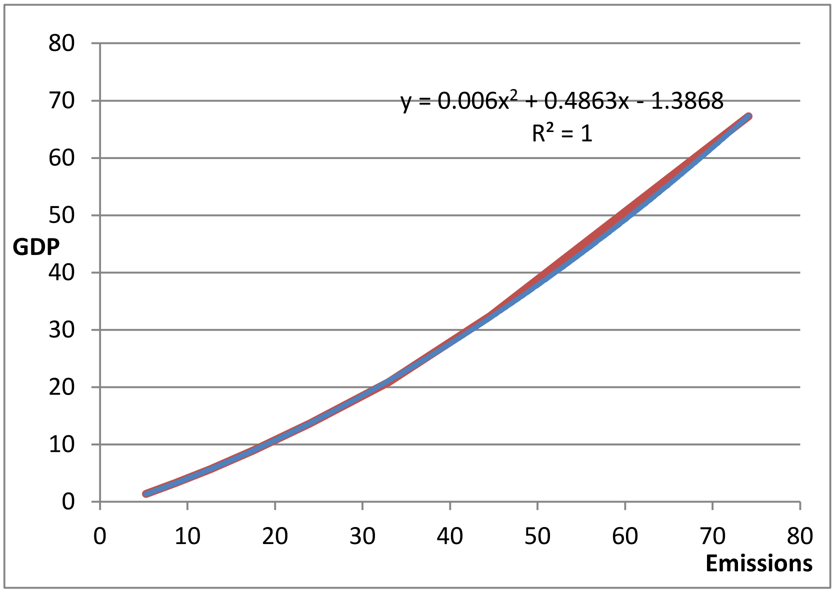
Figures 5.1 and 5.2 are analogous to Figures 4.1 and 4.2, but using our basic case under unemployment and real wages inflexibility. This second case could be interpreted as a short-run pessimistic case. It can be seen that costs of mitigation are increasing, thus the marginal cost of mitigation is positive.

Figure 4.1. Brazil's GDP and CC Taxes



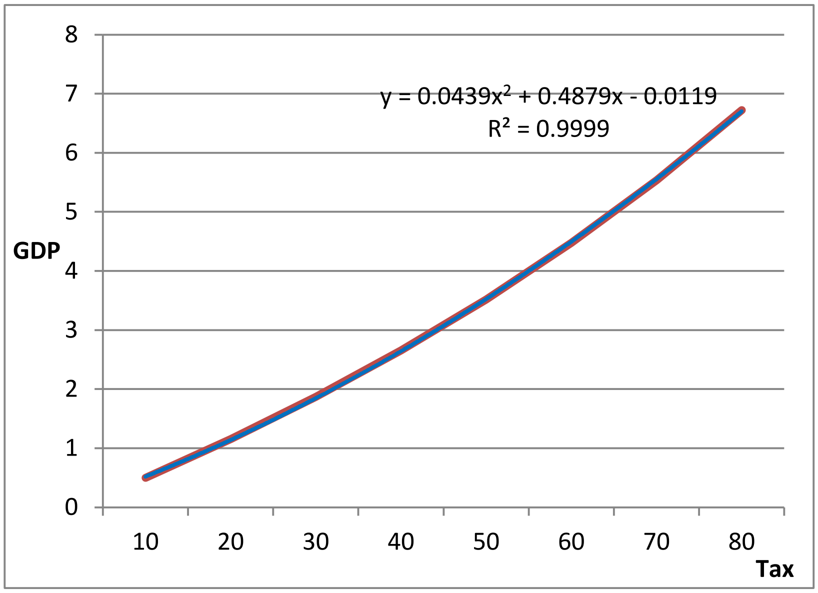
Note: Model 0 in red and quadratic trend in shaped blue.

Figure 4.2. Brazil's GDP and Emissions



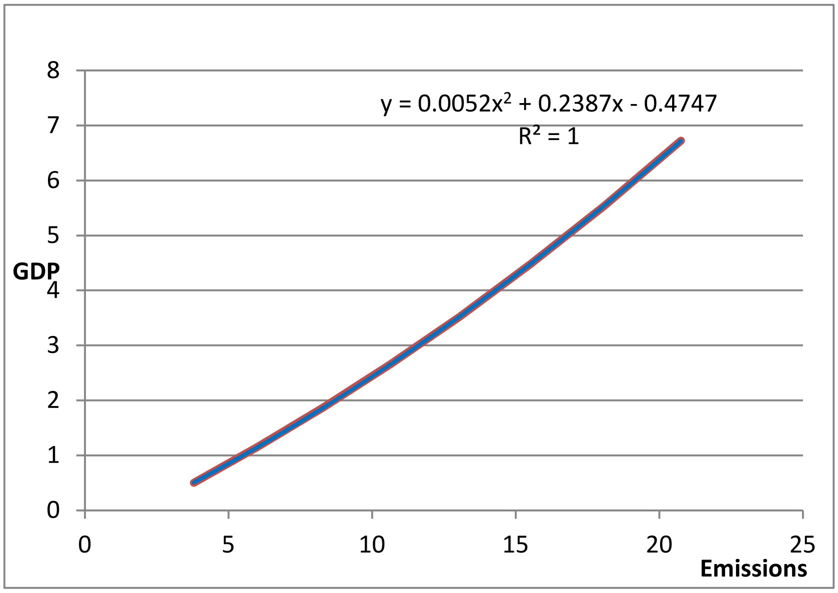
Note: Model 0 in red and quadratic trend in shaped blue.

Figure 4.3. El Salvador's GDP and CC Taxes



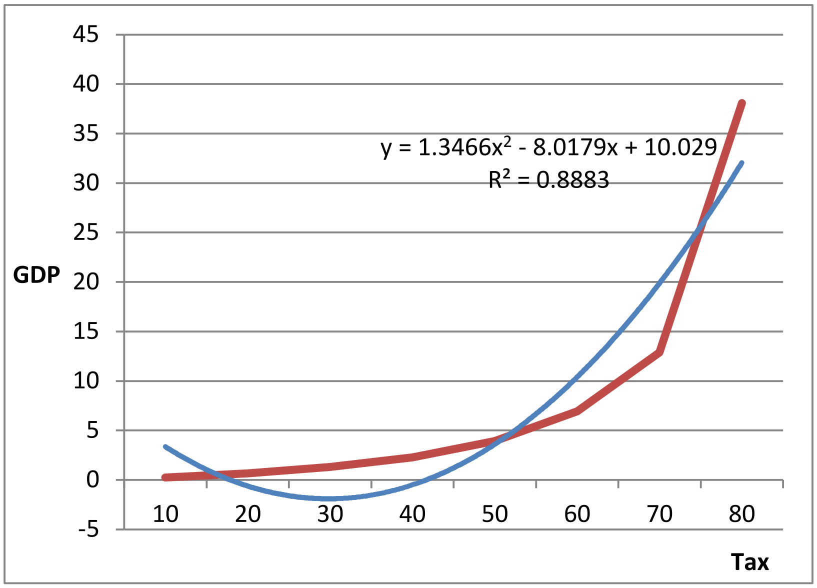
Note: Model 0 in red and quadratic trend in shaped blue.

Figure 4.4. El Salvador's GDP and Emissions



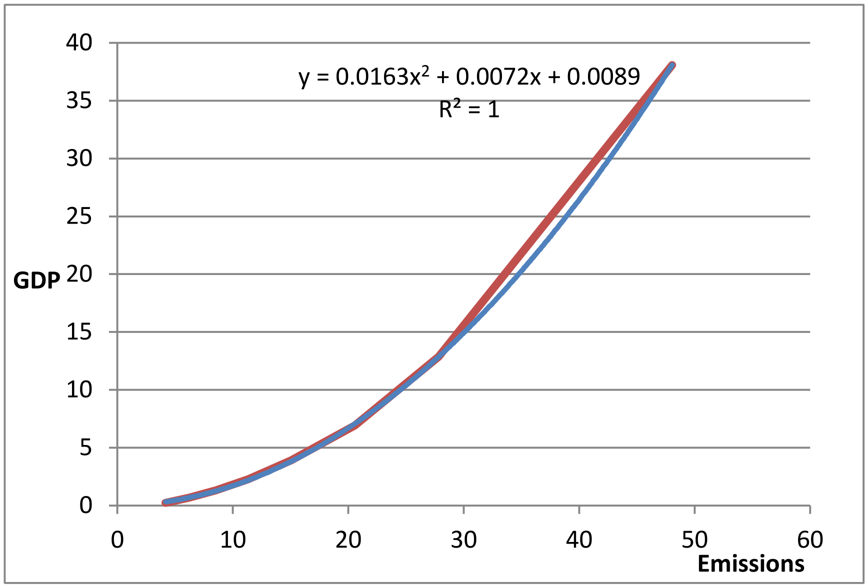
Note: Model 0 in red and quadratic trend in shaped blue.

Figure 5.1. Brazil's GDP and CC Taxes



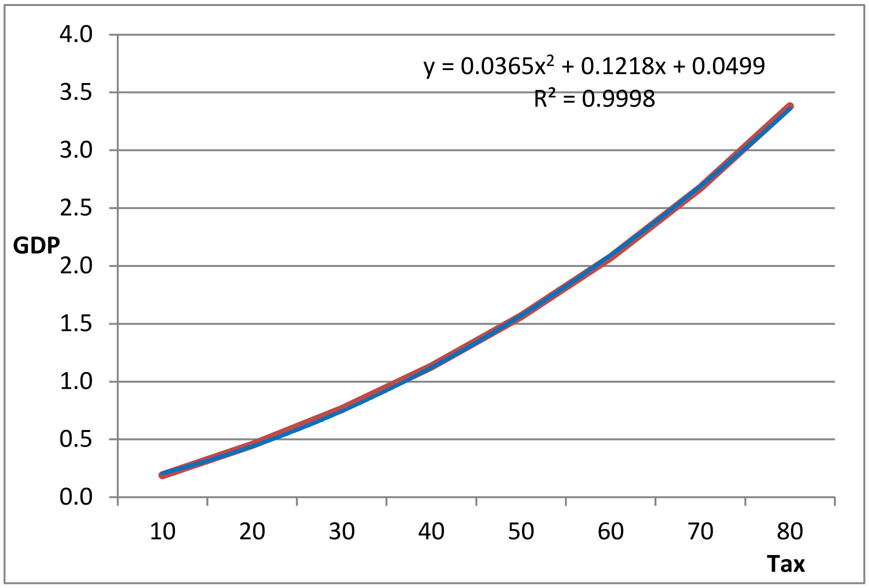
Note: Model 1 in red and quadratic trend in shaped blue.

Figure 5.2. Brazil's GDP and Emissions



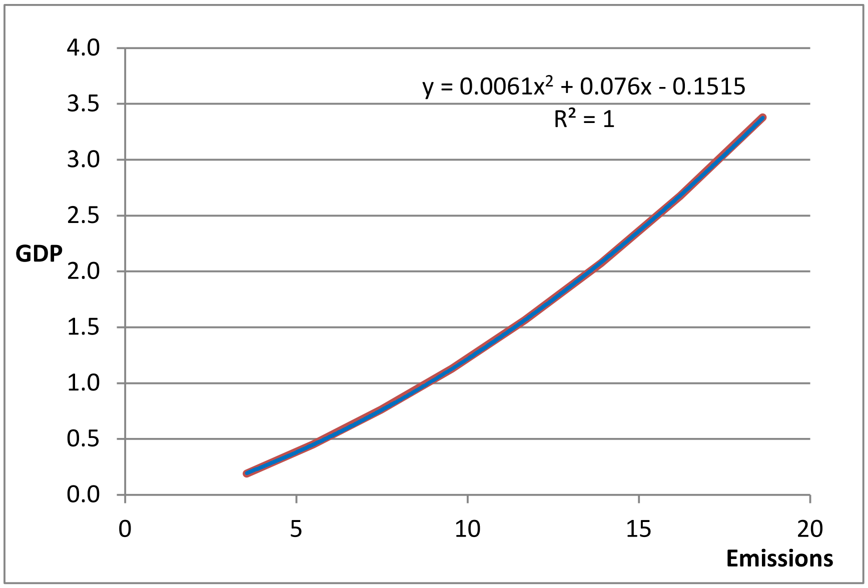
Note: Model 1 in red and quadratic trend in shaped blue.

Figure 5.3. El Salvador's GDP and CC Taxes



Note: Model 1 in red and quadratic trend in shaped blue.

Figure 5.4. El Salvador's GDP and Emissions



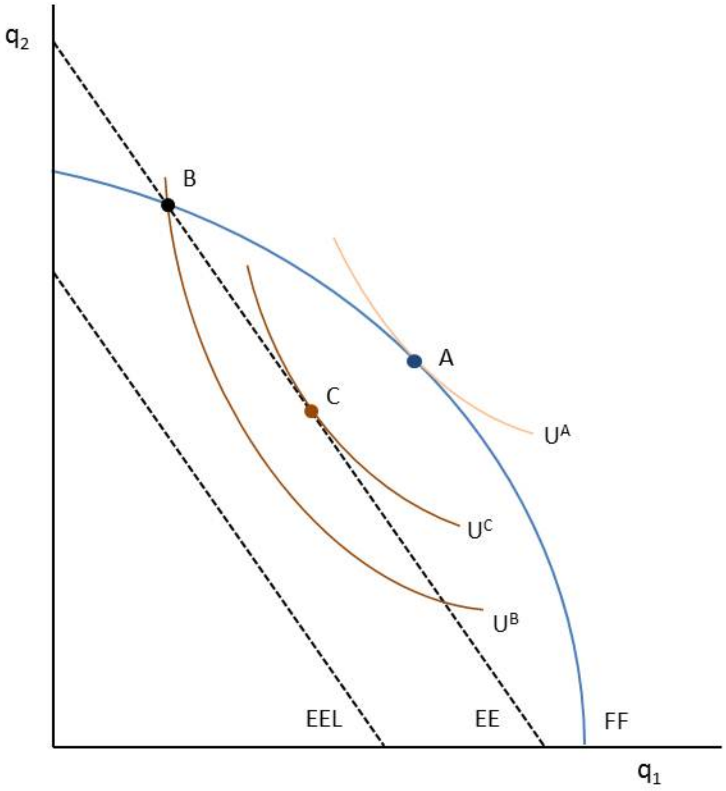
Note: Model 1 in red and quadratic trend in shaped blue.

A different approach would be one that establishes a goal in terms of emissions and endogenously determines the carbon taxes necessary to reach it. This strategy is more difficult to implement and is not widely discussed in the literature, though it is implicitly the strategy in cap-and-trade models; given an emissions reduction target, the price of carbon becomes endogenous.[26]

Beyond specific difficulties of computation, it is possible to give examples that carbon taxes could create a second best situation, and that relaxing some other initial first best conditions could help to increase total welfare.

Figure 6 presents an example. This is the case of a very simple economy that can use its resource to produce goods 1 or 2. FF represents the frontier of possibilities of production. The line EE stands for the total admissible emissions, taking into account the emission coefficients in the production of both goods, and it can be seen that the initial optimal solution A cannot be reached.

Figure 6. Optimal Second Best Solution



---

[26] See, for example, Bergman (1991) and Tchouto (2007).

The application of carbon taxes under full employment could move the economy to point B at a welfare cost indicated by the difference between indifference curves U^A and U^B. However, if the assumption of full employment of resources were relaxed, U^C could be reached and total welfare could be higher than with carbon taxes.

Of course, the unemployment "solution" is not easy to implement, and the limited geometrical illustration and the level of aggregation of the example that considers one representative agent and two aggregate goods are certainly insufficient. However, it suggests two possibilities. The first is that, if the emissions limit is too tight, it will be impossible to meet under full employment; to see this, just displace the line EE towards the origin to EEL. The second is that full employment of resources could become undesirable given emissions limits.

This reasoning assumes that there is neither technological progress nor alternative technologies that can use the resources in different ways and reduce emissions per unit of production. Thus, it looks only at scale and composition effects, and does not take into consideration the intensity effect. Also, the unemployment solution only corresponds to a short run case; in the long run, the total supply of factors would be reduced (by decreasing investments) and FF would move towards the origin.

7. The Cost of Inaction in an Integrated Assessment Model

7.1. The Cost of a Shock to Total Factor Productivity

A relevant benchmark to take into account in comparing the estimated costs of carbon taxes and other emissions reduction policies is the costs of damages due to climate change, assuming that those policies are effective and not the result of implementing abatement policies. Those costs could be sanctions by the international community or climate shocks that affect industries and citizens. The former have been already estimated in Section 4.2 for the price of exports.

In this section we focus on physical impacts and estimate not only how they could influence the performance of the economies and the welfare of their citizens,[27] but also emissions themselves. Notably, the negative effects that shock the productivity of economies could become an unpleasant and involuntary mechanism to reduce emissions. Table 7 shows the results of assuming a 5 percent loss in total factor productivity for domestic agriculture and manufactures

---

[27] Döll (2009) surveys the estimates of damages and adaptation policies in four CGE models: DICE, MERGE, PAGE and FUND.

due to climate shocks, both under full employment and under unemployment. It can be seen that the cost of damages varies from 2.35 percent for Peru to 4.32 percent for El Salvador, and that the loss of productivity damages exports and increases the unemployment rate. Resources move to services, however, which helps to compensate for the shock.

Many models evaluate the shocks of climate to the economies using a macroeconomic model (like DICE) and therefore do not pay attention to the composition effect which would result from the reallocation of resources between industries as a response to changes in relative prices. Table 7 then shows an aggregated shock, but includes the effects of the composition effect (derived in this case from the damage and not from the costs of mitigation).

Table 7. Potential Costs of Inaction under a Hypothetical 5 Percent Shock to TFP of Agriculture and Manufactures

		Argentina	Brazil	Chile	El Salvador	Jamaica	Peru
Model 7	GDP	-4.31	-3.43	-3.76	-4.32	-3.97	-2.35
	X	-3.99	-3.10	-3.86	-0.87	-5.45	-1.40
	Unemployment rate (av.)	12.80	11.01	6.90	7.79	13.31	8.55
	CO2 Emissions	-5.62	-5.09	-4.10	-5.53	-3.38	-4.29
	CC Taxes/GDP	0.00	0.00	0.00	0.00	0.00	0.00
	Cost of Lowering Emissions	0.766	0.673	0.918	0.780	1.172	0.548
Model 7.1	GDP	-1.72	-1.70	-2.14	-3.58	-2.07	-1.91
	X	-0.97	-1.05	-1.86	0.62	-2.25	-0.89
	Unemployment rate (av.)	x	x	x	x	x	x
	CO2 Emissions	-4.12	-4.45	-2.74	-5.17	-1.70	-4.09
	CC Taxes/GDP	0.00	0.00	0.00	0.00	0.00	0.00
	Cost of Lowering Emissions	0.418	0.381	0.779	0.693	1.216	0.466

In general terms, it can be seen that when the loss of productivity (in terms of Total Factor Productivity) is 5 percent, the costs of inaction are higher than those of carbon taxes, and this is also reflected in the cost of lower emissions, which is noticeably higher. Again, downward inflexibility of wages amplifies the losses.

One interesting point to emphasize is that the reduction in emissions, due basically to the negative shock on the activity levels and the scale effect, is smaller than that obtained by domestic policies of taxation of emissions. However, the cost of a 1 percent reduction in terms of GDP is much higher than when taxes are used (compare with Table 1)!

This suggests that, if the damage of emissions were fully internalized and there were no other sources of emissions, economies would have a clear incentive to act on emissions rather than wait passively for the shock. However, the choice of policies is more complicated still, because economies could opt between the costs of mitigation policies, such as carbon taxes, and expenses in adaptation to prevent or compensate damages; mitigation is not always the preferred policy (see Chisari, Galiani and Miller, 2013).

7.2 The Damage Function and Recursive Dynamic Models

We have to complete our estimates of mitigation costs using taxes with a damage function that takes into account the social cost of carbon, i.e., the cost to economies of accumulating additional GHG in the atmosphere, to address items 2 and 3 listed in Section 1. Item 1 in Section 1 will be obtained from the emission estimates models based on the static general equilibrium models, and regarding 4 item we will use GDP, though additional measures of welfare can be used and are available for the economies (e.g., welfare measure with Equivalent Variation).

We will consider a recursive dynamic model developed in Chisari, Maquieyra and Miller (2012). This is a single country model with several goods and services, and for which investments and mitigation expenses are not forward looking; instead, households and the government plan their savings (and firms use them for investment) using only information of the current period. Investments become additional endowment of capital of households, who hire it to firms. This new capital is freely mobile between production sectors, and hence the rate of return is equalized. Thus it is allocated endogenously following the marginal product of capital in different sectors of production until it is equalized.

The costs of mitigation are similar to those estimated using the static CGE models assuming that mitigation can be reduced via the introduction of carbon taxes. Higher carbon taxes will imply reduction of emissions but also additional costs to the economies. Thus, the cost of reducing emissions will not be based on estimates of other models, but instead obtained from the simulation of the static or dynamic versions of our models.

We shall focus on the case of two economies, Brazil and El Salvador, to illustrate the main results of our analysis. With regard to the damage function, it is assumed that the calibrated damage function is similar to the function estimated in Chisari, Galiani and Miller (2013). Thus we assume that the negative shock is the inverse of the equivalent growth of temperature of the world for the next 50 years, estimated as a 3^{o}C increase, due to the accumulation of GHG in the atmosphere. Then we consider two cases. In the first, we assume that countries' respective shares of total world emissions are the same as those obtained in Model 1 (under full employment) and that the economies are therefore small in relation to total pollution. In the second, we consider a counterfactual case—in which Brazil and El Salvador represent the whole world—to see how the difference in size of countries could have an impact on damage and on incentives to spend resources in mitigation.

Table 8 presents the results for those economies. We can see changes in percentage of GDP and Emissions for seven cases: i) the case of full employment, Model 1; ii) Model 1 plus taxes of $20 per Ton of GHG; iii) Model 1 under a climatic shock, assuming that the country's share of total world emissions is that obtained in the model, so that the economy is "environmentally small" (SEE), in the sense of Chisari, Galiani and Miller (2013); iv) the same, but assuming that the country taxes emissions at $20 per Ton; v) Model under climatic shock, but assuming that the economy represents total world emissions, i.e., its coefficient of share of emissions is 1 and it is "environmentally big" (BEE); vi) the same assumptions of v) but assuming that a $20 tax is imposed; vii) the economy (BEE) computes the tax endogenously responding to climatic shocks (when climatic shocks are higher, the tax is increased).

The last simulation tries to address the case of an economy that is reactive to climate change, that is myopic and does not take advantage of intertemporal substitution possibilities, but realizes that something has to done, and then reacts to climate shocks increasing (or decreasing) carbon taxes according to observed (or not observed) climate shocks.

Table 8. Recursive Dynamic Model Results for Brazil and El Salvador

		Brazil		El Salvador	
		GDP (%)	Emissions (%)	GDP (%)	Emissions (%)
T1	Model 1	2.385	3.344	4.512	3.787
	Model 1 + Taxes	1.772	-3.446	4.191	-1.113
	Model 1 with shock (SEE)	2.385	3.344	4.512	3.787
	Model 1 with shock (SEE) + Taxes	1.772	-3.446	4.191	-1.113
	Model 1 with shock (BEE)	2.385	3.344	4.512	3.787
	Model 1 with shocks (BEE) + Taxes	1.772	-3.446	4.191	-1.113
	Model 1 with shock (BEE) + Endogenous Taxes	1.772	-3.446	4.191	-1.113
T2	Model 1	4.822	6.788	9.067	7.548
	Model 1 + Taxes	4.204	-0.889	8.867	3.225
	Model 1 with shock (SEE)	4.421	6.368	8.599	7.102
	Model 1 with shock (SEE) + Taxes	3.806	-1.294	8.399	2.794
	Model 1 with shock (BEE)	4.419	6.367	8.596	7.099
	Model 1 with shocks (BEE) + Taxes	3.830	-1.269	8.418	2.811
	Model 1 with shock (BEE) + Endogenous Taxes	3.732	-1.687	8.358	2.405
T5	Model 1	12.446	17.757	22.960	20.005
	Model 1 + Taxes	11.823	7.175	23.150	16.404
	Model 1 with shock (SEE)	10.739	15.925	20.964	18.108
	Model 1 with shock (SEE) + Taxes	10.124	5.441	21.150	14.561
	Model 1 with shock (BEE)	10.738	15.924	20.956	18.100
	Model 1 with shocks (BEE) + Taxes	10.159	5.477	21.157	14.568
	Model 1 with shock (BEE) + Endogenous Taxes	9.727	3.681	20.977	12.891
T10	Model 1	26.273	38.344	46.861	42.292
	Model 1 + Taxes	25.629	25.126	47.801	38.905
	Model 1 with shock (SEE)	22.008	33.581	41.892	37.597
	Model 1 with shock (SEE) + Taxes	21.383	20.795	42.801	34.323
	Model 1 with shock (BEE)	22.009	33.582	41.879	37.584
	Model 1 with shocks (BEE) + Taxes	21.429	20.842	42.798	34.320
	Model 1 with shock (BEE) + Endogenous Taxes	20.252	12.907	42.635	30.441
T15	Model 1	41.625	62.182	71.722	65.175
	Model 1 + Taxes	40.951	46.404	73.520	62.084
	Model 1 with shock (SEE)	34.264	53.630	63.225	57.200
	Model 1 with shock (SEE) + Taxes	33.622	38.646	64.938	54.266
	Model 1 with shock (BEE)	34.269	53.635	63.218	57.193
	Model 1 with shocks (BEE) + Taxes	33.677	38.705	64.938	54.266
	Model 1 with shock (BEE) + Endogenous Taxes	31.444	22.435	65.106	48.114

For the sake of simplicity, let us focus on the results of the last period, T15. Notice that the figures in the table represent cumulative increases in percentage terms. It can be seen that in the case of Brazil the imposition of carbon taxes reduces GDP by about 0.7 percent and emissions by about 16 percent. This is basically the result of a composition effect in the long run, when capital is almost fully mobile between production sectors. The inclusion of a climatic shock reduces further GDP and emissions but, as in Table 7, the impact on GDP is more significant than the reduction in emissions. Finally, the inclusion of endogenous taxes reduces GDP and emissions further still. The tax is increased to approximately $40 per Ton to respond to the negative climatic shock. While taxes now reduce total GDP by about 2 percent, they are effective for mitigation since emissions fall by about 16 percent.

In the case of El Salvador, the most interesting result comes from comparing the results of Model 1 and Model 1 + Taxes. It can be seen that the introduction of taxes initially reduces the GDP growth rate (for example, for period two, the accumulated growth rate falls from 9.067 percent to 8.867 percent) as well as that of emissions, which after taxes grow 3.225 percent instead of 7.548 percent. However, when we look to the results for the last period reported, T15, we can see that the GDP growth rate is higher than without taxes, and that the reduction of emissions declines from more than 4 percent to almost 3 percent. This is explained by an increase in government investment; the model assumes that any additional revenue is distributed in constant proportions among different government expenses (a Cobb-Douglas assumption for the utility function of the government), including investments. Since we find for El Salvador that the government's propensity to save is higher than that of the private sector, taxes increase the rate of growth, and this change in scale compensates for the reduction of emissions due to taxes and the composition effect. The use of the additional revenue therefore becomes again, as in the case of compensation of taxes, a relevant issue.

It can also be seen that both countries increase taxes under BEE, i.e., when they are big with respect to the rest of the world, and in both cases total emissions are reduced. However, in the case of Brazil this is not enough to compensate for the negative impact of damages on total GDP with respect to the case of constant taxes; instead, in the case of El Salvador, the economy is able to reduce the shock and emissions with additional taxes.

8. Main Lessons and Concluding Remarks

The simulations have illustrated some interesting points to take into account in designing policies and understanding countries' reluctance to adopt taxes to curb GHG emissions. In this paper we borrowed the classification of environmental effects proposed by Brock and Scott Taylor (2004): the scale effect, the composition effect and the intensity effect.

Our basic static model in the first part of the paper takes as its benchmark economies with unemployment and assumes that the trade balance must be equilibrated. The model further assumes that there are no alternative technologies less intensive in emissions and thus evaluates the impact of carbon taxes of $20 per Ton for scale and composition effects. That is, economies can reduce emissions only by reducing their scale of activity or the composition of their industrial production. Under full employment, the costs are not far from international studies, and their impact on GDP is not big.

In the short run and under unemployment, the results change dramatically. We find that the costs of the policy depend on the rule of determination of wages (how the social and political environment will react to the new taxes) as well as on the mobility of resources domestically and internationally (since the fall of the domestic rate of return could exacerbate migration of capital, reduce GDP still further and amplify the scale effect). It is confirmed that economies become less GHG-intensive after taxes, due to the composition effect. However, there is a price for that. The model shows that, although taxes on emissions seem effective for reducing emissions, the costs as a percentage of GDP can be significant for most of the economies in the short run or with mobility of capital.

There are two main elements that explain this result: the state of the labor market and the impact on exports. The increase of costs due to taxes might also trigger increases of nominal wages; in turn, this reduces the activity level of firms and total employment. Additionally, domestic goods become less competitive and that diminishes exports (the model assumes that the economies are "small").

For that reason we study how the results could differ if the price of exports were increased by some plausible percentage due to two possible reasons: one, that the application of carbon taxes were not an isolated policy, but a movement coordinated with the rest of the world; and second, that the economies were not small, and could pass through part of the cost of taxes to the rest of the world.

Thus there are two important fronts on which to appraise the costs of climate change policies. One is the domestic front, in terms of how wages are determined institutionally or by the market, because additional costs could be passed through to wages and therefore reduce employment (with the obvious political consequences). The second front is external; well-intended individual countries initiatives could be jeopardized by loss of competitiveness when not accompanied by the rest of the world (since a simultaneous move by all countries could help to stabilize the relative changes in competitiveness). Thus, if domestic carbon taxes were accompanied by carbon taxes in the rest of the world, their negative impacts would be reduced. We also find that the composition effect, that is the reallocation of resources due to taxes, is relevant for reducing the costs in terms of GDP.

However, reduction in the absolute level of emissions achieved may not be enough to stop the long-run growth of emissions beyond the safety thresholds. Although carbon taxation helps to delay total GHG accumulation in the atmosphere, even in cases where the economies' emission intensity is lowered, growing population and per capita consumption cannot necessarily be compensated only with a shift of the industrial structure towards less polluting activities. Thus, the presence of technological alternatives is a key element in evaluating the effectiveness of emissions reduction.

It is consequently relevant to know how healthy an economy is on the external front to evaluate whether a new technology will be put in place in response to environmental taxes. However, the replacement of polluting technologies could be far from fast and easy. The capital already sunk in old technologies could have no alternative use and could accept deep reductions in its remuneration before leaving the activity or becoming obsolete (see Chisari, Maquieyra and Miller, 2012, for some examples).

To appraise the relevance of the intensity effect, which involves the reduction of emissions per unit of output, we assume that there is a latent technology that can become operative in highly emissions-intensive industries. The new technology is one that substitutes incumbent capital with new capital that has to be imported from the rest of the world. The operation of the new technology dramatically reduces emissions and is highly successful, though there are limitations on its use due to economic factors. Even though the technologies are less expensive, since they do not pay carbon taxes, they have to use international capital and remunerate its opportunity cost. If the new technology is too intensive in the use of that capital, it will become unaffordable and will be abandoned. An interesting corollary is that bottom-up models require not only a description of technologies but also an explicit indication of the scarce resources they will use. Volatility in the current account, which is pervasive in Latin American and Caribbean economies, could be a strong limitation on the adoption of low-carbon technologies, and the role of international financing could be very relevant in this regard.

These results naturally lead to the need for a taxonomy of models that estimate the costs of climate change policies. Do those models assume full employment or admit the possibility of unemployment? Is the economy assumed to be small with respect to the rest of the world? Is capital mobile with respect to the rest of the world? When firms can reallocate capital to the rest of the world, there will be an amplification of GDP losses, and the net result in terms of emissions would depend on relative pollution in different regions of the world.

Though the results presented here are based on a static model, the second part of the paper evaluated recursive dynamic versions for two countries: Brazil and El Salvador. These versions include an estimated damage function, which is a complementary element to move the models closer to the Integrated Assessment literature.

One main finding of these simulations is that the additional funds obtained by governments also help to limit the reduction of GDP and stimulate growth in some cases, if used properly. The expenses in employment and public investments compensate for the loss of income and welfare of the private sector and could even help to increase the rate of growth. In that case, as illustrated by the results of El Salvador, additional investment by the government (which in that country has a higher propensity to invest than the private sector) could compensate for the reduction of the activity level and tend to increase total emissions in the long run.

If the additional revenue were collected by the government, the results in terms of GDP would probably be higher than the case when those taxes were collected by the rest of the world (which is equivalent to a reduction of prices of exports). On the other hand, there exists the possibility of compensation and alternative uses of public additional revenue. Compensation for carbon taxes by a reduction of all other taxes to keep public sector purchasing power constant helps to reduce GDP losses.

In fact, a more detailed examination of the tax structure is needed to determine the best way to substitute for the taxes that create the greatest welfare losses; our simulations show that there are important gains from substituting taxes on labor.

The structure of the economy matters when computing the costs of reducing GHG emissions. While industrial structure is obviously important, other important factors include the social environment (in terms of how the government redistributes income through transfers) and the share of rural population (since agriculture is a main source of emissions).

Carbon taxation produces redistribution of income and has an impact on welfare too. Those changes are important and could trigger political opposition that could block their use. The model helps to see how costs will be distributed between the poor and the rich. In that sense, the determination of wages (assumed constant in real terms in the model) and capital mobility are key elements in assessing the quantitative impact of carbon taxes.

The paper’s findings can be summarized as follows:

- There are fundamental differences in the estimates of costs of lower emissions between short run models with unemployment and models that assume full employment. Most models assume full employment and therefore might underestimate those costs in the short run. Those costs depend on the rules of adjustment of wages and on the mobility of resources.
- However, the composition effect is significant in reducing emissions even under unemployment. The reduction of emissions due to reallocation of resources seems to be effective for abatement.
- Equal yield corrections of taxes, that is, compensation for the additional revenue produced by carbon taxes can help to reduce costs and can even produce a net benefit. That net benefit is higher when labor taxes are reduced.
- Mobility of capital can increase or decrease those costs. However, it is clear that international mobility of resources could magnify the fall of GDP when capital moves to the rest of the world after taxes are applied.
- Compensation for domestic carbon taxes by similar taxes applied in the rest of the world can help to reduce the costs of lowering emissions.
- The presence of alternative technologies is very relevant in reducing emissions at low cost. However, the effective use of those technologies depends on the stress they put on scarce resources and on the downward flexibility of remuneration of specific capital used by incumbent technologies.

- In a dynamic setting, it is necessary to take into account the differential propensity to invest of the government with respect to private agents. When it is higher, the additional revenue could lead to an increase in GDP in the long run and to an increase in emissions or to a reduction of the abatement gains.[28] Thus growth could be stimulated by an indirect mechanism. Though the final result depends on deep parameters of economies (e.g., the propensity to import consumption and investment goods), it is not possible to rule out the case of higher growth cum trade openness. Thus it is necessary to address two aspects. On the one hand, it is necessary to specify the taxation of imports and consequently of exports (probably in the framework of international agreements and the impact of taxation on exports and imports (see Winchester, Paltsev and Reilly, 2011). In these cases it would be necessary to determine who will collect the revenue, for that could make a significant difference for the results.

---

[28] In some cases, costs are reduced and even become even gains when a dynamic setting is considered (see Chisari and Miller, 2013). This is due to the change in relative prices in favor of imports (that are not taxed) and on the differential propensity to save between the government and the private sector, as well as by the presence of full employment. Since investments are intensive in imported capital goods, and increase of taxes to domestic activities increases growth, i.e. a tax on domestic goods stimulates the demand of imported goods and the imports of capital goods stimulates growth in turn. There is also another force playing a role. The fiscal result is positive, and there is an expansion of public sector investment and employment.

Appendix: Equivalent Ad Valorem Taxes

This section summarizes the taxes applied for the case of each individual country. Notice that GHG emissions and energy intensity are not equivalent. A more thorough analysis can be found in Chisari, Maquieyra and Miller and (2012). In that paper, taking the reported emissions by country and industry, we constructed estimates of GHG. However, one important lesson of the work was that most of the emissions are linked to use of energy or to production of agricultural goods. For example, approximately half of the emissions of Argentina are the result of primary production, while the other half result from energy use. Thus, in Argentina, taxation of carbon content will impact agriculture and cattle production, and energy-intensive manufacturing sectors.

Table A1. Taxes CO2 Emissions Equivalent, Argentina

SECTORS			**Taxes on model**	
			5 us$/CO2 tn emitted	**20 us$/CO2 tn emitted**
Energy	***is applied to***	***modeled sectors***		
Combustion	Energy consumption (2)			
Energy Industry		2,4	2.420%	9.680%
Manufactures		3	1.393%	5.570%
Transport		5	9.213%	36.853%
Others		final consumption,1,6	6.013%	24.052%
Fugitive Emissions	production	2	0.243%	0.973%
Industrial Processes	production	3	0.054%	0.216%
Agriculture + LULUCF	production	1	2.599%	10.397%
Waste	production	3	0.064%	0.258%

Source: Authors' estimates.

Table A2. Taxes CO2 Emissions Equivalent, Brazil

SECTORS			**Taxes on model**	
			5 us$/CO2 tn emitted	**20 us$/CO2 tn emitted**
Energy	***is applied to***	***modeled sectors***		
Combustion	Energy consumption (4,7)			
Energy Industry		7,8	0.352%	1.409%
Manufactures *(intensive energy use)*		5	0.916%	3.664%
Manufactures *(non-intensive energy use)*		6	0.715%	2.860%
Transport		11	2.849%	11.396%
Residential		final consumption	0.283%	1.131%
Agriculture		1	1.804%	7.216%
Trade		10	0.448%	1.791%
Non-energy		5	0.125%	0.500%
Fugitive Emissions	production	4,7	0.042%	0.168%
Industrial Processes				
Manufactures *(intensive energy use)*	production	5	0.249%	0.997%
Manufactures *(non-intensive energy use)*	production	6	0.002%	0.009%
Agriculture				
Agriculture	production	1	0.731%	2.924%
Livestock	production	3	0.692%	2.767%
LULUCF	production	1,2,3	4.546%	18.183%

Source: Authors' estimates.

Table A3. Taxes CO2 Emissions Equivalent, Chile

SECTORS			**Taxes on model**	
			5 us$/CO2 tn emitted	**20 us$/CO2 tn emitted**
Energy	***is applied to***	***modeled sectors***		
Combustion	Energy consumption (2,4)			
Energy Industry		4,5	0.825%	3.301%
Manufactures		3	0.840%	3.362%
Transport		6	3.079%	12.318%
Others		final consumption,1,7	0.220%	0.878%
Fugitive Emissions	production	2,4	0.012%	0.046%
Industrial Processes	production	3	0.037%	0.148%
Waste	production	3	0.017%	0.069%

Source: Authors' estimates.

Table A4. Taxes CO2 Emissions Equivalent, Jamaica

SECTORS			**Taxes on model**	
			5 us$/CO2 tn emitted	**20 us$/CO2 tn emitted**
Energy	***is applied to***	***modeled sectors***		
Combustion	Energy consumption (2,3)			
Energy Industry		4	4.617%	18.466%
Manufactures		3	1.732%	6.930%
Transport		7	1.393%	5.571%
Others		final consumption,1,5,6,8	0.037%	0.150%
Industrial Processes	production	3	0.040%	0.162%
Agriculture + LULUCF	production	1	0.000%	0.000%
Waste	production	3	0.000%	0.000%

Source: Authors' estimates.

Table A5. Taxes CO2 Emissions Equivalent, El Salvador

SECTORS			**Taxes on model**	
			5 us$/CO2 tn emitted	**20 us$/CO2 tn emitted**
Energy	***is applied to***	***modeled sectors***		
Combustion	Energy consumption (2,3)			
Energy Industry		4	3.023%	12.090%
Manufactures		3	0.104%	0.415%
Transport		5	2.122%	8.486%
Others		final consumption,1,6,7	0.010%	0.038%
Industrial Processes	production	3	0.071%	0.283%
Agriculture + LULUCF	production	2	2.006%	8.024%
Waste	production	3	0.110%	0.440%

Source: Authors' estimates.

Table A6. Taxes CO2 Emissions Equivalent, Peru

SECTORS			Taxes on model	
			5 us$/CO2 tn emitted	**20 us$/CO2 tn emitted**
	is applied to	***modeled sectors***		
Energy				
Combustion	Energy consumption (2,4)			
Energy Industry		4,6	0.241%	0.965%
Manufactures		5,7	0.509%	2.034%
Transport		9	2.844%	11.377%
Residential, Commercial		final consumption,8	0.623%	2.493%
Agriculture		1	1.300%	5.202%
Mining		2,3	0.922%	3.687%
Fugitive Emissions	producction			
Solid Fuels		3	0.000%	0.001%
Oil		2,4	0.016%	0.063%
Industrial Processes	producction			
Manufactures		5	0.096%	0.383%
Chemicals		4	0.004%	0.017%
Agriculture + LULUCF	producction	1	3.115%	12.458%
Waste	producction	5	0.090%	0.359%

Source: Authors' estimates.

References

Aldy, J.E., E. Levy and I. Parry. 2010. “What Is the Role of Carbon Taxes in Climate Change Mitigation?” PREMnotes 2. Washington, DC, United States: World Bank. Available at: http://www1.worldbank.org/prem/PREMNotes/Note2_role_carbon_taxes.pdf

Aldy, J.E., and W.A. Pizer. 2009. “The Competitiveness Impact of Climate Change Mitigation Policies.” Pew Center on Global Climate Change. Available at: http://www.c2es.org/docUploads/competitiveness-impacts-report.pdf

Baumol, W.J., and W. Oates. 1988. *The Theory of Environmental Policy*. Cambridge, United Kingdom: Cambridge University Press.

Bergman, L. 1991. “General Equilibrium Effects of Environmental Effects: A CGE Modeling Approach.” *Environmental and Resource Economics* 1(1): 43-61.

Bickel, J.E., and L. Lane. 2010. “Climate Engineering.” In: B. Lomborg, editor. *Smart Solutions to Climate Change: Comparing Costs and Benefits*. Cambridge, United Kingdom: Cambridge University Press.

Boccanfuso, D., A. Estache and L. Savard. 2011. “Intra-Country Distributional Impact of Policies to Fight Climate Change: A Survey.” *Journal of Development Studies* 47(1): 97-117.

Bosetti, V. et al. 2011. “Emissions Pricing to Stabilize Global Climate.” Nota di lavoro 2011.080. Milan, Italy: Fondazione Eni Enrico Mattei.

Brock, W., and M.S. 2004. “Economic Growth and the Environment: A Review of Theory and Empirics.” NBER Working Paper 10854. Cambridge, United States: National Bureau of Economic Research.

Carraro, C., and G.E. Metcalf. 2000. “Behavioral and Distributional Effects of Environmental Policy: Introduction.” NBER Working Paper 7648. Cambridge, United States: National Bureau of Economic Research.

Chisari, O.O., S. Galiani and S. Miller. 2013. “Optimal Climate Change Mitigation and Adaptation Expenses in Environmentally Small Economies.” Working Paper IDB-WP-417. Washington, DC, United States: Inter-American Development Bank.

Chisari O.O., J.A. Maquieyra and S. Miller. 2012. “Manual sobre Modelos de Equilibrio General Computado para Economías de LAC con Énfasis en el Análisis Económico del

Cambio Climático." Nota Técnica IDB-TN 445. Washington, DC, United States: Inter-American Development Bank.

Chisari, O.O., and S. Miller. 2013. "The Cost of Lower Emissions: An Appraisal for Five LAC Economies Using CGE Models." Working Paper IDB-WP-453. Washington, DC, United States: Inter-American Development Bank.

Davis, S.J., and K. Caldeira. 2010. "Consumption-Based Accounting of CO2 Emissions." *Proceedings of the National Academy of Sciences* 107(12): 5687-5692.

Dell, M., B.F. Jones and B.A. Olken. 2014. "What Do We Learn from the Weather? The New Climate-Economy Literature." *Journal of Economic Literature* 52(3): 740–798.

Dervis, K., J. de Melo and S. Robinson. 1982. *General Equilibrium Models for Development Policy*. Washington, DC, United States: World Bank.

Döll, S. 2009. "Climate Change Impacts in Computable General Equilibrium Models: An Overview." HWWI Research Paper 1-26. Hamburg, Germany: Hamburg Institute of International Economics (HWWI).

Fullerton, D., A.B. Lyon and R.J. Rosen. 1983. "Uncertainty, Welfare Cost, and the 'Adaptability' of U.S. Corporate Taxes." NBER Working Paper 1239. Cambridge, United States: National Bureau of Economic Research.

Giordano, P., and M. Watanuki. 2012. "A Global Carbon Tax on Climate Change: Policy Implications for Latin America." Paper presented at the 15th Annual Conference on Global Economic Analysis, Global Trade Analysis Project, Geneva, Switzerland.

Goettle, R. et al. 2009. "Analyzing Environmental Policies with IGEM, an Intertemporal General Equilibrium Model of US Growth and the Environment: Part 2." Washington, DC, United States: Environmental Protection Agency. Available at: http://people.hmdc.harvard.edu/~mho/dja/igem_doc/sep2009/pdf_parts/part2chap1.pdf

Golosov, M. et al. 2011. "Optimal Taxes on Fossil Fuel in General Equilibrium." NBER Working Paper 17348. Cambridge, United States: National Bureau of Economic Research.

Goulder, L.H. 1998. "Environmental Policy Making in a Second-Best Setting." *Journal of Applied Economics* 1(2): 279-328.

Goulder, L.H. 2013. "Climate Change Policy's Interactions with the Tax System." *Energy Economics* 40: S3–S11.

Hertel, T.W., S. Rose and R.S.J. Tol. 2009. "Land Use in Computable General Equilibrium Models: An Overview." In: T.W. Hertel, S. Rose and R.S.J. Tol, editors. *Economic Analysis of Land Use in Global Climate Change Policy*. New York, United States: Routledge.

Hope, C. 2011. "How High Should Climate Change Taxes Be?" Working Paper Series 9/11. Cambridge, United Kingdom: Cambridge University, Judge Business School.

Kiuila, O., and T. Rutherford. 2012. "The Costs of Reducing CO2 Emissions: Integrating Abatement Technologies into Economic Modelling."

Koskela, E., and R. Schöb. 2000. "Optimal Factor Income Taxation in the Presence of Unemployment." CESifo Working Paper 279. Munich, Germany: CESifo.

Lomborg, B., editor. 2010. *Smart Solutions to Climate Change: Comparing Costs and Benefits*. Cambridge, United Kingdom: Cambridge University Press.

Löschel, A. 2002. "Technological Change in Economic Models of Environmental Policy: A Survey." Nota di Lavoro 4.2002. Milan, Italy: Fondazione Eni Enrico Mattei.

Marchand, M., P. Pestieau and S. Wibaut, 1989. "Optimal Commodity Taxation and Tax Reform under Unemployment." Scandinavian Journal of Economics 91(3): 547-563.

Neary, J.P. 1985. "International Factor Mobility, Minimum Wage Rates and Factor Price Equalization: A Synthesis." *Quarterly Journal of Economics* 100: 551-70.

Paltsev, S. et al. 2005. "The MIT Emissions Prediction and Policy Analysis (EPPA) Model: Version 4." Report 125. Cambridge, United States: Massachusetts Institute of Technology. Available at: http://globalchange.mit.edu/files/document/MITJPSPGC_Rpt125.pdf

Peterson, S. 2003. "CGE Models and their Application for Climate Policy Analysis." Presentation at the 1st International Workshop on Integrated Climate Models: An Interdisciplinary Assessment of Climate Impacts and Policies, Trieste, Italy.

Rose, S. et al. 2008. "Land in Climate Stabilization Modeling: Initial Observations." EMF Report 21. Stanford, United States: Stanford University, Energy Modeling Forum. Available at: https://web.stanford.edu/group/emf-research/docs/emf21/EMF21FinalReport.pdf

Ross, M.T. 2009. "Documentation of the Applied Dynamic Analysis of the Global Economy (ADAGE) Model." Working Paper 09_01. Washington, DC, United States: Environmental Protection Agency.

Schöb, R. 2003. "The Double Dividend Hypothesis of Environmental Taxes: A Survey." CESifo Working Paper Series 946. Munich, Germany: CESifo.

Shoven, J., and J. Whalley. 1992. *Applying General Equilibrium*. Cambridge, United Kindgom: Cambridge University Press.

Tchouto, J. 2007. "Tradable Emission Permits and General Equilibrium through Applied OLG Models: A Survey." *Journal of Environmental Research and Development* 2(1): 48-61.

Tol, R. 2008. "Why Worry about Climate Change? A Research Agenda." *Environmental Values* 17: 437-470.

Winchester, N., S. Paltsev and J.M. Reilly. 2011. "Will Border Carbon Adjustments Work?" *B.E. Journal of Economic Analysis & Policy* 11(1): Article 7.

Wing, I.S. 2004. "Computable General Equilibrium Models for the Analysis of Energy and Climate Policies." In: J. Evans and L.C. Hunt, editors. *International Handbook on the Economics of Energy*. Cheltenham, United Kingdom: Elgar.

Zhang, Z.X., and A. Baranzini. 2003. "What Do We Know about Carbon Taxes? An Inquiry into Their Impacts on Competitiveness and Distribution of Income." MPRA Paper 13225. Munich, Germany: Munich Personal RePec Archive. Available at: http://mpra.ub.uni-muenchen.de/13225/