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Abstract

We develop a two-good general equilibrium model of a small open economy to decompose a country's unilateral strengthening of environmental policy's effects on pollution emissions in the rest of the world, known as emissions leakage. We show analytically and numerically that the level of emissions leakage depends on the level of trade friction in the service sector. In the model, production in the manufacturing sector is associated with pollution emissions, and production in the service sector is clean. In a special case with free trade in manufacturing and no trade in services, no leakage occurs. Allowing for trade in services, we solve for the relationship between trade frictions in the service sector and leakage. At lower levels of service sector's trade friction, leakage from a small strengthening of environmental regulation decreases (increases) if services are imported (exported). Finally, we simulate the model, calibrating the to the Canadian economy to compare these effects' relative sizes over a range of plausible parameter values. Leakage is about 18% lower when using trade friction levels estimated from the literature rather than assuming no trade friction in services.

JEL classification: H23, Q54, F18

Key words: Climate change, emissions leakage, trade costs, trade in services

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1 Introduction

Unilateral changes in environmental policy in one region may cause countries with weaker environmental regulation to increase production of pollution-intensive goods. The associated increase in emissions in these regions is known as emissions leakage. The issue of carbon leakage has been a particular concern to policy makers because of the lack of global consensus on policies to reduce greenhouse gas emissions. Countries that have considered regulating emissions in the absence of coordinated global action have been concerned that production in polluting sectors would relocate to unregulated jurisdictions, thus reducing domestic employment without a corresponding reduction in global pollution emissions.[1]

In this paper we develop a two-good, one-factor, small open-economy model with pollution emissions associated with one of the good's production. We show that the level of leakage from a unilateral strengthening in environmental regulation depends on the level of trade frictions in the model. We present a special case of our model with free trade in the dirty good (which we term manufacturing), but the clean good (services) is not traded. We show that increases in the stringency of environmental regulation, which we model as a pollution tax, do not affect emissions in the rest of the world. In other words, unilateral environmental regulation is associated with zero emissions leakage when no trade is in the clean good.

This result demonstrates the importance of carefully modeling trade costs when evaluating emissions leakage's consequences from a unilateral change in environmental policy. In our model with no trade in services, an increased pollution tax causes a reduction in the relative price of services, but no corresponding change in the price of the polluting good relative to its world price. This leads to an equal reduction in

[1]There is an ongoing debate in the academic literature on the impact of environmental regulation on manufacturing sector competitiveness, but policy makers remain concerned. For example, U.S. President Donald Trump has argued that climate change is a hoax designed to reduce the competitiveness of U.S. manufacturing.

domestic consumption and output of the polluting good and, thus, zero leakage. The consumption and production of services increase the same amount. When we model positive levels of trade in services, we find leakage consistent with the existing literature. We use the model to analytically decompose the impact of unilateral strengthening of domestic environmental regulation on the rest of the world's emissions into three distinct channels: income effect, output effect and substitution effect.

We find that the income effect causes negative leakage. Pollution tax increases lead to a reduction in consumers' real wages, thus reducing consumption. As a result, the exports of manufacturing goods increase, and the rest of the world's production decreases by a corresponding amount. Through the income effect, increases in the pollution tax lead to decreases in the rest of the world's emissions, if all else is equal.

The output and substitution effects cause positive leakage. Through the output effect, increased pollution tax leads to a decline in the manufacturing sector's production. This decline decreases the exports of manufacturing goods, and the rest of the world's production (and pollution emissions) increases to fill the gap. In the substitution effect, a pollution tax increase leads to a relative price increase. This increase has two impacts on our model. First, exports of manufacturing goods decrease, and again foreign production and pollution emissions rise in response. Secondly, the relative price change also reduces domestic consumption of manufactured goods as households begin using services that increase export of manufacturing goods and that lead to declining production in the rest of the world. We show that the effect on production dominates the effect on consumption and that the net substitution effect causes positive leakage.

While we can analytically sign the leakage effects in the model, their relative magnitudes depend on parameters and initial values. To compare the effects' size, we simulate a numerical version of the model calibrated to the Canadian economy. We simulate a 1% increase in environmental regulation at service sector trade cost estimates taken from the literature and under zero service sector trade costs. Emissions leakage is 18% higher using parameter estimates from the literature. The simulations also demonstrate that among the channels in our model the substitution effect dominates. The income effect, which could be a source of negative leakage (decreasing the rest of the world's emissions) from an emissions tax increase, is more than an order of magnitude smaller than the other two effects. For the chosen set of parameter values, we find positive leakage for all non-zero levels of the service sector trade.

Two distinct methods are used in the literature to study leakage: analytical and computable general equilibrium (CGE) models. Typically theoretical models assume trade costs in services to be zero, potentially because they are difficult to quantify across all the countries or regions modeled. Many analytic studies focus on identifying channels through which leakage operates and on exploring the potential for negative leakage. Karp (2013) develops a two-good (clean and dirty), two-factor, one-country model with both goods freely traded. The study decomposes emissions leakage into two effects: income effects and production effects. The reallocation of factors across the two sectors in his model because of an environmental policy causes the income and production effects. He argues that, if the income effect is dominant, an increase in environmental regulation may cause negative emissions leakage. Our paper extends this model by allowing for trade costs in both sectors and evaluating how leakage varies with trade costs in the non-polluting sector.

Modeling a two-good, two-factor, two-country framework, Baylis, Fullerton, and Karney (2014) shows that the emissions leakage depends on the two elasticities of substitution: the elasticity of substitution between the two-factor inputs in production, and the elasticity of substitution between the two commodities. The authors decompose leakage into the terms-of-trade effect (TOT) and the abatement resource effect (ARE). An increased price of the home-country's good leads to positive leakage as consumers substitute with the other country's good (the terms-of-trade effect). Firms in the dirty sector substitute dirty inputs with clean inputs, leading to negative leakage (the abatement resource effect). In this paper we focus on another potential avenue of lower emissions leakage estimates. We demonstrate that an increase in environmental regulation can be associated with less leakage if the service sector's trade costs are modeled directly.

Baylis, Fullerton, and Karney (2015) extends Baylis, Fullerton, and Karney (2014) to analytically decompose a CGE model's results into seven distinct leakage effects. We identify three analogous effects in our model: income, output, and substitution. We also find that the income effect reduces leakage and the output and substitution effects increase leakage. Many of the effects in Baylis, Fullerton, and Karney (2015) do not appear in our model because of our focus on a small economy. Because our economy is a price taker, its environmental policy has no impact on world prices.[2] The price taker assumption reduces the number of channels through which environmental policy (or trade costs) can affect emissions leakage. Thus the assumption allows us to focus on trade cost in the service sector's impact on leakage from increased environmental regulation. Because Baylis, Fullerton, and Karney (2015) (and Baylis, Fullerton, and Karney (2014)) focus on environmental policy, they do not address the relationship between trade costs in the service sector and emissions leakage. This simplifying assumption shuts down other channels through which environmental policy may cause emissions leakage, which while important are not the focus of this paper. For that reason we cannot credibly estimate total leakage in this framework. We choose to highlight the importance of this particular channel for leakage relative to a subset of other, previously identified channels.

Trade costs in services represent a significant barrier to free trade. In addition to traditional tariffs, the service sector is exposed to a variety of non-tariff barriers. Professional services often face technical standards, licensing requirements, and lan-

[2]For example, several researchers have modeled a "fuel price" effect, in which introducing environmental regulation reduces dirty fuels' global price. In these models the reduction in fuel price is one of the largest sources of leakage. We assume our economy's policy actions do not affect world prices, so this effect is not present in our model.

guage or cultural barriers that inhibit trade. Many personal services must be provided on location in real time (for example, haircuts, restaurants and construction) and are therefore untradeable. Gervais and Jensen (2014) find service sector trade costs in the U.S. are 137% for business services and 168% for personal services. Anderson, Milot, and Yotov (2013) estimate Canadas trade costs in services with the rest of the world as 163% tariff equivalent.

Most of the leakage literature has focused on trade in the polluting sector.[3] While it is widely understood that in general equilibrium the linkage between the level of trade across sectors would affect leakage, this concept has not been widely studied. The impact that the clean sector's trade costs can have on emissions leakage has been largely overlooked.[4] We show that at lower levels of service-sector trade costs, a stricter environmental regulation is associated with less leakage for a service importer and more leakage for a service exporter. We show that service sector trade costs amplify leakage. At lower levels of service sector trade costs a stricter environmental policy induces less leakage for service importer and more leakage from a service exporter. This is driven by the income and substitution effects which vary in sign with service trade orientation.

Our small open-economy framework has been used in several studies that examine the relationship between trade and the environment.[5] While this approach is extremely tractable, one shortcoming is that small open-economy models do not explicitly quantify emissions in the rest of the world. To estimate leakage we assume that economies in the rest of the world are symmetric in emissions intensity but differ only by the environmental regulation's stringency, we show that the direction and the determinants for emissions leakage can be evaluated in a small open-economy model.[6] Moreover, our re-

[3]The literature has also focused largely on the effect of changes in tariff rates rather than the more general trade costs we use to motivate our model. The contribution of our paper comes from modelling these trade costs in the non-polluting sector explicitly, not from our distinction between tariff rates and trade costs.

[4]See Hoel (1996) for a notable exception.

[5]See Copeland (1994) and Copeland and Taylor (2005) for examples.

[6]Different levels of emissions intensity between the domestic economy and that of the rest of the world would merely scale our results by the relative difference in emissions intensities.

sults imply that a small-open economy's environmental policy can have non-negligible effects on the rest of the world's pollution emissions.

Our approach rests on the assumption that changes in the small open economy's environmental regulation would not affect the level of environmental regulation in other jurisdictions. We believe that assumption is plausible in this context. A number of small countries and sub-national jurisdictions have introduced unilateral CO_2 regulation without any corresponding global policy action. For example, the Regional Greenhouse Gas Initiative introduce a carbon price for electricity generators in the northeastern United States. California has introduced an emissions trading scheme covering industrial, electric and transport emissions. Seven Chinese regions, covering 12% of emissions, have developed emissions trading markets. A recent World Bank report found that as of 2015 there were more sub-national ETS programs than national ETS programs.

While we use an analytical model to evaluate the impact of trade costs in services on leakage, we believe these results have implications for the large number of studies that investigate emissions leakage using a computable general equilibrium (CGE) framework. Paltsev (2001); Elliott, Foster, Kortum, Munson, Cervantes, and Weisbach (2010); Babiker (2005) each develop multi-region Computable General Equilibrium (CGE) models of the world to estimate a magnitude of leakage under an environmental regulation. These papers present net results and do not identify the effects of trade costs in services on emissions leakage.

To demonstrate the policy relevance of modelling trade in services explicitly, we examine the optimal emissions tax at different levels of trade costs in services. We find that the optimal emissions tax decreases as service sector trade costs decrease. This is driven by increasing leakage. We also model a "Border Adjustment Tax" (BTA) on imports of the polluting good to offset leakage. We find that decreases in service trade costs have a nonlinear impact on the BTA needed to reduce leakage, but that decreases in service sector trade cost require larger BTA's to reduce leakage by a specified amount.

CGE models that include services calibrate their models to the realized trade flows in services. This implicitly fixes trade costs in services at the level in the calibration data and implies they remain unchanged throughout the forecast period. These studies suggest that a unilateral increase in carbon taxes may increase emissions elsewhere in the world by as much as 10%-130% of the reductions in the country that imposes the tax. Our results suggest that a fall in trade costs in services could affect the estimated emissions leakage negatively (or positively) depending upon whether an economy imports (or exports) services. These CGE studies are able to capture leakage from a variety of sources and estimate an overall leakage rate from increases in the stringency of environmental regulation. In this paper we do not attempt to estimate overall leakage rates, instead we focus on identifying additional channels through which leakage may occur.

Several studies also explore the potential for negative leakage in a CGE model (see Elliott and Fullerton (2014); Baylis, Fullerton, and Karney (2013); Winchester and Rausch (2013); Carbone (2013)). They analyze leakage with respect to various levels of counterfactual elasticities across inputs and products in a CGE model. These studies find that elasticities of substitution in the production and utility functions affect leakage. Winchester and Rausch (2013), and Carbone (2013) also note little prospect of negative leakage (in a large multi-region model of the United States) because of the assumption of small fossil fuel supply elasticities. While our model is much simpler than these CGE models, incorporating a given level of trade cost in services allows us to introduce another dimension across which leakage may vary.[7]

The rest of this paper is organized as follows. Section 2 outlines the model. Section 3 solves the model and evaluates the impact of a small increase in the emissions tax

[7]Many of the channels through which environmental regulation can affect the rest of the world's emissions in these CGE models do not exist in our model. Most importantly, the small open economy in our model is a price taker. Thus, it is difficult to predict how introducing trade costs into these large scale CGE models may affect the results as compared to our simple (and tractable) model.

on leakage. To provide intuition, this section offers analytical solutions for the amount of leakage in two special cases: i) free trade in goods with completely non-traded services, and ii) free trade in goods and services. Then the marginal effects of trade cost in services on the emissions leakage are investigated, and a more general solution, showing how the amount of leakage varies with trade costs in the service sector, is provided. Section 4 illustrates solutions for two special cases of the model to provide intuition for the results. Section 5 calibrates the model to Canadian data, decomposes the channels of leakage at different levels of service sector trade costs. Section 5.3 examines the policy implications of the results including how service sector trade cost affect the optimal pollution tax and the level of border tax adjustment required to offset leakage. Section 6 concludes.

2 The Model

We model a small open economy with two representative sectors. A representative firm in each sector produces one good: manufacturing (x) and services (y). The manufacturing good is a composite good representing all goods that emit some level of carbon during their production process. The service good represents all outputs that do not emit any carbon during their production process.[8] Initially, we assume that manufacturing goods are freely traded internationally, but the service sector faces a trade friction, which represents the degree of trade costs in services. These trade costs may result from visa fees, required licenses or other professional standards, country-specific technical standards, legal hurdles, or differences in language and culture. We chose to model these barriers as iceberg trade costs while abstracting from the details of how these non-tariff barriers are designed and implemented. Initially, we assume a fixed world price ratio for goods and services such that the economy exports manufacturing

[8]This classification is consistent with Levinson (2010), who finds that in the U.S. economy, services account for a tiny fraction of overall emissions. So, no sector is completely clean and furthermore, some services are actually far from emissions free if one counts embodied (indirect) emissions.

goods and imports services from the rest of the world.[9]

On the demand side, we assume a representative domestic household that consumes both manufactured goods and services to maximize utility. The household has access to international debt at a fixed (world) interest rate $\bar{R}$. The domestic government's role is limited to implementing an exogenous emissions tax per unit of emissions in the manufacturing sector and redistributing revenues collected to the households in a lump-sum transfer.[10] The balance of payment in the economy is unaffected by a change in environmental regulation.

In both sectors, if domestic absorption is greater (less) than domestic production, the economy imports (exports) from (to) the rest of the world. Firms have the option to abate emissions or pay an emissions tax. Although mobile across sectors, labor is immobile across countries. For simplicity, we assume that population growth is zero. The parameters and policy variables are assumed such that an interior solution always exists for all decision variables.

We employ a constant relative risk aversion (CRRA) utility function with a constant elasticity of substitution (CES) aggregated over the consumption of goods and services.

The representative household's preferences are given by

$$U(c_x, c_y) \; = \; \frac{\left\{ \left(\gamma^{\frac{1}{\rho}} c_x^{\frac{\rho-1}{\rho}} + (1-\gamma)^{\frac{1}{\rho}} c_y^{\frac{\rho-1}{\rho}} \right)^{\frac{\rho}{\rho-1}} \right\}^{1-\sigma} - 1}{1-\sigma} - D\frac{e^{1+\sigma}-1}{1+\sigma} \tag{1}$$

where, c_x and c_y are consumption of manufacturing goods and services, respectively, $\gamma \in (0,1)$ is the weight in consumption of manufacturing goods, ρ is the constant elasticity of substitution between goods and services each period, and σ is the constant relative risk aversion parameter. We denote e as the level of domestic pollution emissions and $D \geq 0$ as the weight of dis-utility from pollution emissions.[11] We assume that the

[9] This assumption is convenient because our application simulates the Canadian economy and Canada is a service importer.

[10] For simplicity, we assume that the government maintains a balanced budget.

[11] The damages from climate change are driven by the stock of global emissions, but households

representative household inelastically supplies her labor ($\bar{h}$) to firms (i.e. $h_x + h_y = \bar{h}$), where h_x is labor supply to the manufacturing sector and h_y is labor supply to the service sector. The emissions' stock is a negative externality that lowers utility but that has no effect on production.[12]

The household is subject to the following budget constraint

$$c_x + p\,\mu\,c_y + \bar{R}\bar{d} = w\bar{h} + \pi + G \tag{2}$$

where p is the fixed world relative price ratio of services to manufacturing goods and μ is the trade factor defined such that $p^d = p\,\mu$ represents domestic price and π is the firm's profit.[13] In a world with costless trade in services $\mu = 1$.[14] The amount of debt servicing is $\bar{R}\bar{d}$. The real wage per unit of labor supplied is w, and the real lump-sum transfer of tax revenues from the government to the household is represented by G. The manufacturing good is the numeraire with an assumed price of 1 so that all other prices can be interpreted as units of the manufacturing goods' price.

The representative household chooses c_x and c_y to maximize her utility (Eq. (1)) subject to her budget constraint (Eq. (2)). Using λ as the Lagrangian multiplier for the budget constraint, the household's maximization problem is represented by the following Lagrangian:

$$\max_{c_x,c_y} \mathscr{L} = \frac{\left\{\left(\gamma^{\frac{1}{\rho}} c_x^{\frac{\rho-1}{\rho}} + (1-\gamma)^{\frac{1}{\rho}} c_y^{\frac{\rho-1}{\rho}}\right)^{\frac{\rho}{\rho-1}}\right\}^{1-\sigma} - 1}{1-\sigma} + \lambda\left\{w\bar{h} + G + \pi - c_x - p\,\mu\,c_y - \bar{R}\bar{d}\right\} \tag{3}$$

optimize only over the portion of emissions they control.

[12]Copeland (1994) and Angelopoulos, Economides, and Philippopoulos (2010) each models pollution's impact on consumers in a similar way

[13]In equilibrium firm profits are zero so the term does not appear in the household maximization problem.

[14]Note that μ can be defined as $\mu = 1 + f$ for service importers, where f is the iceberg trade cost in services. For service exporters, $\mu = \frac{1}{1+f}$. If services are exported, then the domestic price $p^d = \frac{p}{1+f}$. If services are imported, then the domestic relative price of services is $p^d = p(1+f)$.

The first order conditions are

$$\left(\gamma^{\frac{1}{\rho}} c_x^{\frac{\rho-1}{\rho}} + (1-\gamma)^{\frac{1}{\rho}} c_y^{\frac{\rho-1}{\rho}}\right)^{\frac{1-\sigma\rho}{\rho-1}} \left(\frac{\gamma}{c_x}\right)^{\frac{1}{\rho}} = \lambda \tag{4}$$

$$\frac{C_x}{C_y} = \frac{\gamma}{1-\gamma}\left(\frac{1}{p\,\mu}\right)^{-\rho} \tag{5}$$

Eq. (4) ensures that the marginal utility from the consumption of goods is equal to the marginal utility of income. Eq. (5) shows that households' relative demand of the two consumption goods depends upon the world relative price ratio p, μ, ρ and γ.

On the supply side, production in both sectors uses labor as the only input.[15] The production function in the manufacturing sector is $x = h_x^{\alpha_1}$, and the production function in the service sector is $y = h_y^{\alpha_2}$. The parameters $\alpha_1 \in (0,1)$ and $\alpha_2 \in (0,1)$ are the factor input elasticities in manufacturing goods and service outputs, respectively. Following Copeland and Taylor (2003), we assume that the output production in the manufacturing sector (x) generates emissions (e) as the production's joint output.[16] Following Copeland and Taylor (2003), we assume that firms have access to pollution abatement technology and spend a fraction (θ) of its output on the abatement process. Hence, the net output of manufacturing goods is $(1-\theta)x$, where θ is the fraction of gross output x used for the emissions abatement.

The structure of abatement technology in our model allows the firms to choose zero abatement if there is no emissions regulation or if the abatement is not cost effective. As in Copeland and Taylor (2003), we use a specific abatement technology that models emissions as $e = (1-\theta)^{\frac{1}{\xi}} x$, where $0 \leq \theta \leq 1$ is the fraction of gross output (x) firms spend on abatement and ($0 > \xi > 1$) such that $e \leq x$. Here, ξ is the share of emissions expenditure in the net output of manufacturing goods. As ξ increases, abatement

[15]The labor factor can also be interpreted as a composite of capital and labor, or any arbitrary non-pollution inputs.

[16]This approach has been used in a series of influential general equilibrium trade and environment studies, including those of Copeland (1994) and Antweiler, Copeland, and Taylor (2001).

becomes less effective and more gross output is required to reduce emissions by the same amount. A non-zero level of emissions tax (T) is assumed to always exist in the economy, and the tax level is higher than ξ.[17]

The representative firm in each sector maximizes the following profit functions:

$$\max_{h_x, e} \pi_x = e^{\xi}(h_x^{\alpha_1})^{1-\xi} - wh_x - Te \tag{6}$$

$$\max_{h_y} \pi_y = p\ \mu\ h_y^{\alpha_2} - wh_y \tag{7}$$

The optimal conditions are

$$\alpha_1(1-\xi)\ \left(\frac{e}{x}\right)^{\xi} \frac{x}{h_x} = p\mu\alpha_2 \frac{y}{h_y} \tag{8}$$

$$\xi \left(\frac{x}{e}\right)^{1-\xi} = T \tag{9}$$

Firms employ labor (Eq. (8)) such that the marginal return to labor is equal across the two sectors.[18] Eq. (9) shows that firms optimally abate such that the marginal cost of abatement of emissions is equal to the per-unit emissions tax.[19]

Plugging the firm's zero profit conditions into the budget constraint Eq. (2), the economy's resource constraint is thus

$$e^{\xi}(h_x^{\alpha_1})^{1-\xi} - c_x + p\ \mu\ (h_y^{\alpha_2} - c_y) = \bar{R}\bar{d} \tag{10}$$

[17] We require this assumption since for any emissions tax level below ξ firms do not find it cost effective to abate emissions and, thus, choose to pay the tax. This abatement technology does not admit emissions taxes of 0. See Copeland and Taylor (2003) for a full description.

[18] Labor is mobile across sectors, but not across countries.

[19] In this study we assumed that the emission tax is exogenously imposed by the domestic government and is not necessarily set at the optimal level. It is straightforward to model an optimal tax policy from social planners point of view at the second stage. The underlying implementation mechanism is as follows: given the way we setup the model, first combining the optimal conditions of the households and the firms and solve for C_x,C_y,h_x,h_y and the level of emission for a given tax rate, prices and other preference parameters to obtained the indirect utility or the value function of the social planner (V(p,μ,T)). Then, the endogenous optimal tax rate will be determined by the following condition: ∂V(.)/∂T=0. Under the preferences and production in our model we cannot interpret that expression. In section 5.3 we explore the optimal tax rate and border tax adjustment numerically.

The trade balance is then equal to the interest payments on the debt,[20] The transfer from the government to households is

$$G = T\ e \tag{11}$$

The trade flows in the manufacturing and service sectors are

$$b_x = e^{\xi}(h_x^{\alpha_1})^{1-\xi} - c_x \tag{12}$$

$$b_y = p\ \mu\ (h_y^{\alpha_2} - c_y) \tag{13}$$

where b_x and b_y are the trade flows in the economy's manufacturing and service sectors.

Because our focus is on identifying the channels through which environmental regulation can lead to emissions leakage, rather than estimating the overall level of emissions leakage, we can abstract from the rest of the world's emission intensity. For that reason we do not explicitly model the rest of the world's production function. Instead, we assume that a unilateral increase in pollution taxes would neither alter the environmental regulation in the rest of the world nor affect the economy's balance of payments in the long run.[21] These assumptions are standard in small-open economy models and we believe they are plausible here. Several countries, and many sub-national jurisdictions, have imposed unilateral environmental regulation with no global policy response. The rest of the world's consumption is not affected by a change in the level of domestic emissions tax since the world's relative price is fixed. The level of outputs in each sector in the rest of the world would vary depending on the changes in the trade flows in the corresponding sectors.[22] Hence, we define the leakage as the reverse of the change

[20]thus allowing the country to run consistent trade deficits or surpluses in aggregate across the two industries.

[21]In practice this leads to modelling how changes in environmental policy affect trade flows and mapping those changes in trade flows into changes in domestic and rest of the world emissions using a constant emissions intensity rate. As noted above, using other fixed emissions intensity rates is a straightforward extension.

[22]The rest of the world is large compared to the small economy, thus implying that the change in

in trade flows in the manufacturing sector b_x.[23] For an economy that imports manufacturing goods, an increase in imports suggests an increase in the rest of the world's emissions and thus leakage.[24]

3 Analytical Solution

In this section, we analytically solve the model through log-linearization. Taking logs of the first order equations and totally differentiating, the change in each variable is represented by a proportional change from its initial level (which we denote with $\hat{()}$). For example, a small change in x is indicated by $\hat{x} = \frac{dx}{x}$.

On the supply side, taking logs on both sides of Eq. (8) and totally differentiating yields

$$\xi\hat{e} + (1-\xi)\hat{x} - \hat{h_x} = \hat{y} - \hat{h_y} \tag{14}$$

Taking logs on both sides of Eq. (9) and totally differentiating yields

$$\hat{e} = \hat{x} - \frac{1}{1-\xi}\hat{T} \tag{15}$$

Log-linearization of the production functions yields

$$\hat{x} = \alpha_1\hat{h_x} \tag{16}$$

$$\hat{y} = \alpha_2\hat{h_y} \tag{17}$$

Also, from $h_x + h_y = \bar{h}$, we have

$$\theta_{hx}\hat{h_x} + \theta_{hy}\hat{h_y} = 0 \tag{18}$$

the trade flows reflects the change in the emissions level in the rest of the world with respect to the emission level in the small economy.

[23] Alternatively, the emissions intensity in the rest of the world is assumed to be fixed, and the supply of manufacturing goods responds one-to-one to changes in domestic trade flows.

[24] If an economy exports manufacturing goods, then a reduction in exports implies leakage.

where θ_{hx} and θ_{hy} are the shares of labor in manufacturing and service sectors, respectively (hence, $\theta_{hx} + \theta_{hy} = 1$).

On the demand side, taking logs and totally differentiating both sides of Eq. (5) yield

$$\hat{c_x} = \hat{c_y} \tag{19}$$

The relative price ratio and trade friction are fixed. A percentage change in the demand for manufacturing goods must be equal to the percentage change in the demand of services. Unless there are changes in the relative price, the relative demand of each good will not change.

Totally differentiating the resource constraint in equilibrium (Eq. (10)) yields

$$c_x \hat{c_x} + p\ \mu\ c_y \hat{c_y} = e^{\xi} x^{1-\xi}[\xi \hat{e} + (1-\xi)\hat{x}] + p\ \mu\ y\ \hat{y} \tag{20}$$

We have a system of seven equations: optimal labor Eq. (14); optimal emissions Eq. (15); two production functions, Eq. (16) and Eq. (17); labor constraint Eq. (18); optimal relative consumption Eq. (19); and resource constraint Eq. (20). The system has seven unknowns: labor supply in the two sectors, $\hat{h_x}$ and $\hat{h_y}$; outputs in the two sectors, $\hat{x}$ and $\hat{y}$; emissions $\hat{e}$; and consumption of the two goods, $\hat{c_x}$ and $\hat{c_y}$. First, we solve for the change in amount of labor used in services $\hat{h_y}$

$$\hat{h_y} = \frac{\theta_{hx}}{\theta_{hx}(1-\alpha_2) + \theta_{hy}(1-\alpha_1)} \frac{\xi}{1-\xi} \hat{T}; \tag{21}$$

and then, plugging $\hat{h_y}$, we solve for $\hat{h_x}$, $\hat{y}$, $\hat{x}$, and $\hat{e}$ (See appendix). Substituting these solutions in Eq. (20) and simplifying, the change in consumption expenditure on manufacturing goods ($\hat{c_x}$) is then

$$\hat{c_x} = \left[\frac{\alpha_2 S_y \theta_{hx} - \alpha_1 S_x \theta_{hy}}{\theta_{hx}(1-\alpha_2) + \theta_{hy}(1-\alpha_1)} - S_x \right] \frac{\xi}{1-\xi} \hat{T}; \tag{22}$$

where, letting $C = c_x + p\ \mu\ c_y$ be the aggregate consumption, $S_x = \frac{e^{\xi} x^{1-\xi}}{C}$ and $S_y = \frac{p\ \mu\ y}{C}$ represent the shares of manufacturing goods and services in the aggregate consumption, respectively.

As shown in Eq. 22, a small increase in the emissions tax ($\hat{T}$) has two effects on consumption of manufacturing goods: an income effect and a substitution effect. The first term inside the bracket $\left[\frac{\alpha_2 S_y \theta_{hx} - \alpha_1 S_x \theta_{hy}}{\theta_{hx}(1-\alpha_2)+\theta_{hy}(1-\alpha_1)}\right]$ is the income effect; and the second term $[S_x]$ is the price effect, which we refer to as the substitution effect.[25]

The third term outside the bracket is a scale factor $\left[\frac{\xi}{1-\xi}\right]$, the ratio of emission expenditure to potential output in the manufacturing sector, which we term as the abatement resource factor. This factor augments the income and substitution effects such that higher ξ increases the emissions tax's net effect on consumption as abatement becomes less effective. This factor's impact differs from other studies that have found an abatement resource effect leading to negative leakage. In those studies, the taxed sector substitutes clean resources shrinking output in other sectors, leading to negative leakage.[26]

From Eq. (19) and (22), we note that a small increase in the emissions tax in a small open economy also has similar negative effects on consumption of services.

Proposition 1. *A small increase in the emissions tax in a small open economy has a negative effect on consumption of manufacturing goods because of the negative impact of both the income and the substitution effects.*

Proof: See appendix.

After an increased producer price in the manufacturing sector because of an increased emissions tax, income is affected through two channels. First, the effective price of

[25]These terms can also be rearranged such that $\hat{c_x} = \left[\frac{\alpha_2 S_y \theta_{hx}}{\theta_{hx}(1-\alpha_2)+\theta_{hy}(1-\alpha_1)} - S_x\left(\frac{\alpha_1 S_x \theta_{hy}}{\theta_{hx}(1-\alpha_2)+\theta_{hy}(1-\alpha_1)} + 1\right)\right] \frac{\xi}{1-\xi}\hat{T}$. In this case, the first term should be interpreted as the indirect effect and the second term as the direct effect of the emissions tax on consumption.

[26]Our model has only a single (clean) input and thus no scope for factor substitution. Polluting firms endogenously abates emissions by reducing output.

consumption is increased; thus, consumption of both goods and services decreases. Secondly, labor is reallocated to the service sector, reducing the real wage. This reduction reduces the real income available to consumers; and, as a result, consumption of manufacturing goods decreases. This effect is particularly important when we consider negative leakage. The more negative the income effect, the larger the increase in manufacturing goods' exports and thus the larger the leakage decreases.[27]

Corollary 1.1. *A small increase in emissions tax in a small open economy has a negative effect on consumption of services. The decline in consumption of services and manufacturing are proportional.*

Evident from Eq. (19), it implies that the emissions tax increase has negative effects on consumption of services, similar to the consumption of manufacturing goods.

Net imports are equal to consumption minus production in our model, $c_x - e^{\xi}x^{1-\xi}$. We define leakage as the rate of change in net imports and define it as $\hat{L}$ where $L = c_x - e^{\xi}x^{1-\xi}$. Hence, total differentiating L and plugging solutions for change in consumption of manufacturing goods $\hat{c_x}$, emissions $\hat{e}$, and outputs in the manufacturing sector $\hat{x}$ with rearrangement yields the leakage

$$\begin{aligned}\hat{L} = &\Bigg[\frac{S_{cx}}{S_{mx}}\left(\frac{\alpha_2 S_y \theta_{hx} - \alpha_1 S_x \theta_{hy}}{\theta_{hx}(1-\alpha_2) + \theta_{hy}(1-\alpha_1)}\right) \\ &+ \frac{S_x}{S_{mx}}\left(\frac{\alpha_1 \theta_{hy}}{\theta_{hx}(1-\alpha_2) + \theta_{hy}(1-\alpha_1)}\right) \\ &+ \left(\frac{S_x}{S_{mx}} - \frac{S_x S_{cx}}{S_{mx}}\right)\Bigg]\frac{\xi}{1-\xi}\hat{T}\end{aligned} \tag{23}$$

where, $S_{mx} = \frac{b_x}{C}$ and $S_{cx} = \frac{c_x}{C}$ are the shares of manufacturing goods' exports and consumption in the aggregate consumption, respectively. Note that b_x is the trade flows in the manufacturing sector. $S_{cy} = \frac{c_y}{C}$ is the share of services' consumption in

[27] This finding is consistent with Baylis, Fullerton, and Karney (2015) who identify a "pure income effect" that reduces leakage. The pure income effect in that study arises from the assumption that tax revenue is spent on a public good rather than rebated.

the aggregate consumption.

Proposition 2. *A small increase in an emissions tax in a small open economy has three leakage effects: income, output and substitution. The income effect is negative, and both output and substitution effects are positive. The net effect on leakage is positive.*

Proof:

As shown in Eq. (23), the first term $\left[\frac{S_{cx}}{S_{mx}}\left(\frac{\alpha_2 S_y \theta_{hx} - \alpha_1 S_x \theta_{hy}}{\theta_{hx}(1-\alpha_2)+\theta_{hy}(1-\alpha_1)}\right) < 0\right]$ is the income effect. As noted in Proposition 1, this effect is negative, which increases exports of manufacturing goods and reduces leakage.

The second term $\left[\frac{S_x}{S_{mx}}\left(\frac{\alpha_1 \theta_{hy}}{\theta_{hx}(1-\alpha_2)+\theta_{hy}(1-\alpha_1)}\right) > 0\right]$ is the output effect, which is positive. Outputs in the manufacturing sector decline because of increased input prices resulting from the emissions tax policy (See Eq. (16)). These increased prices decrease exports of manufacturing goods and lead to a positive leakage effect.

The third term on the right $\left[\frac{S_x}{S_{mx}} - \frac{S_x S_{cx}}{S_{mx}}\right]$ is the substitution effect, which has two components: effects on (1) consumption and (2) output of manufacturing goods because of the goods' increased relative price. The increased emissions tax increases the producer's price and worsens terms of trade in the manufacturing sector, thus decreasing the exports of manufacturing goods. As a result, a positive leakage effect which is shown by $\frac{S_x}{S_{mx}}$. As mentioned earlier, the increase in the producer's price also negatively affects consumption of goods, as households substitute goods with services. The substitution in consumption reduces leakage. This effect is shown by $-\frac{S_x S_{cx}}{S_{mx}}$. However, the output component dominates the consumption component, and the net effect is positive $\left[\frac{S_x S_{cy}}{S_{mx}}\right]$.

The scale factor $\left[\frac{\xi}{1-\xi} > 0\right]$ has the same effect as in Eq. (22). This factor describes how effective an environmental policy is at affecting the net emissions leakage. Furthermore, this factor has an economy-wide resource effect and increases with an increase in ξ (the share of abatement expenditure in output in the manufacturing sector). Abatement uses real output resources from the manufacturing sector. The lower the fraction of the manufacturing sector's output spent on abatement, the less effect the emissions tax has on leakage, as fewer resources will be spent on abatement.

We note that whether the economy imports or exports manufacturing goods, an increase in emissions tax yields emissions leakage. We model an emissions tax, but in practice countries use several different policy instruments. Modeling different policy instruments is beyond the scope of this paper, but the choice of instrument can affect the amount of leakage. For example, Holland (2012) shows that emissions taxes and cap-and-trade policies are equivalent, but an intensity standard (emissions per dollar of output) can be more efficient. An intensity standard combined with a consumption tax can lead an efficient outcome and offset leakage.

3.1 Effect of Service Trade Cost on Emissions Leakage

In this section, we explore how emissions leakage varies at different levels of the service sector's trade costs. Trade costs in services have generally decreased over time. Information technology has facilitated trade in services, and countries have been pressured to roll back services' trade restrictions (Miroudot and Shepherd, 2014; Gervais and Jensen, 2014). The special cases above suggest that the level of trade cost in services is crucial regarding the amount of leakage from changes in environmental policy. In this section, we show that a fall in trade costs in services affects emissions leakage.

We differentiate the emissions leakage $\hat{L}$ in Eq. (23) with respect to the trade friction (μ) to find the effect of changes in trade costs on emissions leakage from increased environmental regulation

$$\begin{aligned}\frac{\partial \hat{L}}{\partial \mu} = &\left[\frac{S_{cx}}{\mu\ S_{mx}}\left(\frac{\alpha_2 S_y S_{cx}\theta_{hx} + \alpha_1 S_x S_{cy}\theta_{hy}}{\theta_{hx}(1-\alpha_2) + \theta_{hy}(1-\alpha_1)}\right)\right.\\ &\left. + \left(\frac{S_x S_{cy}}{\mu\ S_{mx}}\right)\right]\frac{\xi}{1-\xi}\hat{T}\end{aligned} \tag{24}$$

where the first term, $\frac{S_{cx}}{\mu\ S_{mx}}\left(\frac{\alpha_2 S_y S_{cx}\theta_{hx}+\alpha_1 S_x S_{cy}\theta_{hy}}{\theta_{hx}(1-\alpha_2)+\theta_{hy}(1-\alpha_1)}\right) > 0$, is the change in the income effect as the service sector's trades increase. This effect suggests that the negative income effect from an increase in the level of environmental regulation is dampened in countries with high service-sector trade costs. The second term, $\left(\frac{S_x S_{cy}}{\mu\, S_{mx}}\right) > 0$, is the change in the substitution effect on emissions leakage, which is also positive. This effect suggests that the positive substitution effect from an increased level of environmental regulation on leakage is amplified by higher service sector trade costs. The fact that both effects are positive suggests increased level of environmental regulation has larger leakage effects in countries with high trade costs. Higher service sector trade costs amplify leakage through both the income and substitution effects, both driven by higher prices for services. Higher costs for services increase the price level reducing consumption, thus amplifying the (negative) income effects of increases in environmental regulation. Higher costs for services also make imported manufactured goods more attractive, also amplifying leakage. This result suggests an ancillary benefit of reduction in service sector trade barriers: reduced leakage from environmental regulation.

To explore this result's implications, we consider two countries, which are both service importers. One country has relatively high service-sector trade costs and the other relatively low. Both countries increase the level of environmental regulation by the same amount. Equation 23 shows that our model predicts leakage will increase in both countries. Equation 24 indicates that leakage will increase more in the country with high service sector trade costs.

In both countries the income effect on leakage from the increased environmental tax will be negative. Consumers will consume less of both goods and services after the environmental tax increase. This consumption decrease will lead to excess supply in the home country and more manufacturing exports, reducing the rest of the world's production and, thus, the rest of the world's emissions.[28] Equation 24 reveals that this effect will be dampened in the country with high trade cost. The relatively high price

[28] Also, a "pure income effect" results in which labor reallocation across sectors reduces wages and consumption.

of services in the high trade cost country means that the loss in consumption associated with increased environmental tax will be smaller. The smaller the reduction in consumption, the lower the negative leakage associated with an increased environmental tax.

In both countries the substitution effect will be positive. An increased environmental tax will make the (imported) manufacturing good more expensive, thus leading to reduced manufacturing consumption, increased manufacturing production in the rest of the world, and increased pollution emissions. The country whose service sector's trade cost is high will find it relatively more expensive to substitute manufactured goods with services after the price change. This will magnify the positive leakage effect in the country with high service sector trade costs.

In our model the service sector's trade costs have no impact on output, holding income, and substitution constant. Therefore, there is no difference in the output effect across the low and high service sector trade cost countries. The trade cost's reduction decreases only the nominal wage in both sectors, while the real wage remains the same. The nominal wage falls in proportion to the trade cost because price is defined relative to manufacturing goods' output price in our model. In other words, the domestic prices of services and manufacturing goods fall by the same proportion as the trade cost, for increased emissions tax. That means that the labor allocation will not change, and output in both sectors is constant.[29]

After rearranging Eq. (24), the equation can be rewritten as

$$\frac{\partial \hat{L}}{\partial \mu} = \frac{S_{cx}}{\mu}\hat{L} > 0 \tag{25}$$

where, $S_{cx} = \frac{c_x}{c_x + p\mu c_y}$. This leads to proposition 3.

[29]Also, differentiating manufacturing goods' output $\hat{x}$ and $\hat{e}$ (see appendix) with respect to μ shows no effect on these variables' changes. As expected, the change in output and, thus, the change in domestic emissions for a constant level of emissions tax should not change with μ.

Proposition 3. *Services' trade costs amplify emissions leakage. For service importers, increased environmental regulation is associated with more leakage when services' trade costs are high. If services are exported, a fall in trade costs in services increases the emissions leakage.*

The emissions leakage from a constant change in the level of emissions tax is affected by changes in consumption as a result of the income and substitution effects. For a fall in the trade costs in services, the sign of change in μ is negative when services are imported and positive when they are exported. Thus, the fall in trade costs in services decreases the income and substitution effects on emission leakage if services are imported and increases the income and substitution effects on the emissions leakage if services are exported. The output effect, however, does not change with the trade friction's sign. Hence, if services are imported, the fall in trade cost in services has a negative effect on the emissions leakage; and if services are exported, a positive effect on emissions leakage results.

Corollary 3.1. *The marginal effect of a fall in trade cost in services on the emissions leakage is larger for a higher share of manufacturing goods in aggregate consumption, smaller μ, and higher initial emissions leakage from the emissions tax policy.*

The trade costs' marginal effect on emissions leakage depends on the existing trade costs' magnitude, the manufacturing goods' consumption share in aggregate consumption, and the magnitude of the emissions leakage itself. Evident from Eq. (25), the emissions leakage is affected by falling trade cost through income and terms-of-trade effects on the manufacturing goods' consumption. When services are imported, the relative price of domestic services decreases as services' trade costs fall, leading to decreased consumption of manufacturing goods at the margin. This decrease in manufacturing goods' consumption increases exports, if all else is equal, and thus reduces the substitution effect on emissions leakage. The larger the share of manufacturing goods' consumption in aggregate consumption, the larger the substitution effect on emissions leakage.

A fall in trade costs in services also increases households' real income, leading to increased manufacturing goods' consumption, thus reducing the income effect on emissions leakage. The marginal effect on the emissions leakage because of the income effect is higher if the initial μ is smaller, implying a bigger effective relative change in μ compared to its initial level.

4 Specific Cases

In this section we explore extreme cases of an economy with no trade in services (section 4.1) and costless trade in services (section 4.2) to better understand how the level of trade in the clean good affects leakage. The results presented here represent special cases that illustrate the crucial mechanisms linking service sector trade costs and leakage in our model. In section 5.3, we explore the policy implications of these specific cases on the optimal pollution tax and the optimal level of border tax adjustment required to offset leakage.

The case with freely traded goods and services assumes that the world's relative price is exogenous to the emissions tax change. In the case with no trade in services, the emissions tax affects the domestic relative price of services. Both of these cases make extreme assumptions about tradability of goods and services. However, the emissions tax change's impact on the relative price is an empirical question. Hoel (1996) argues that the relative price's insensitivity to the emissions tax change is not practical. On the other hand, Baylis, Fullerton, and Karney (2014) find a causal relationship between the change in the relative price and the negative leakage because of the abatement resource effect (ARE) present in their model. In our model, the case with no trade in services highlights the importance of change in relative prices by showing that emissions leakage is zero when relative prices adjust. The case with free trade in goods and services also highlights the relative importance of the channels through which an emissions tax change affects leakage.

4.1 No Trade in Services

We begin by considering an extreme case of an economy with no trade in services. In our model, no trade in services means zero trade balance in the service sector, which requires the following market clearing constraint

$$y = c_y \tag{26}$$

Then, the economy's trade balance is just the trade flows in the manufacturing sector. Manufacturing goods are exported; and the receipts are used to service international debt, balancing the capital and current accounts.[30]

Proposition 4. *In the two-sector small open economy with goods and services, if services are completely non-traded then a small increase in the emissions tax on pollution from the manufacturing sector leads to zero emissions leakage. The reduction in relative price of services proportionally decreases consumption and outputs of manufacturing goods, thus leading to zero emissions leakage.*

Proof: See appendix

Since, in this case, the world relative price (p) is fixed and services are non-traded, the effective domestic relative price of services declines with an increased emissions tax. As a result of the decline, manufacturing goods' consumption declines in proportion with the decline in the manufacturing sector's output. In aggregate, the export level of manufacturing goods remains the same. The adjustment in the relative price of services affects both consumption and output proportionately, preventing emissions

[30] In this way the economy can run a persistent trade surplus in the steady state.

leakage. No emission leakage occurs because of assumption in the model that a stricter environmental regulation has no effect on the economy's trade balance in the long run. This is a standard result in small-open economy models. Because regulation does not affect the trade balance changes in regulation imply a proportionate decline in manufacturing goods' consumption and also outputs. This is, of course, a special case, but one worth considering as it highlights the channel through which changes in service sector trade costs will lead to leakage.

The producer price increases in the manufacturing sector after an increase in the emissions tax. As a result, the effective relative price in the service sector decreases, and the relative demand for services increases. On the production side, labor is reallocated to the service sector. As a result, output in the service sector increases while output in the manufacturing sector declines. Hence, in this case, the increased emissions tax affects consumption and production in the service sector in the same direction, driven by the reduced domestic effective relative price in services. As mentioned earlier, the implicit assumption that SOE's stricter environmental regulation do not affect rest of the world's emissions dictates a proportionate increase in services consumption and production. The trade balance's lack of response to the environmental policy requires that the effects on consumption and production in the manufacturing goods' sector are balanced. As a result, this case yields zero emissions leakage.

4.2 Zero Trade Costs

We now turn to the other extreme case, an economy with zero trade costs in polluting manufacturing goods or clean services. Free trade in services ($\mu = 1$) ties domestic prices to world prices and re-introduces emissions leakage from the environmental policy. Total differentiation of the resource constraint in the long-run equilibrium (Eq. (10)) yields

$$c_x \hat{c_x} + p\ c_y \hat{c_y} = e^{\xi} x^{1-\xi}[\xi \hat{e} + (1-\xi)\hat{x}] + p\ y\ \hat{y} \tag{27}$$

We have the system of seven equations: (Eq. (14), (15), (16), (17), (18), (19) and (27), and seven unknowns: $\hat{h_x}$, $\hat{h_y}$, $\hat{x}$, $\hat{y}$, $\hat{e}$, $\hat{c_x}$ and $\hat{c_y}$. Again, the system is first solved for the change in the amount of labor in the service sector $\hat{h_y}$ and then, plugging $\hat{h_y}$ back in, we solve for $\hat{h_x}$, $\hat{y}$, $\hat{x}$, and $\hat{e}$ as before. Substituting these solutions in Eq. (27) and simplifying we find the consumption expenditure on manufacturing goods ($\hat{c_x}$). As before, letting net imports be the leakage level $L = c_x - e^{\xi} x^{1-\xi}$ totally differentiating L, plugging $\hat{c_x}$, $\hat{e}$ and $\hat{x}$ with rearrangement yields

$$\begin{aligned}\hat{L}_{free} = \Bigg[& \frac{S_{cx}}{S_{mx}} \left(\frac{\alpha_2 S_y \theta_{hx} - \alpha_1 S_x \theta_{hy}}{\theta_{hx}(1-\alpha_2) + \theta_{hy}(1-\alpha_1)} \right) \\ & + \frac{S_x}{S_{mx}} \left(\frac{\alpha_1 \theta_{hy}}{\theta_{hx}(1-\alpha_2) + \theta_{hy}(1-\alpha_1)} \right) \\ & + \frac{S_x}{S_{mx}} S_{cy} \Bigg] \frac{\xi}{1-\xi} \hat{T} \end{aligned} \tag{28}$$

where, $C = c_x + p\ c_y$, $S_x = \frac{e^{\xi} x^{1-\xi}}{C}$, $S_y = \frac{p\ y}{C}$, $S_{cx} = \frac{c_x}{C}$, $S_{cy} = \frac{c_y}{C}$ and $S_{mx} = \frac{b_x}{C}$. These shares are different from Eq. (23) since $\mu = 1$. This case has all three effects on emissions leakage, as in $\hat{L}$ in Eq. (23). The income effect is negative, and the output and substitution effects are positive with respect to emissions leakage from a change in environmental policy. In contrast to the case with no trade in services, the increased emissions tax affects consumption and production in the service sector in the opposite direction. However, the effects on consumption and production in the manufacturing sector are in the same direction. Because of the balance of payments constraint, the positive surplus in the service sector must balance with a deficit in the manufacturing sector. Thus, this case yields positive emissions leakage.

5 Numerical Analysis

In the analytical solution, the effects on leakage depend on the initial equilibrium condition and the economy's deep structural parameters. Furthermore, in the analytical solution, the relative sizes of these effects are indistinguishable. In this section, we numerically simulate these effects by calibrating our model to macroeconomic data from Canada. The results highlight the potential importance of service sector trade costs in estimating emissions leakage. We note that this approach is not an estimate of the total leakage expected if Canada were to introduce a carbon tax. To highlight the impact of service sector trade costs our model restricts other channels through which environmental regulation can lead to emissions leakage.

5.1 Data Aggregation and Calibration

In this section, we provide a numerical simulation of the theoretical model to explore the magnitude of the leakage effects we identify here for plausible parameter values. We use long-run empirical relationships to identify our model's deep structural parameters. The model is calibrated such that the calibrated economy's structure can simulate the long-run equilibrium that matches the Canadian economy's historical annual data. The data on the historical annual expenditure-based GDP of Canada during 1981-2010 is available from Statistics Canada.[31] To be consistent with our model specification, GDP is imputed by netting out government expenditure and gross fixed-capital formations. The durable, semi-durable, and non-durable goods in the data are aggregated as manufacturing goods.[32]

During the period, manufacturing goods account for 53.1% of GDP and services account for the remaining 46.9%. Of the manufacturing goods 18.9% are exported (equivalent to 10.11% of GDP), and 2.2% of services are imported (equivalent to 1.0% of total GDP). Consumption of goods accounts for 43.3% of GDP while consumption of services accounts for 48.3%. The imputed debt-to-output ratio is 2.11.[33] the total

[31]Source: Statistics Canada. Table 380-0106 Gross domestic product.

[32]The definitions of durable and non-durable goods and services are in accordance with Statistic Canada's description. The services include transportation and storage, communication, finance, insurance, real estate, professional, educational, accommodation, and wholesale.

[33]The ratio is higher than the observed debt-to-GDP ratio because of the imputed GDP.

output in our model corresponds to Canadian $ 668 billion, the average Canadian GDP during 1981-2010.

The parameter values used to calibrate the model's steady state to the Canadian economy are shown in Table 1. The share of consumption goods in the utility function (γ) is estimated by rearranging Eq. (5) and using the observed average consumption of goods and services. The average employee compensation in the Canadian economy's manufacturing and service sectors is 21% and 37% of gross outputs respectively.[34] Labor share of manufacturing's and services' output is 0.21 and 0.37, respectively. We implicitly assume a fixed payments to capital in our theoretical model. In the numerical calibration, ignoring the fixed payment to capital may not accurately represent the true calibration to the Canada's economy. However, since the model is log-linearized, the assumption of fixed payment to the capital does not affect our numerical estimates in percentage terms. The share of abatement expenditure in the manufacturing sector's output is assumed to be 2.2%, which is the level reported in Canada's Environmental Protection Expenditures in the Business Sector report.[35] The exogenous international real interest rate is 4% per annum.

The services' trade cost is available from Anderson, Milot, and Yotov (2013). The authors' estimate for the sample period (1997-2007) shows that the Canadian border is 1.63 tariff equivalent with the rest of the world .[36] The Canadian border's effect on services in the rest of the world ranges from the tariff equivalent of 23% in accommodations to 163% in wholesale services to 63% in aggregate services. Thus, we set the services' trade cost at 0.63 with $\mu(= 1 + \text{trade cost})$ as 1.63 in our model.

The world relative price of services (p) in terms of manufacturing goods is calibrated

[34]These shares are estimated over our sample period. Source: Statistics Canada. Table 383-0032 - Multifactor productivity, gross output, value-added, capital, labor, and intermediate inputs at a detailed industry level, by North American Industry Classification System (NAICS)

[35]These survey based data are only available for few irregular periods. Using levels of abatement expenditure from 1% to 10% affects the leakage rate, but not the impacts of service sector trade costs.

[36]The estimate assumes that the elasticity of substitution is 6 across the following services in Canada: transportation, communication, wholesale, finance, business, education, health, accommodation, among others.

to match the empirical trade-flow shares of manufacturing goods and services to the imputed GDP. The export share of goods to the GDP in the calibrated economy is 10.11%, and the import share of services to GDP is 1.03%.

Table 1: Parameters in the Calibrated Economy

Parameter	Description	Value
	Deep structural parameters	
$\bar{R}$	Real interest rate	0.04
ξ	Share of abatement in output of goods	0.022
$\bar{h}$	Household's endowment of labor	1
γ	Share of goods in consumption	0.57
α_1	Labor share in goods	0.21
α_2	Labor share in services	0.37
μ	Trade friction(1 + trade cost)	1.63
	Calibrated parameters	
σ	Intertemporal elasticity (risk parameter)	2
ρ	Elasticity of substitution between goods and services	2.2
p	World relative price of services in terms of goods	0.51
$\frac{\bar{d}}{Y}$	Debt-to-output ratio	2.11

5.2 Results

We first solve the system of equations for the equilibrium with an exogenously fixed emissions tax. This emissions tax is arbitrarily set at 0.1, which is equivalent to 10% of the world price of manufacturing goods in our model.[37] Then, we estimate the share of consumption, output, and both goods' and services' share of trade flows in aggregate consumption. These shares are then used to estimate the income, output, and substitution effects on emissions leakage. The sum of these effects is the total effect of an increased environmental regulation on emissions leakage, which can also be treated as the "leakage multiplier" for a unit-percentage increase in the emissions tax. The leakage multiplier is a useful way to summarize the total emissions leakage resulting from the emissions tax change. Then the leakage multiplier is used to obtain

[37] The tax rate is arbitrary, but it is set to around one quarter of the optimal tax rate in our model. Canadas recently required province level carbon taxes with a minimum tax rate of around one quarter of Canadas estimates of the social cost of carbon. Increasing the tax rate from the baseline level decreases emissions, increases leakage and increases welfare at a decreasing rate.

the total emissions leakage for a unit-percentage emissions reduction.

Table 2 shows the calibrated trade-flow shares of goods and services to aggregate output. Also the shares of consumption of goods and services to the aggregate output in the Canadian economy are shown in the table. The economy's initial steady state is provided in Table 3.

Table 2: Empirical and Calibrated Data

Description	Empirical Data (1981-2010)	Calibrated Economy
Share of traded goods in GDP	10.11%	9.50%
Share of traded services in GDP	-1.03%	-1.04%
Share of consumption of goods in GDP	43.34%	42.93%
Share of consumption of services in GDP	48.26%	46.81%

Table 3: Initial Steady State in the Calibrated Economy

Variable	Value
Aggregate output(Y)	1.512
Output of goods(x)	0.793
Output of services($p\mu y$)	0.692
Consumption of goods(c_x)	0.649
Consumption of services($p\mu c_y$)	0.708
Labor in goods(h_x)	0.389
Labor in services(h_y)	0.611
Trade flows of goods(b_x)	0.144
Trade flows of services(b_y)	-0.016
Emissions(e)	0.174
Emissions tax(T)	0.1

The estimates for the three channels through which an increased pollution tax affects emissions leakage (income, output, and substitution) are provided in Table 4. The results indicate that the income effect is negative and small, while the output and substitution effects are positive and much larger. For these parameter values, the substitution effect comprises just over three-quarters of the total leakage from increased environmental regulation. The substitution effect accounts for the largest share of emissions leakage followed by the output effect. These effects dominate the income effect. As a result, the emissions leakage is positive.

We estimate that a 1% increase in the emissions tax in Canada will reduce domestic emissions by 1.03%. This reduction in Canadian emissions is associated with a 0.086% increase in the rest of the world's emissions. This generates leakage rate of 8.4%.[38] This means for every ton Canadians reduce their CO_2 emissions, the rest of the world's emissions increase by 0.084 tons and global emissions fall by 0.916 tons.[39] While we are not seeking to estimate the overall leakage from a change in environmental policy we note that this emissions leakage estimate is comparable to estimates from similar policy counterfactuals for developed countries discussed in the existing literature. We are unaware of any estimates for Canada comparable to those presented here. Felder and Rutherford (1993) use a similar approach to estimate a policy counterfactual for OECD countries and finds 45% emissions leakage. More recently, Elliott, Foster, Judd, Kortum, Munson, Cervantes, and Weisbach (2010) estimates 40% emissions leakage for the United States.[40]

Table 4 reports emissions leakage rates for 1% reduction in domestic emissions at three levels of trade cost in services: no trade in services, non-zero trade costs, and freely traded services. For non-traded services, the emissions leakage is zero. In our model with 63% trade cost in services, the total leakage is 8.4%. For zero trade cost in services, we estimate 6.9% emissions leakage. Zero trade cost in services lowers the emissions leakage by over 18% relative to the level when using parameter values based on the literature. Our model suggests that for Canada the emissions leakage from a stricter environmental regulation is positive, but a fall in the service sector's trade cost may lower emissions leakage. These estimates may be relatively small as a fraction of the rest of the world's emissions but are significant when compared to the domestic

[38] Leakage rate is simply the change in ROW emissions divided by the reduction in domestic emissions.

[39] This discussion assumes our small economy's emissions intensity is equal to the rest of the world's. If they differed, evaluating global (net) emissions reduction would require scaling the leakage by the difference in relative emissions intensity.

[40] Many CGE models estimate leakage, but tend to focus on leakage estimates' sensitivity to parameter choices or specific policies like the Kyoto Protocol rather than emissions policy's counterfactual analysis.

economy's emissions level.

Table 4: Effects on the Emission Leakage Under Unit % Emissions Reduction

	μ	Income	Output	Terms of Trade	Total Leakage
Non-traded services	∞	-	-	-	0
Trade cost in services	1.63	-0.0002	0.021	0.063	0.084
		(-0.2%)	(25.3%)	(74.9%)	
Zero trade cost in services	1	-0.0002	0.017	0.052	0.069
		(-0.2%)	(25.3%)	(74.9%)	

Note: Each row represents the emissions leakage from a 1% reduction in domestic emissions at different levels of trade cost in services. The emissions leakage is the change in the rest of the world's emissions as a percent of domestic emissions reduction. The top row represents the emissions leakage when services are completely non-traded. The second row represents the effects on leakage under the services level of trade cost as reported in the literature. The third row (in parentheses) shows each effect's share in the emissions leakage. The fourth row represents the emissions leakage when the services' trade cost is zero. The last column represents the total emissions leakage, which is the sum of the effects identified in our model. Emissions leakage is linear for small changes in the emission tax. The domestic emissions' reduction units are percentages of baseline Canadian emissions, and the emissions leakage units are a percentage of the unit % reduction in the domestic emissions. For example, 0.084 positive leakage implies that the rest of the world's emissions will increase by 0.084% if Canada reduces 1% of its emissions compared to its pre-policy change in emissions level.

Recall that these results do not project leakage from small increases in environmental regulation in Canada. Rather, these results demonstrate the potential magnitudes of the channels we model. We make a number of simplifying assumptions to identify the effect of service sector trade costs on leakage cleanly. A full estimation of leakage from carbon regulation in Canada is beyond the scope of this paper and would require a large scale CGE model. These results indicate that carefully considering trade costs in non-polluting industries may affect the estimated leakage from those models. The magnitude of the estimated leakage is driven by a number of parameters taken from the literature. For example, ρ denotes the elasticity of substitution between goods and services. If goods and services were to become better substitutes for each other (ρ increases) the impact of higher service sector trade costs would have been muted.

5.3 Policy Implications

We can use the numerical model to analyze how modelling service sector trade costs affects environmental policies. In this section we consider how different levels of service sector trade costs impact the optimal environmental tax rate. We also analyze the effect of service sector trade costs on the effectiveness of border adjustment taxes ability to reduce leakage. For each policy we briefly discuss the implications in terms of the analytic model before employing the numerical model to document service sector trade cost's policy implications. All numerical results are calculated using the initial parametrization described in Section 5.2.

The optimal environmental tax rate is simply the environmental tax that maximizes welfare in our model. We can re-imagine the model presented in Section 2 as a social planner's problem where we first combine the optimal conditions of the households and the firms and solve for C_x,C_y, h_x, h_y and the level of emission for a given tax rate, prices and other preference parameters to obtained the indirect utility or the value function of the social planner: V(p,μ,T). The endogenous optimal tax rate will be determined by the following condition: $\frac{\partial V(.)}{\partial T}$=0.

Unfortunately, the complexity of the model makes solving for the optimal difficult. Instead we turn to the numerical model described above. We solve that model for the emissions tax level that maximizes utility at the same three levels of trade costs presented in section 5.2: infinite, 63% and zero. The results are presented in table 5. When trade costs are infinite there is no trade in services and no leakage in the small open economy. In that case, the optimal emissions tax is simply the marginal damages from emissions (D). In the baseline numerical model we have assumed that the marginal damages from emissions are 0.40, or 40% of the cost of a unit of manufacturing output. Using the level of service trade costs reported in the literature, the optimal emissions tax is 31%. Allowing for leakage reduces the optimal tax by nearly twenty-five percent. When we allow for costless trade in services the optimal emissions tax falls slightly, to

30%.

Next we turn to the impact of trade costs in services on border tax adjustments (BTA). A BTA is a tariff on imports of polluting goods that strives to offset leakage from a change in the emissions tax. The model presented in Section 2 did not include tariffs, so we must modify the key equations to allow for tariffs and to account for tariff revenue, which we assume is lump sum redistributed to consumers.[41] The model suggests that the leakage depends on three policy variables: domestic pollution tax levels (T), the BTA (τ_B) and the trade cost (μ). So, $L = L(T, \tau_B, \mu)$. At the conceptual level, the change in total leakage can be written:

$$dL = \frac{\partial L}{\partial T} dT + \frac{\partial L}{\partial \mu} d\mu + \frac{\partial L}{\partial \tau_B} d\tau_B \tag{29}$$

In the absence of a BTA, the amount of leakage caused by a change in the domestic pollution tax depends on the presence of trade costs in the service sector. As noted above, we find that trade cost amplifies leakage. The BTA, on the other hand, distorts the link between the pollution tax and leakage. As discussed in the appendix, the BTA reduces the leakage caused by domestic tax policy. The key question is how much change in the BTA is required to offset the amount of leakage caused by a particular domestic environmental policy. The required change in BTA ($d\tau_B$) is:

$$d\tau_B = [-(\frac{\partial L}{\partial T} \Big/ \frac{\partial L}{\partial \tau_b})]dT + [-(\frac{\partial L}{\partial \mu} \Big/ \frac{\partial L}{\partial \tau_b})]d\mu \tag{30}$$

The magnitude of these partial derivatives are in turn driven by consumers' price elasticities of demand. Moreover, given the general equilibrium nature of the model, the magnitude of these partials are endogenous and very much depend on the policy regimes in effect.[42] From Proposition 2, equation 25 and equation B.11 (in the ap-

[41]In the appendix we describe the changes to the model required to estimate the impact of tariffs on trade and leakage.

[42]In partial equilibrium we could separate these distortions by decomposing leakage into three terms: $dL = \frac{\partial L}{\partial \mu}|_{(\bar{T},\bar{\tau_B})} d\mu + \frac{\partial L}{\partial \tau_B}|_{(\bar{T},\bar{\mu})} d\tau_B + \frac{\partial L}{\partial T}|_{(\bar{\mu},\bar{\tau_B})} dT$. We could then partially differentiate the third term

pendix), it is clear that the magnitude of the ratios in parentheses on the RHS are positive. This implies that for a given domestic environmental policy, the amount of BTA required to offset the leakage depends on whether there is additional trade costs in the service sector. At the same time, as shown before, the amount of leakage caused by a given environmental policy depends on the presence of additional trade cost in the service sector. Without making assumptions on parameter values we cannot find these magnitudes. Generally, increasing the BTA increases the price of consuming the dirty good (c_x), which leads to less consumption of both goods through price and income effects. The more price sensitive dirty good consumers are, the smaller the BTA required to offset leakage.

Table 5: Policy implications of service sector trade costs

Case	μ	(1) Optimal Emissions Tax	(2) No Leakage BTA	(3) 50% Leakage BTA
Non-traded services	∞	40%	0	0
Trade cost in services	1.63	31%	0.0136%	0.0069%
Zero Trade cost in services	1	30%	0.0178%	0.0090%

Note: Each row reports results of the model for a particular level of service sector trade costs. The optimal emissions tax column reports the pollution tax that maximizes welfare in the model. The "No Leakage BTA" column reports the tariff rate needed to completely offset leakage from a 1% increase in the pollution tax. The "50% Leakage BTA" column reports the tariff rate needed to offset fifty percent of the leakage from a a 1% increase in the pollution tax.

We investigate two levels of BTA in our simulations. A BTA that offsets 100% of the leakage from imports and a BTA that offsets 50% of leakage from imports. We use the numerical model to perform a search over possible tariff rates and identify the level that eliminates leakage, which we report in column 2 as the "No Leakage BTA". In every case, we model the same 1% increase in the emissions tax, from 0.1 to 0.101, as described in Section 5.2.[43] The magnitude of the BTA's are relatively low because the change in emissions tax is fairly small. The results are presented in columns 2 and

which is the leakage effect with respect to the BTA. Unfortunately, the resulting expression does not have obvious economic interpretation.

[43] As we describe in the appendix, the initial level of emissions tax and leakage play a role in determining the level of the BTA. At different parameterizations of the model the BTA can differ significantly.

3 of Table 5. In the absence of trade in services there is no leakage in our small open economy and thus no BTA is required. Using the level of service trade costs reported in the literature, the BTA that eliminates leakage is 0.0136% and the BTA required to reduce leakage by half is 0.0069%. That implies that a 0.014% tariff on imported manufactured goods can offset the leakage from a 1% increase in the emissions tax. When we assume costless trade in services the border adjustment that offset leakage increases to 0.018%.

It is not obvious that the border adjustment tax would increase as service sector trade costs decrease. The leakage rate decreases from 8.4% to 6.9%, but the BTA required to offset that leakage actually increases. A net service importer with no trade cost or lesser trade cost in services will have less consumption and more production of the dirty good compared to an economy facing trade cost in service sector. With lesser trade cost, the economy will import and consume more service good. As a result consumption of manufacturing good will drop. In this parametrization of the model, the trade costs effect is larger than the lower leakage affect. This means that it takes a higher BTA to offset the lower level of leakage.

Returning to equation 30, we can use the results of our numerical simulation to understand the effect of BTAs on leakage. The zero trade cost in services simulations eliminate the second term from equation 30 and lead to leakage BTA estimates of 0.0178%. The 63% service sector trade cost simulation produces a BTA estimate of 0.0136%, implying that allowing for that level of service sector trade costs reduces the BTA required to fully offset leakage by around a third. At these parameter values, service sector trade costs reduce the BTA necessary to offset leakage. As long as $\left[-\frac{\partial L}{\partial T}\Big/\frac{\partial L}{\partial \tau_B}\right]_{\mu=1} > \left[-\frac{\partial L}{\partial T}\Big/\frac{\partial L}{\partial \tau_B}\right]_{\mu>1}$, a higher BTA will be required to offset 100% of the leakage in an economy with no trade cost in service sector than an economy with service sector trade costs.

The results of the policy simulations reported in this section imply that carefully modelling trade costs in the service sector can impact policy prescriptions. Introducing leakage into the model by allowing trade in services lowers the optimal emissions tax. Leakage reduces the benefits of lowering emissions by increasing emissions elsewhere, which reduces the optimal emissions tax level. Reductions in service sector trade costs increase the Border Tax Adjustment, while decreasing leakage because reduced service sector trade costs lead to reduced consumption of the dirty good. This result highlights the benefit of using the numerical model for policy analysis.

6 Conclusion

In this study, we build an analytical general equilibrium model of a small open economy in which we include both freely traded polluting manufacturing goods and allow for trade costs in the (clean) service sector. We decompose a small increase in pollution taxes' effects on emissions, known as emissions leakage, in the rest of the world. We extend the extensive literature on leakage from unilateral environmental regulation to show that the degree of tradability in non-polluting sectors greatly affects the amount of leakage. We also investigate the channels through which changes in environmental regulation affect emissions leakage.

When services are completely non-traded, we find that increases in environmental regulation lead to zero emissions leakage. The non-traded service sector's relative price will adjust to the new equilibrium. The global price of the polluting good, and thus global production and pollution emissions, will remain unchanged. The current literature typically assumes that services are freely traded and thus could misattribute leakage associated with services' trade costs.

In our model a stricter environmental policy leads to leakage through three channels: income, output, and substitution effects. The income effect negatively affects emissions leakage (i.e., increases in domestic pollution taxes reduce the rest of the world's emissions). The output and substitution effects lead to positive emissions leakage. Based on a model calibrated to the Canadian economy, our results suggest that the output and substitution effects dominate the income effect; thus, there is positive net emissions leakage. Our results suggest that with a stricter emissions tax, a 1% reduction in domestic emissions yields an emissions leakage of 8.4%, reducing global emissions by 0.916 ton for each ton of domestic reduction. Furthermore, we find over 18% lower emissions leakage if services' trade costs fall from the level estimated in the literature (63%) to zero.[44]

We also explore the policy implications of modelling service sector trade costs explicitly. We solve the numerical model for the optimal pollution tax at three different levels of service sector trade costs and show that the optimal tax decreases as service sector trade costs decrease. We also consider how the level of service sector trade costs affects the rate of a Border Tax Adjustment (BTA) needed to offset leakage from emissions of imports. The results indicate that the BTA needed to offset a small increase in the pollution tax is increasing as service sector trade costs fall.

In this study, we employ a small open-economy framework to simplify our model and derive analytical results for the three channels of leakage. The small economy assumption means that some channels (for example, the fuel-price effect) identified elsewhere in the literature through which leakage can occur are not present in our model. In practice our approach is equivalent to examining how changes in environmental policy affect trade flows between countries holding rest of the world environmental policy constant. While this approach is tractable and allows us to highlight how service sector trade costs affect leakage, it is not the best proxy for estimating overall levels of leakage. Future work should address whether the assumption of constant trade costs in services affect estimated emissions leakage in large-scale CGE models.

[44] Recall that these estimates are not projections of leakage, but rather demonstrate the importance of the channel we identify here.

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A Appendix: Reduced form solutions and proofs

The reduced form solutions of $\hat{h_x}$, $\hat{y}$, $\hat{x}$, and $\hat{e}$ in section 3 are

change in the manufacturing sector's labor supply

$$\hat{h_x} = -\frac{\theta_{hy}}{\theta_{hx}(1-\alpha_2)+\theta_{hy}(1-\alpha_1)}\frac{\xi}{1-\xi}\hat{T}; \tag{A.31}$$

change in the service sector's outputs

$$\hat{y} = \alpha_2\frac{\theta_{hx}}{\theta_{hx}(1-\alpha_2)+\theta_{hy}(1-\alpha_1)}\frac{\xi}{1-\xi}\hat{T}; \tag{A.32}$$

change in the manufacturing goods sector's outputs

$$\hat{x} = -\alpha_1\frac{\theta_{hy}}{\theta_{hx}(1-\alpha_2)+\theta_{hy}(1-\alpha_1)}\frac{\xi}{1-\xi}\hat{T}; \tag{A.33}$$

and change in emissions

$$\hat{e} = -\left(\frac{\alpha_1\theta_{hy}}{\theta_{hx}(1-\alpha_2)+\theta_{hy}(1-\alpha_1)}\frac{\xi}{1-\xi}+\frac{1}{1-\xi}\right)\hat{T}. \tag{A.34}$$

Proof of Proposition 1:

Income effect on consumption

From Eq. (22)

$$\text{Income effect} = \frac{\alpha_2 S_y \theta_{hx} - \alpha_1 S_x \theta_{hy}}{\theta_{hx}(1-\alpha_2) + \theta_{hy}(1-\alpha_1)} \tag{A.35}$$

Plugging $\alpha_1 = \frac{1}{(1-\xi)} \frac{w h_x}{e^{\xi} x^{1-\xi}}$ and $\alpha_2 = \frac{w h_y}{p\,\mu\,y}$ from the firm's first order conditions (where w is wage in an initial equilibrium) and plugging the shares $S_x = \frac{e^{\xi} x^{1-\xi}}{C}$, $S_y = \frac{p\,\mu\,y}{C}$, $\theta_{hx} = \frac{h_x}{h}$ and $\theta_{hy} = \frac{h_y}{h}$, it yields:

$$\text{Income effect} = \frac{1}{C} \frac{w h_x h_y}{h_x(1-\alpha_2) + h_y(1-\alpha_1)} \left(-\frac{\xi}{1-\xi} \right) \tag{A.36}$$

which is negative.

Terms of trade effect on consumption

From Eq. (22)

$$\text{Terms of trade effect} = -S_x \tag{A.37}$$

which is negative.

Since, $\hat{c_x} = \hat{c_y}$ (Eq. (19)), increased emissions tax has negative effect both goods and services' consumption in a small open economy.

Proof of Proposition 4:

Substituting Eq. (26) in the resource constraint Eq. (10), the economy's trade balance (which is also the manufacturing goods' export level) is

$$e^{\xi}x^{1-\xi} - c_x = \bar{R}\bar{d} \tag{A.38}$$

Taking the log and total differentiating of both sides yields

$$s_x[\xi\hat{e} + (1-\xi)\hat{x}] - \hat{c_x} = 0 \tag{A.39}$$

where $s_x = \frac{e^{\xi}x^{1-\xi}}{c_x}$ is the share of output to consumption of goods in the manufacturing sector.

B Appendix: Border Tax Adjustment

We assume an initial border tax level τ_B on imports of the manufacturing goods at the border. Then, to accommodate the new tax level, the model extends as below.

The representative household now chooses c_x and c_y to maximize her utility (Eq. (1)) subject to a new budget constraint Eq. (B.1) which will now reflect increase in prices of the manufacturing goods as these prices now accommodate the tariff.

$$(1+\tau_B)c_x + p\ \mu\ c_y + \bar{R}\bar{d} = w\bar{h} + \pi + G \tag{B.1}$$

Recall that all prices in our model are in terms of the manufacturing good's world output price. As with the emission tax level, the border tax is also then interpreted in terms of the output price.

As before, using λ as the Lagrangian multiplier for the budget constraint, the household's maximization problem is now

$$\begin{aligned}\max_{c_x,c_y}\ \mathscr{L} = &\frac{\left\{\left(\gamma^{\frac{1}{\rho}} c_x^{\frac{\rho-1}{\rho}} + (1-\gamma)^{\frac{1}{\rho}} c_y^{\frac{\rho-1}{\rho}}\right)^{\frac{\rho}{\rho-1}}\right\}^{1-\sigma} - 1}{1-\sigma} \\ &+ \lambda\Big\{w\bar{h} + \pi + G - (1+\tau_B)c_x - p\ \mu\ c_y - \bar{R}\bar{d}\Big\}\end{aligned} \tag{B.2}$$

where the government transfer to the household now includes the border tax revenue i.e. $G = Te + \tau_B(c_x - e^{\xi}x^{1-\xi})$, where $c_x - e^{\xi}x^{1-\xi}$ is the net import of the manufacturing goods.

The first order conditions are then

$$\left(\gamma^{\frac{1}{\rho}} c_x^{\frac{\rho-1}{\rho}} + (1-\gamma)^{\frac{1}{\rho}} c_y^{\frac{\rho-1}{\rho}}\right)^{\frac{1-\sigma\rho}{\rho-1}} \left(\frac{\gamma}{c_x}\right)^{\frac{1}{\rho}} = \lambda(1+\tau_B) \tag{B.3}$$

$$\frac{C_x}{C_y} = \frac{\gamma}{1-\gamma}\left(\frac{1+\tau_B}{p\ \mu}\right)^{-\rho} \tag{B.4}$$

On the firms side, the representative firm in each sector maximizes the following profit functions:

$$\max_{h_x, e} \pi_x = (1+\tau_B) e^{\xi} (h_x^{\alpha_1})^{1-\xi} - w h_x - T e \tag{B.5}$$

$$\max_{h_y} \pi_y = p \, \mu \, h_y^{\alpha_2} - w h_y \tag{B.6}$$

The optimal conditions in this case are

$$(1+\tau_B)\alpha_1(1-\xi) \, \left(\frac{e}{x}\right)^{\xi} \frac{x}{h_x} = p\mu\alpha_2 \frac{y}{h_y} \tag{B.7}$$

$$(1+\tau_B)\xi \left(\frac{x}{e}\right)^{1-\xi} = T \tag{B.8}$$

As the tariff is simply an exchange in hands within the economy, the economy's resource constraint remains the same

$$e^{\xi}(h_x^{\alpha_1})^{1-\xi} - c_x + p \, \mu \, (h_y^{\alpha_2} - c_y) = \bar{R}\bar{d} \tag{B.9}$$

Keeping the border tax level constant, taking logs and totally differentiating Eq. (B.4), (B.7), (B.8), (B.9), the two production functions and the labor market clearing condition, we get a system of seven equations in terms of emission tax percentage change for a given border tax level. As before, then, the system is solved for the seven unknowns: labor supply in the two sectors, $\hat{h_x}$ and $\hat{h_y}$; outputs in the two sectors, $\hat{x}$ and $\hat{y}$; emissions $\hat{e}$; and consumption of the two goods, $\hat{c_x}$ and $\hat{c_y}$. Keeping the border tax constant under a emission tax change, the reduced form solutions yields the same as before.

Then, the leakage from a small increase in the emission tax for a given border tax level is obtained by total differentiating the net imports i.e. $L = (1+\tau_B)(c_x - e^{\xi} x^{1-\xi})$ which yields

$$\hat{L} = \left[\frac{S_{cx}}{S_{mx}} \left(\frac{\alpha_2 S_y \theta_{hx} - \alpha_1 S_x \theta_{hy}}{\theta_{hx}(1-\alpha_2) + \theta_{hy}(1-\alpha_1)} \right) + \frac{S_x}{S_{mx}} \left(\frac{\alpha_1 \theta_{hy}}{\theta_{hx}(1-\alpha_2) + \theta_{hy}(1-\alpha_1)} \right) + \frac{S_x}{S_{mx}} S_{cy} \right] \frac{\xi}{1-\xi} \hat{T} \tag{B.10}$$

where, $C = c_x + p\ \mu c_y$ is an aggregate consumption with zero border tax level, $S_x = \frac{e^{\xi} x^{1-\xi}}{C}$, $S_y = \frac{p\mu y}{C}$, $S_{cx} = \frac{c_x}{C}$, $S_{cy} = \frac{p\mu c_y}{C}$ and $S_{mx} = \frac{(1+\tau_B)b_x}{C}$. Except S_{mx}, these shares are similar from Eq. (23).

To solve for the marginal effect on the leakage from the increase in emission tax, we partially differentiate Eq.(B.10) w.r.t. the border tax τ_B. Rearranging, the differentiation yields

$$\frac{\partial \hat{L}}{\partial \tau_B} = -\frac{\hat{L}}{1+\tau_B} < 0 \tag{B.11}$$

This shows that an increase in border tax reduces the leakage, from an emission tax increase, in proportion to the initial border tax level and the initial amount of leakage. The higher the initial border tax level, the lower the marginal effect on the leakage reduction.