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GTAP Annual Conference on Global Economic Analysis
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Emissions Leakage, Environmental Policy and Trade Frictions

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March 2016

Abstract

We develop a two-good general equilibrium model of a small open economy to decompose effects of a unilateral strengthening of environmental policy in a country on pollution emissions in the rest of the world, known as emissions leakage. We show analytically and numerically that the level of emissions leakage crucially depends upon the level of trade frictions 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. We solve for the amount of leakage from a small strengthening in environmental regulation. In a special case with free trade in manufacturing and no trade in services there is no leakage. Allowing for trade in services, we analytically solve for three effects of environmental regulation on emissions leakage: income, output and terms of trade. The income effect generates negative leakage while the output and terms of trade effects generate positive leakage. We solve for the relationship between trade frictions in the service sector and leakage, and show that at lower levels of service sector trade friction, leakage from a small strengthening of environmental regulation decreases (increases) if services are imported (exported). Finally, we calibrate the model to the Canadian economy to estimate relative sizes of these effects. We find that leakage is about eighteen percent lower when using trade friction levels estimated from the literature rather than assuming no trade frictions 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 reducing domestic employment without a corresponding reduction in pollution emissions.

In this paper we develop a two good, one factor, small open economy model with pollution emissions associated with production of one of the goods. 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 there is no trade in the clean good.

This result demonstrates the importance of carefully modeling trade costs when evaluating the emissions leakage consequences of unilateral changes in environmental policy. In our model with no trade in services, an increase in the 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 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 changes in rest of the world emissions after a unilateral strengthening of domestic environmental regulation into three distinct channels: an income effect, an output effect and terms of trade effect.

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

The output and terms of trade effects cause positive leakage. Through the output effect a pollution tax increase leads to a decline in manufacturing sector production. This decreases the exports of manufacturing goods and rest of the world production (and pollution emissions) increases to fill the gap. In the terms of trade effect a pollution tax increase leads to a relative price increase, reducing the terms of trade for the manufacturing sector. This has two impacts in our model. First it decreases exports of manufacturing goods and again foreign production and pollution emissions rise in response. Secondly, the relative price change also reduces domestic consumption of manufactured goods as households substitute away from consuming manufactured products to services which increases exports of manufacturing goods and leading to a fall in rest of the world production. We show that the effect in production dominates the effect on consumption and that on net the terms of trade effect is to cause 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 size of the effects we calibrate our model to the Canadian economy. In simulations with trade costs in services taken from the literature emissions leakage is 18% higher than when we simulate free trade in services. The simulations also demonstrate that among the channels in our model the terms of trade effect dominates. The income effect, which could be

a source of negative leakage (decreased rest of the world 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 service sector trade.

Two distinct methods are used in the literature to study leakage - analytical and computable general equilibrium (CGE) models. Among analytical models, recent papers have focused on identifying channels through which leakage operates and 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 paper decomposes emissions leakage into two effects: income and production effects. The reallocation of factors across the two sectors in their model due to an environmental policy leads to the income and production effects.

Baylis, Fullerton, and Karney (2014) models a two good, two factor, two country framework. The paper shows that the emissions leakage depends upon the two elasticities of substitutions: 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 two effects: terms of trade effect (TOT) and abatement resource effect (ARE). An increase in the price of the home-country's good leads to positive leakage as consumers substitute to the other country's good (the terms of trade effect), while firms in dirty sector substitute dirty inputs to 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 service sector trade costs are modeled directly.

Baylis, Fullerton, and Karney (2015) extends Baylis, Fullerton, and Karney (2014) to analytically decompose the results of a CGE model into seven distinct leakage effects. We are able to identify three analogous effects in our model: income, output

and terms of trade effects. We also find the income has negative, output effect and the terms of trade have positive effects on emissions leakage. Many of the effects in Baylis, Fullerton, and Karney (2015) do not appear in our model due to our focus on a small economy. Because our economy is a price taker, its environmental policy has no impact on world prices.¹ This assumption reduces the number of channels through which environmental policy (or trade costs) can affect emissions leakage allowing us to focus on the impact of trade costs in the service sector 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 focus on the emissions leakage impact of trade costs in the service sector.

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, language or cultural barriers that inhibit trade. Many personal services must be provided on location in real time (haircuts are the classic example) and are therefore untradeable.²

Most of the leakage literature has focused on trade in the polluting sector. While it is widely understood that in general equilibrium the linkage between the level of trade across sectors would affect leakage, it has not been widely studied. The impact that trade costs in the clean sector can have on emissions leakage has been largely overlooked.³ 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.

¹For example, several researchers have modeled a “fuel price” effect, in which the introduction of environmental regulation reduces the global price of dirty fuels. In these models this is one of the largest sources of leakage. We assume our economy’s policy actions do not affect world price so this effect is not present in our model.

²Anderson, Milot, and Yotov (2012) finds that trade barriers in services in Canada are much larger than trade barriers in goods. See Borchert, Gootiiz, and Mattoo (2012) for more details on service trade restriction comparison across over one hundred countries. See van der Marel and Ben (2013) for a discussion on the trade costs for different types of services.

³See Hoel (1996) for a notable exception.

Our small open economy framework is new to the leakage literature, but it has been used in several papers that examine the relationship between trade and the environment.⁴ One possible reason is that small open economy models do not explicitly quantify emissions in the rest of the world. However, assuming that economies in the rest of the world are symmetric in emissions intensity but differ only by the stringency of environmental regulation, we show that the direction and the determinants for emissions leakage can be evaluated in a small open economy model.⁵

While we use an analytical model to evaluate the impact of trade costs in services on leakage, our results also 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. 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.⁶

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

⁴See Copeland (1994) and Copeland and Taylor (2005) for examples.

⁵Different levels of emissions intensity between the domestic and rest of the world economy would merely scale our results up or down depending on the direction of the difference.

⁶Fugazza and Maur (2008) discusses the importance of modeling non-tariff barriers, which are a form of trade costs, in a CGE model. Walsh (2006) has a review of the difficulties in estimating trade costs in services. Neither of these papers is focused on the relationship between environmental policy and leakage.

emissions leakage negatively (or positively) depending upon whether an economy imports (or exports) services.

Several papers 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 papers find that elasticities of substitution in the production and utility functions affect leakage. The authors also note that little prospect of negative leakage (in a large multiregion model of the United States), because of the assumption of small fossil fuel supply elasticities. While our model is much simplified relative to these CGE models, by incorporating a given level of trade cost in services allows us to introduce another dimension across which leakage may vary.⁷

The rest of the 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 on leakage. To provide intuition this section provides 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 section investigates the marginal effects of trade cost in services on the emissions leakage. It then provides a more general solution showing how the amount of leakage varies with trade costs in the service sector. Section 4 examines the relative magnitudes of leakage at different levels of service sector trade costs by calibrating the model to the Canadian macroeconomic data. Section 5 concludes.

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

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 that represents all goods that emit some level of carbon emissions during their production process. The service good represents all outputs that do not emit any carbon emissions during their production process.⁸ Initially, we assume that manufacturing goods are freely traded internationally, but the service sector faces a trade friction. The friction represents the degree of trade costs in services. The trade costs in services may result from visa fees, requirement of licenses or other professional standards, country specific technical standards, legal hurdles, or differences in language and culture. In our model, we are agnostic about the types of barriers that cause these trade costs in services but we model them generally as iceberg trade costs. We, initially, assume a fixed world price ratio for goods and services such that the economy exports manufacturing 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 role of the domestic government 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

⁸This classification is consistent with Levinson (2010) which finds that in the U.S. economy, services account for a tiny fraction of overall emissions.

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

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

to abate emissions or pay an emissions tax. Labor is immobile across countries though mobile across sectors. For simplicity, we assume that the population growth is zero. The parameters and policy variables are assumed such that an interior solution always exists for all decisions variables.

We employ a constant relative risk aversion (CRRA) utility function with a constant elasticity of substitution (CES) aggregated over the consumption of the goods and services. The preferences of the representative household are given by

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

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 while σ is the constant relative risk aversion parameter. We denote S as the stock of pollution emissions and $D \geq 0$ is the weight of dis-utility from pollution emissions. The stock of pollution emissions $S = e + e_{row}$ where e is the level of emissions and e_{row} is the level of emissions in the rest of the world. We assume that the representative household inelastically supplies her labor (\bar{h}) to firms (i.e. $h_x + h_y = \bar{h}$), where h_x is the supply of labor to the manufacturing sector and h_y is the supply of labor to the service sector. The stock of emissions is a negative externality that lowers utility but it has no effect on production.¹¹

The household is subject to the following budget constraint

$$c_x + p \mu c_y + \bar{R}\bar{d} = w\bar{h} + \pi + G \quad (2)$$

where p is the fixed world relative price ratio of services to manufacturing goods and

¹¹Copeland (1994) and Angelopoulos, Economides, and Philippopoulos (2010) each model the impact of pollution on consumers in a similar way.

μ is the trade factor defined such that $p^d = p \mu$ represents domestic price. In a world with costless trade in services $\mu = 1$.¹² 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 government to the household is represented by G . The manufacturing good is the numeraire with an assumed price of 1 so 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

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

The first order conditions are

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

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

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.¹³ The production function in the manufacturing sector is $x = h_x^{\alpha_1}$ and the production function

¹²Note that μ can be defined as $\mu = 1 + f$ for service importers where, f is the iceberg trade cost on services. For service exporters $\mu = \frac{1}{1+f}$. If services are exported then the domestic price $p^d = \frac{p}{1+f}$ and if services are imported then the domestic relative price of services is $p^d = p(1+f)$.

¹³The labor factor can also be interpreted as a composite of capital and labor, or any arbitrary non-pollution inputs.

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 elasticities of factor inputs in outputs of manufacturing goods and services respectively. Following Copeland and Taylor (2003), we assume that the production of output in the manufacturing sector (x) generates emissions (e) as a joint output of the production.¹⁴ Continuing to follow Copeland and Taylor (2003), we assume that firms have access to a pollution abatement technology and that firms spend a fraction (θ) of its output in 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 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 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 level of the tax is higher than ξ .¹⁵

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

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

$$\max_{h_y} \pi_y = p \mu h_y^{\alpha_2} - wh_y \quad (7)$$

¹⁴This approach has been used in a series of influential general equilibrium trade and environment papers including Copeland (1994) and Antweiler, Copeland, and Taylor (2001) among others.

¹⁵We require this assumption since for any emissions tax level below ξ firms do not find it cost effective to abate emissions and thus choose only to pay the tax. This abatement technology does not admit emissions taxes of 0. See Copeland and Taylor (2003) for a full description.

The optimal conditions are

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

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

Firms employ labor (Eq. (8)) such that the marginal return to labor is equal across the two sectors.¹⁶ Eq.(9) shows that firms optimally abate such that the marginal cost of abatement of emissions is equal to per unit emissions tax.

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

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

The trade balance is then equal to the interest payments to the debt.¹⁷ The transfer from the government to households is

$$G = T e \quad (11)$$

The trade flows in the manufacturing and service sectors are

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

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

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

In our model the level of emissions in the rest of the world is not explicit since

¹⁶Recall that labor is mobile across sectors, but not across countries.

¹⁷This allows the country to run consistent trade deficits or surpluses in aggregate across the two industries.

the model does not have an explicit production function of the rest of the world. We assume that a unilateral increase in pollution taxes would not alter the environmental regulation in the rest of the world. The rest of the world's consumption is not affected by a change in domestic emissions tax level since the world's relative price is fixed. The level of outputs in each sector in the rest of the world would vary depending upon the changes in the trade flows in the corresponding sectors.¹⁸ Hence, we define the change in trade flows in the manufacturing sector b_x as the "leakage" of emissions.¹⁹ For an economy that imports manufacturing goods, an increase in imports suggests an increase in the rest of the world emissions and thus leakage.²⁰

3 Analytical Solution

In this section, we analytically solve the model through log-linearization. Taking log 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 $\hat{\cdot}$). 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

$$\xi \hat{e} + (1 - \xi) \hat{x} - \hat{h}_x = \hat{y} - \hat{h}_y \quad (14)$$

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

$$\hat{e} = \hat{x} - \frac{1}{1 - \xi} \hat{T} \quad (15)$$

¹⁸The rest of the world is large in size compared to the small economy which implies that the change in the trade flows reflects the change in level of emissions in the rest of the world with respect to the emission level in the small economy.

¹⁹Alternatively, 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.

²⁰If an economy exports manufacturing goods then a reduction in exports implies leakage.

Log-linearization of the production functions yields

$$\hat{x} = \alpha_1 \hat{h}_x \quad (16)$$

$$\hat{y} = \alpha_2 \hat{h}_y \quad (17)$$

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

$$\theta_{hx} \hat{h}_x + \theta_{hy} \hat{h}_y = 0 \quad (18)$$

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) yields

$$\hat{c}_x = \hat{c}_y \quad (19)$$

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

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

We have a system of seven equations: optimal labor Eq. (14), optimal emissions (15), two production functions: (16) and (17), labor constraint (18), optimal relative consumption (19) and resource constraint (20); and 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} , 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

$$\hat{h}_y = \frac{\theta_{hx}}{\theta_{hx}(1 - \alpha_2) + \theta_{hy}(1 - \alpha_1)} \frac{\xi}{1 - \xi} \hat{T} \quad (21)$$

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

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

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 terms of trade 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 terms of trade effect.²¹

The third term outside of the bracket is a scale factor $\left[\frac{\xi}{1 - \xi} \right]$ which is the ratio of emission expenditure to potential output in the manufacturing sector, which we term as the abatement resource factor. This augments the income and terms of trade effect such that higher ξ increases the net effect of emissions tax on consumption as abatement becomes less effective. The impact of this factor differs from other studies in this literature that find an abatement resource effect leading to negative leakage. In those studies, the taxed sector substitutes to clean resources shrinking output in other sector leading to negative leakage.²²

From Eq.(22) and (19), we note that a small increase in the emissions tax in a small

²¹These 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, then the first term should be interpreted as the indirect effect and the second term as the direct effect of the emissions tax on consumption.

²²Our model has only a single (clean) input and thus no scope for factor substitution. Polluting firms endogenously abate emissions by, in effect, reducing output.

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 due to the negative impacts of both the income and the terms of trade effect.*

Proof: See appendix.

After an increase in the producer price in the manufacturing sector due to an emissions tax increase there are two channels through which income is affected. First, the increase in the emissions tax also increases the effective price of consumption, and so consumption of both goods and services decreases. Secondly, labor is reallocated to the service sector, reducing the real wage. This will reduce the real income available to consumers and, as a result, consumption of manufacturing goods will decrease. 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 decrease.²³

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.*

It is evident from Eq. (19) which 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 or 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

²³This is consistent with Baylis, Fullerton, and Karney (2015) that identifies a “pure income effect” that reduces leakage. The pure income effect in that paper arises from the assumption that tax revenue is spent on a public good rather than rebated.

consumption of manufacturing goods \hat{c}_x , emissions \hat{e} and outputs in the manufacturing sector \hat{x} , with rearrangement yields the leakage

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

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 the aggregate consumption.

Proposition 2. *A small increase in an emissions tax in a small open economy has three leakage effects: income, output and terms of trade. The income effect is negative, and both output and terms of trade 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 reducing 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 an increase in input prices due to the emissions tax policy (See Eq.(16)). This decreases the exports of manufacturing goods and leads 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 terms of trade effect, and it has two components: effects on (1) consumption and (2) output of manufacturing goods due to the increase in the relative price of the good. The increase in the emissions tax

increases the producer's price and worsens terms of trade in the manufacturing sector. This decreases the exports of manufacturing goods. This leads to a positive leakage effect which is shown by $\frac{S_x}{S_{mx}}$. As mentioned earlier, the increase in the producer's price also impacts consumption of goods negatively, as households substitutes goods with services. The substitution in consumption thus 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. This factor has economy wide resource effect, and it increases with an increase in ξ (the share of abatement expenditure on output in the manufacturing sector). Abatement uses real output resources from the manufacturing sector. The lower the fraction of output in the manufacturing sector 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.

3.1 Specific Cases

In this section we explore extreme cases of an economy with no trade in services (section 3.1.1) and costless trade in services (section 3.1.2) to better understand how leakage is affected by the level of trade in the clean good. The general effects of trade costs on emissions leakage is examined in section 3.1.3.

The case with freely traded goods and services assumes that the world relative price is exogenous to the emissions tax change. In the case with no trade in services, the emission tax affects the domestic relative price of services. Both of these cases adopt extreme assumptions on tradability of goods and services. However, the impact of the emissions tax change on the relative price is an empirical question. Hoel (1996) argues

that the immunity of relative price to the emissions tax change is not practical. On the other hand, Baylis, Fullerton, and Karney (2014) find a causal relation between the change in the relative price and 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 do not adjust. The case with free trade in goods and services also highlights the relative importance of the channels through which emissions tax change affects leakage.

3.1.1 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

$$y = c_y \tag{24}$$

Then, the trade balance of the economy 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.²⁴

Proposition 3. *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 manufacturing sector leads to zero emissions leakage. The reduction in relative price of services proportionally decreases consumption and outputs of manufacturing goods and thus zero emission leakage.*

Proof:

Substituting Eq. (24) in the resource constraint Eq. (10), the trade balance (which is

²⁴In this way the economy can run a persistent trade surplus in the steady state.

also the export level) of the economy is

$$e^\xi x^{1-\xi} - c_x = \bar{R}\bar{d} \quad (25)$$

Taking the log and total differentiating of both sides yields

$$s_x[\xi\hat{e} + (1 - \xi)\hat{x}] - \hat{c}_x = 0 \quad (26)$$

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

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 increase in the emissions tax. As a result of the decline in the relative price of services, the consumption of manufacturing goods declines in proportion with the decline in output in the manufacturing sector. In aggregate, the export level of manufacturing goods remains the same. The adjustment in the relative price of services affects both consumption and output in proportion, preventing emissions 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 increase in emissions tax affects consumption and production in the service sector in the same direction, driven by the reduction in the domestic effective relative price in services. Also, the effects on consumption and production in the manufacturing good sector are balanced. As the result, this case yields zero emissions leakage.

3.1.2 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 ($\mu = 1$) pins down domestic prices to world prices and re-introduces emissions leakage from environmental policy. Total differentiation of the resource constraint in the long-run equilibrium (Eq.(10)) yields

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

Then, 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 amount of labor in the service sector \hat{h}_y

$$\hat{h}_y = \frac{\theta_{hx}}{\theta_{hx}(1 - \alpha_2) + \theta_{hy}(1 - \alpha_1)} \frac{\xi}{1 - \xi} \hat{T} \quad (28)$$

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, the consumption expenditure on manufacturing goods (\hat{c}_x) is then

$$\hat{c}_x = \left[\frac{\alpha_2 S_y \theta_{hx} - \alpha_1 S_x \theta_{hy}}{\theta_{hx}(1 - \alpha_2) + \theta_{hy}(1 - \alpha_1)} - S_x \right] \frac{\xi}{1 - \xi} \hat{T} \quad (29)$$

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

As before, letting net imports be the level of leakage $L = c_x - e^\xi x^{1-\xi}$ totally differentiating L , plugging \hat{c}_x , \hat{e} and \hat{x} with rearrangement yields

$$\begin{aligned}\hat{L}_{free} = & \left[\frac{S_{cx}}{S_{mx}} \left(\frac{\alpha_2 S_y \theta_{hx} - \alpha_1 S_x \theta_{hy}}{\theta_{hx}(1 - \alpha_2) + \theta_{hy}(1 - \alpha_1)} \right) \right. \\ & + \frac{S_x}{S_{mx}} \left(\frac{\alpha_1 \theta_{hy}}{\theta_{hx}(1 - \alpha_2) + \theta_{hy}(1 - \alpha_1)} \right) \\ & \left. + \frac{S_x}{S_{mx}} S_{cy} \right] \frac{\xi}{1 - \xi} \hat{T}\end{aligned}\quad (30)$$

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 and their effects on emissions leakage are as in \hat{L} in Eq. (23). The income effect is negative, output and terms of trade are positive with respect to emissions leakage from an change in environmental policy. Note that in contrast to the case with no trade in services, the increase in 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 has to balance with a deficit in the manufacturing sector and thus, this case yields positive emissions leakage.

3.1.3 Effect of Service Trade Cost on Emissions Leakage

In this section, we explore how emissions leakage varies at different levels of service sector trade costs. There has been a general decrease in trade costs in services over time Information technology has facilitated trade in services and countries have been pressured to roll back service trade restrictions (Miroudot and Shepherd, 2014; Gervais and Jensen, 2014). The special cases above suggest that the level of trade cost in services matters crucially for 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

$$\begin{aligned} \frac{\partial \hat{L}}{\partial \mu} = & \left[\frac{S_{cx}}{\mu S_{mx}} \left(\frac{\alpha_2 S_y S_{cx} \theta_{hx} + \alpha_1 S_x S_{cy} \theta_{hy}}{\theta_{hx}(1-\alpha_2) + \theta_{hy}(1-\alpha_1)} \right) \right. \\ & \left. + \left(\frac{S_x S_{cy}}{\mu S_{mx}} \right) \right] \frac{\xi}{1-\xi} \hat{T} \end{aligned} \quad (31)$$

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 service sector trades increase. This suggests that the negative income effect from an increase in the level of environmental regulation is dampened in high service sector trade cost countries. The second term $\left(\frac{S_x S_{cy}}{\mu S_{mx}} \right) > 0$ is the change in the terms of trade effect on emissions leakage which is also positive. This suggests that the positive terms of trade effect from an increase in the level of environmental regulation on leakage is amplified by higher service sector trade costs. As both effects are positive this suggests that increases in the level of environmental regulation have larger leakage effects in high trade cost countries.

To explore the implications of this result, consider two countries, both service importers. One country has relatively high service sector trade costs and the other relatively low. Imagine they both increase the level of environmental regulation by the same amount. Equation 23 shows that our model predicts leakage will increase in both countries. Equation 31 tells us that leakage will increase by more in the high service sector trade cost country.

In both countries the income effect on leakage from an increase in the environmental tax will be negative. Consumers will consume less of both goods after the environmental tax increase. This will lead to excess supply in the home country and more manufacturing exports, reducing rest of the world production and thus rest of the world emissions.²⁵ Equation 31 tells us that this effect will be dampened in the high trade cost country. The relatively high price of services in the high trade cost country

²⁵There is also a “pure income effect” in which labor reallocation across sectors reduces wages and consumption.

means that the loss in consumption associated with an increase in the environmental tax will be smaller. The smaller the reduction in consumption, the lower the negative leakage associated with an increase in the environmental tax.

Similarly, in both countries the terms of trade effect will be positive. An increase in the environmental tax will make the (imported) manufacturing good more expensive. That will lead a reduction in manufacturing consumption, and an increase in manufacturing production in the rest of the world and an increase in pollution emissions. The high service sector trade cost country will find it relatively more expensive to substitute from the manufactured good to services after the price change. This will magnify the positive leakage effect in the high service sector trade cost country.

In our model service sector trade costs have no impact on output, holding income and terms of trade constant. For that reason there is no difference in the output effect across the low and high service sector trade cost countries. The trade cost reduction reduces 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, in our model, price is defined relative to the output price of manufacturing goods. In other words, the domestic prices of services and manufacturing goods fall by the same proportion as the trade cost, for an increase in emissions tax. That means that the labor allocation will not change and output in both sectors is constant.²⁶

After rearranging Eq. (31), the equation can be rewritten as

$$\frac{\partial \hat{L}}{\partial \mu} = \frac{S_{cx}}{\mu} \hat{L} > 0 \quad (32)$$

where, $S_{cx} = \frac{c_x}{c_x + p\mu c_y}$. This leads to proposition 4.

Proposition 4. *Emissions leakage is amplified by trade costs in services. For service*

²⁶Also, differentiating manufacturing goods output \hat{x} and \hat{e} (see appendix) with respect to μ shows no effect on the change in these variables. 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 .

importers, an increase in environmental regulation is associated with more leakage when trade costs in services 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 the result of the income and terms of trade effect. For a fall in the trade costs in services, the sign of change in μ is negative when services are imported and positive when services are exported. The fall in trade costs in services thus decreases the income and terms of trade effect on emission leakage if services are imported and increases the income and terms of trade effects on the emissions leakage if services are exported. The output effect, however, does not change with the sign of the trade balance. Hence, if services are imported, the fall in trade cost in services has negative effect on the emissions leakage and if services are exported, there is a positive effect on emissions leakage.

Corollary 4.1. *The marginal effect of a fall in trade cost in services on the emissions leakage is larger for higher share of manufacturing goods in aggregate consumption, smaller μ and higher emissions leakage from the emissions tax policy.*

The marginal effect of trade costs on emissions leakage depends upon the magnitude of existing trade costs, the share of consumption of manufacturing goods in aggregate consumption and the magnitude of the emissions leakage itself. Evident from Eq. (32), the emissions leakage is affected by trade cost reduction through the income and terms of trade effect on the consumption of manufacturing goods. When services are imported the relative price of domestic services decreases as trade costs in services fall, leading to a decrease in consumption of manufacturing goods at the margin. This decrease in manufacturing good consumption increases exports, all else equal, and thus reduces the terms of trade effect on emissions leakage. The larger the share of consumption of manufacturing goods in aggregate consumption the large the terms of trade effect on emissions leakage.

A fall in trade costs in services also increases households' real income. This leads to an increase in consumption of manufacturing goods which reduces the income effect on emissions leakage. The marginal effect on the emissions leakage due to the income effect is higher if the initial μ is smaller, implying a bigger effective relative change in μ compared to the initial μ .

4 Numerical Analysis

In the analytical solution, the effects on leakage depend on the initial condition and deep structural parameters of the economy. Further, in the analytical solution, the relative size of these effects are not distinguishable. In this section, we numerically estimate these effects by calibrating our model to macroeconomic data from Canada.

4.1 Data Aggregation and Calibration

We use long-run empirical relationships to identify the deep structural parameters in our model. The model is calibrated such that the structure of the calibrated economy can simulate the long-run equilibrium that matches the historical annual data of the Canadian economy. The data on the historical annual expenditure based GDP of Canada from 1981-2010 is available from Statistics Canada.²⁷ 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.²⁸

During the period manufacturing goods account for 53.1% of GDP and services account for remaining 46.9%. 18.9% of the manufacturing goods are exported (equivalent to 10.11% of GDP) and 2.2% of services are imported (equivalent to 1.0% of

²⁷Source: Statistics Canada. Table 380-0106 - Gross domestic product.

²⁸The definition 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 services, professional, educational, accommodation, wholesale and other services.

total GDP). Consumption of goods accounts for 43.3% of GDP while consumption of services account for 48.3% of GDP. The imputed debt to output ratio is 2.11.²⁹ We set $\bar{d} = 3.195$ and the total output in our model then corresponds to Canadian \$ 668 billion the average Canadian GDP during 1981-2010.

The parameter values used to calibrate the steady state of the model 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 observed average consumption of goods and services. The average compensation to employees in the manufacturing and service sectors for the Canadian economy are 21% and 37% of gross outputs in the respective sectors.³⁰ Labor share in the output of manufacturing and services are 0.21 and 0.37 respectively. The share of abatement expenditure in output of the manufacturing sector is assumed to be 9%, which is the level Fischer and Springborn (2011) use for the United States.³¹ The exogenous international real interest rate is 4% per annum.

The trade cost in services are available from Anderson, Milot, and Yotov (2012). The authors' estimate for a sample period of 1997-2007 shows that the Canadian border with the rest of the world is 1.63 tariff equivalent.³² The Canadian border effect on services to the rest of the world ranges from tariff equivalent of 23% in accommodations to 163% in wholesale services with 63% in aggregate services. So, we set the trade cost of services as 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 to match the empirical trade flow shares of manufacturing goods and services to the

²⁹The ratio is higher than the observed debt-to-GDP ratio which is because of the imputed GDP.

³⁰Estimated over our sample period. Source: Statistics Canada. Table 383-0032 - Multifactor productivity, gross output, value-added, capital, labour and intermediate inputs at a detailed industry level, by North American Industry Classification System (NAICS)

³¹Our estimate from the Canadian abatement expenditure data shows that the share is 7.5% but the data is only available for few and irregular periods. So, we follow Fischer and Springborn (2011). Using 7.5% would not materially affect the results.

³²The estimate assumes that the elasticity of substitution is 6 across the services: transportation, communication, wholesale, finance, business, education, health, accommodation and others in Canada.

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		
σ	Intertemporal elasticity (risk parameter)	2
\bar{R}	Real interest rate	0.04
ξ	Share of abatement in output of goods	0.09
\bar{h}	Household's Endowment of Labor	1
ρ	Elasticity of substitution between goods and services	2.2
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		
\bar{p}	World relative price of services in terms of goods	0.51
\bar{d}	Debt-level	3.195

4.2 Results

We first solve the system of equations for the equilibrium with an exogenously fixed emissions tax. The emissions tax is arbitrarily set at 0.1 which is equivalent to 10% of the world price of manufacturing goods in our model. Then, we estimate the share of consumption, output, trade flows of both goods and services in aggregate consumption. These shares are then used to estimate the income, terms-of-trade and output effects on emissions leakage. The sum of these effects is the total effect of an increase in 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 from the emissions tax change. The leakage multiplier is then used to obtain 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 and shares of consumption of goods and services to the aggregate output for the Canadian economy. The initial steady state of the economy 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%	9.52%
Share of traded services in GDP	-1.03%	-1.08%
Share of consumption of goods in GDP	43.34%	43.56%
Share of consumption of services in GDP	48.26%	47.49%

Table 3: Initial Steady State in the Calibrated Economy

Variable	Value
Aggregate output(Y)	1.515
Output of goods(x)	0.804
Output of services($p\mu y$)	0.702
Consumption of goods(c_x)	0.660
Consumption of services($p\mu c_y$)	0.719
Labor in goods(h_x)	0.372
Labor in services(h_y)	0.628
Trade flows of goods(b_x)	0.144
Trade flows of services(b_y)	-0.016
Emissions(e)	0.724
Emissions tax(T)	0.1

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

We estimate that a 1% increase in the emissions tax in Canada will reduce domestic emissions by 1.12%. This reduction in Canadian emissions is associated with a 0.384% increase in rest of the world emissions. That generates leakage of 34.3%, meaning for every ton Canadians reduce their CO₂ emissions, rest of the world emissions increase by 0.343 tons and global emissions fall by 0.657 tons.³³ This emissions leakage estimate

³³This discussion assumes our small economy's emissions intensity is equal to the rest of the world's emissions intensity. If they differ evaluating global (net) emissions reduction would require scaling the

is comparable to estimates from similar policy counterfactuals for developed countries in the existing literature. We are unaware of any specific policy experiment estimates for Canada comparable to those presented here. Felder and Rutherford (1993) uses 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.³⁴

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

	Income	Output	Terms of Trade	Total Leakage
Leakage	-0.004 (-1%)	0.089 (26%)	0.257 (75%)	0.343

Note: Top row represents the effects on leakage, decomposed by channels for an 1% reduction in the domestic emissions. The second row (in parentheses) shows the share of each effect in the emissions leakage. The last column represents the total emissions leakage which is simply 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 percentage of the unit % reduction in the domestic emissions. So, 0.343 positive leakage implies that the rest of the world emissions will increase by 0.343% if Canada reduces 1% emission compared to its pre-policy change in emissions level.

Table 5 shows the differences in the estimates of emissions leakage, as a proportion of domestic emissions reduction, for 1% reduction in domestic emissions under the three assumptions on the level of tradability in services: zero trade in services 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 34.3%. For zero trade cost in services, we estimate 27.9% emissions leakage. Zero trade cost in services lowers the emissions leakage by over 18%. Hence, the results suggest that, for Canada, the emissions leakage from a stricter environmental regulation is positive but a fall in service sector trade cost may lower emissions leakage.

leakage by the difference in relative emissions intensity.

³⁴There is a great deal of CGE modelling estimating leakage, but those studies tend to focus on the sensitivity of leakage estimates to parameter choices or specific policies like the Kyoto Protocol rather than emissions policy counterfactual analysis.

Table 5: Effects of Trade Cost on The Emissions Leakage Under 1% Emissions Reduction

Cases	μ	Emissions Leakage
Non-traded services	∞	0
Trade cost in services with	1.63	34.3%
Zero trade cost in services	1	27.9%

Note: Each row represents the emissions leakage from a 1% reduction in domestic emissions at different levels of trade costs in services. The emissions leakage is the change in rest of the world emissions in % of domestic emissions reduction. Top row represents the emissions leakage when services are completely non-traded. The second row represents the emissions leakage under the level of trade cost in services estimated from the literature. The third row represents the emissions leakage when the trade cost in services is zero.

5 Conclusion

In this paper, we build an analytical general equilibrium model of a small open economy where we include both freely traded polluting manufacturing goods and potential trade costs in non-polluting services. We decompose effects of a small increase in pollution taxes on emissions in the rest of the world, known as emissions leakage. 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 relative price of the non-traded service sector 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 mis-attribute leakage associated with trade costs in services.

In our model a stricter environmental policy leads to leakage through three channels. The income, output and terms of trade effects. The income effect has a negative effect on emissions leakage, that is increases in domestic pollution taxes reduce rest of the world emissions. The output and terms of trade lead to positive emissions leakage. Our results, from a model calibrated to the Canadian economy, suggest that the output and

terms of trade effects dominate the income effect and thus, there is positive emissions leakage on net. Our results suggest that with a stricter emission tax, a 1% reduction in domestic emissions yields an emissions leakage of 34.3%, reducing global emissions by 0.66 ton for each ton of domestic reduction. Further, we find over 18% lower emissions leakage if trade costs in services fall from the level to estimated in the literature (63%) to zero.

In this paper, 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, fuel price effect) identified elsewhere in the literature through which leakage can occur are not present in our model. Future work should address whether and how the assumption of no, or constant, trade costs in services affects estimated emissions leakage in large-scale CGE models.

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A Appendix

The reduced form solutions for \hat{h}_x , \hat{y} , \hat{x} , and \hat{e} in section 3.

$$\hat{h}_x = -\frac{\theta_{hy}}{\theta_{hx}(1-\alpha_2) + \theta_{hy}(1-\alpha_1)} \frac{\xi}{1-\xi} \hat{T} \quad (\text{A.33})$$

$$\hat{y} = \alpha_2 \frac{\theta_{hx}}{\theta_{hx}(1-\alpha_2) + \theta_{hy}(1-\alpha_1)} \frac{\xi}{1-\xi} \hat{T} \quad (\text{A.34})$$

$$\hat{x} = -\alpha_1 \frac{\theta_{hy}}{\theta_{hx}(1-\alpha_2) + \theta_{hy}(1-\alpha_1)} \frac{\xi}{1-\xi} \hat{T} \quad (\text{A.35})$$

$$\hat{e} = -\left(\frac{\alpha_1 \theta_{hy}}{\theta_{hx}(1-\alpha_2) + \theta_{hy}(1-\alpha_1)} \frac{\xi}{1-\xi} + \frac{1}{1-\xi} \right) \hat{T} \quad (\text{A.36})$$

Proof of Proposition 1:

Income effect on consumption

From Eq. (22)

$$\text{Income effect} = \frac{\alpha_2 S_y \theta_{hx} - \alpha_1 S_x \theta_{hy}}{\theta_{hx}(1 - \alpha_2) + \theta_{hy}(1 - \alpha_1)} \quad (\text{A.37})$$

Plugging $\alpha_1 = \frac{1}{(1-\xi)} \frac{wh_x}{e^\xi x^{1-\xi}}$ and $\alpha_2 = \frac{wh_y}{p^\mu y}$ from 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:

$$\text{Income effect} = \frac{1}{C} \frac{wh_x h_y}{h_x(1 - \alpha_2) + h_y(1 - \alpha_1)} \left(-\frac{\xi}{1 - \xi} \right) \quad (\text{A.38})$$

which is negative.

Terms of trade effect on consumption

From Eq. (22)

$$\text{Terms of trade effect} = -S_x \quad (\text{A.39})$$

which is negative.

Since, $\hat{c}_x = \hat{c}_y$ (Eq. (19)), the emissions tax has negative effect on the consumption of both goods and services in a small open economy.