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The Effectiveness of Revenue-Neutral Caron Taxes

By

Younes Ahmadi
Akio Yamazaki

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National Graduate Institute for Policy Studies
7-22-1 Roppongi, Minato-ku,
Tokyo, Japan 106-8677

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Younes Ahmadi† Akio Yamazaki‡

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Abstract

This paper investigates the effectiveness of carbon taxes in the manufacturing sector by examining British Columbia's revenue-neutral carbon tax. We theoretically demonstrate that the magnitude of plants' exposure to the policy monotonically increases with its emission intensity. Using detailed confidential plant-level data, we directly exploit the variations in plants' emission intensity to isolate the emission effect of the policy. We find that the carbon tax lowers emission by 2 percent. Furthermore, we find that the policy had a positive output effect, suggesting that the carbon tax encouraged plants to produce more with less energies. These findings are possibly due to the revenue neutrality of the policy, especially through the reduction of the corporate income taxes. It incentivized plants to invest in both energy-saving and productivity-enhancing technologies.

Key Words: Carbon tax; revenue-recycling; manufacturing emission

JEL Codes: H23, Q5, L6

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†Department of Economics, University of Calgary, yahmadi@ucalgary.ca

‡National Graduate Institute for Policy Studies (GRIPS), a-yamazaki@grips.ac.jp

1. Introduction

At the 21st Conference of Parties (COP21[1]) in Paris (December 2015), countries, by consensus, adopted the first universal climate agreement to tackle global warming. Several countries had already implemented carbon policies to reduce their greenhouse gas (GHG) emissions. After the Paris agreement, there is a general expectation in the international community that these carbon policies would be extended. Theoretical models show that a uniform carbon tax is an effective tool to achieve the emission reduction targets at the lowest economic costs.[2] However, political feasibility of the policy is still heavily debated around the world among policymakers and the public. This is partly because empirical evidence on the effectiveness of carbon taxes is limited due to the lack of high quality micro-level data. Thus this paper takes advantage of a unique plant-level dataset to investigate the effect of the carbon tax, implemented by British Columbia (BC) in 2008, on GHG emissions from manufacturing plants.

The carbon tax in BC was unexpectedly announced in February 2008, and has been in effect since July 2008. The tax rate initially began at $10 per tonne of CO_2 equivalent (CO_2eq), and increased by $5 annually, reaching $30 in 2012. The BC carbon tax applies to all fossil fuels purchased within BC, and covers 77% of total provincial emissions (Harrison, 2012). There are three reasons why this policy is ideal to estimate the causal effect of a carbon tax on GHG emissions. First, the BC carbon tax is comprehensive and includes all plants and all fossil fuels purchased within BC.[3] Second, the BC carbon tax rate is high when compared to other existing carbon policies,[4] so companies are more likely to change their behavior in response to the policy. Third, the fact that the tax was introduced shortly after its unexpected announcement eliminates any anticipatory effects (i.e., prior to the implementation of the policy) as plants presumably did not have enough time to adjust their behavior.

Our empirical strategy is motivated by a simple model of multi-region and multi-sector trade model with a carbon tax introduced in one region. We assume perfect competition and abstract

[1]COP is the formal annual meeting of the United Nations Framework Convention on Climate Change (UNFCCC) Parties. In these meetings, the member countries assess countries' progress in reducing greenhouse gas emissions and negotiate over climate change agreements.

[2]A uniform carbon tax is a per-unit charge on fossil fuels based on their carbon embodiment, applied to all consumers at the same rate. The effect of a carbon tax on GHG emissions is less pronounced when the carbon tax is revenue neutral (i.e., all the tax revenues from the policy is returned to consumers to maintain the government revenues constant). Theoretical models show that the effect depends on how the tax revenue is recycled.

[3]The Alberta government introduced a new climate policy in 2018 that is comprehensive. The carbon tax is increased to $30 per tonne for larger emitters and is increased to $20 per tonne for other emitters in 2017. The carbon tax increased to $30 for all emitters in 2018.

[4]Québec was the first province to introduce a carbon tax, but the tax rate is only around 3$ per tonne of CO_2 equivalent and does not include all emitters. Some Scandinavian countries have carbon taxes as high as $150. However, the effective tax rates are smaller due to a lot of tax exemptions and in some cases the energy excise taxes were removed and replaced by carbon taxes.

from trade in intermediate goods. The model decomposes the emission responses to a carbon tax into scale effect and technique effect.[5] We show that the magnitude of emission responses increases monotonically with plants' emission intensity, and therefore it is reasonable to assume that high emission-intensive plants are more affected by the carbon tax relative to low emission-intensive plants.

Using the theoretical insights, we design a triple difference estimator using plant-level emission intensity as a continuous treatment. We directly compare plants based on the intensity of their exposure to the carbon tax. As the magnitude of plants' exposure to the carbon tax monotonically increase with their emission-intensity. We contend that plants with high emission intensity are more likely to respond to the policy by adjusting their operation or production technologies than the low emission-intensive plants. Our triple difference estimator compares changes in emission for plants in BC with changes in emission for plants in the rest of Canada before and after the unilateral implementation of the carbon tax.[6] Furthermore, we exploit the panel structure of data by including various fixed effects to control for possible unobserved confounding factors, such as commodity price shocks, provincial geographic characteristics, and industry factor intensities.

We estimate the emission effect of the policy using the confidential plant-level manufacturing dataset, the Annual Survey of Manufacturing (ASM). This dataset consists of detailed information on plant-level manufacturing activities, such as fuel expenditures, total sales, and employment. What is unique about this dataset is that having access to plant-level fuel expenditures allows us to construct the first-ever plant-level GHG emission dataset for Canada.[7]

We find that the BC carbon tax lowered the GHG emissions. The point estimate shows, on average at \$20/tCO_2e, a statistically significant reduction in emissions by 2 percent. Furthermore, we show that the policy increased outputs, suggesting that the carbon tax provided enough incentives for plants to take actions to produce more with less (fossil-fuel) energy. Our findings are quite appealing, especially to policymakers, because implementing a carbon tax can both reduce emissions and strengthen the economy. There are two factors that could contribute to increased

[5] Antweiler et al. (2001) refer scale effect to be the emission response by increasing the size of the production while referring technique effect to be the emission response by changing the production technology that improves emissions per unit of output.

[6] Some, such as Andersson (2019), argue that the carbon tax may have a general equilibrium effect and lead to carbon leakages into other provinces, which is a violation of the Stable Unit Treatment Value Assumption (SUTVA). To minimize this concern, we also estimate the emission effect using only provinces that have very low trade flows with BC because we expect very limited carbon leakages into these provinces. The selected provinces are Newfoundland and Labrador, Prince Edward Island, Nova Scotia, New Brunswick, Manitoba, and Saskatchewan. The baseline estimation results are robust to this sample difference. The results can be requested upon a request.

[7] Alternatively, one can use the facility-level emission data available at Environment Canada known as Greenhouse Gas Reporting Program (GHGRP). This data includes only large industrial emitters that emit more than 100 kilotonnes per year. The reporting threshold was reduced to 50 kilotonnes in 2009 and further to 10 kilotonnes in 2018. We believe that our data is better suited as it covers all manufacturing plants and provides more variation while the facility-level emission data only covers the large facilities

outputs. First, the amount of money the BC government returned to the economy was about 15% more than what the carbon tax took from the economy in all years between 2008-2016 (i.e., the BC carbon tax raised $1.2 billion in 2012-13 and returned $1.4 billion). This is mainly because the BC government announced tax reduction rates based on the projected carbon revenue, and the actual revenue was less than the projected revenue. This means that the BC economy received a net reduction in taxes.

Second, the revenue recycling feature of the policy may have played an important role in generating the positive output effect. The revenues collected from the carbon tax was used to lower the rates of corporate and personal income taxes. Theoretically, a reduction of corporate income tax (CIT) rate is shown to increase investments and capital formations, resulting in lower emission intensity and higher output. Emission-intensive plants in BC are more capital intensive, these plants receive larger benefits from the CIT cut relative to the low-emission-intensive plants. Therefore, the output of high emission-intensive plants is expected to increase and their emission intensity is expected to decrease relative to the low emission-intensive plants. This argument is consistent with the results found in our paper. Yamazaki (2017, 2019) has a similar argument regarding the importance of the revenue recycling feature of the BC carbon tax and our results are consistent with his findings[8].

A number of studies examine the effect of carbon taxes on GHG emissions using simulation methods, such as Manne et al. (1990), Goto (1995), Floros and Vlachou (2005), and Wissema and Dellink (2007). Although they find that a uniform carbon tax would lead to a significant reduction in GHG emissions, it is difficult to solely rely on these findings for designing of future policies. What we need is more of evidence-based policy suggestions.

The empirical findings, thus far, from ex-post analyses are very much mixed and limited. For instance, Bohlin (1998) and Andersson (2019) both investigate the effect of a carbon tax in Sweden, which was implemented in 1991. Bohlin finds that the transportation sector was not affected and emissions from industrial sectors increased due to exemptions that decreased the effectiveness of the energy tax. He does, however, find that GHG emissions declined in the heating sector as a result of substitution from coal to biofuel. On the other hand, Andersson uses a synthetic control method with the country-level data and finds that emissions from the transportation declined by 11 percent. Lin and Li (2011) use a difference-in-differences (DID) method to estimate the effect of carbon taxes in Scandinavian countries and the Netherlands. They find that there was no significant effect in Denmark, Sweden, and the Netherlands, and that the carbon tax in Norway led to a substantial increase in GHG emissions from the oil and gas sector due to tax exemptions.

This paper is closely related to Pretis (2019). Relying on the DID method with industry-level

[8] Yamazaki (2017) also argues that there is a positive demand effect from lowering the personal income tax, which could also help explaining the positive output effect found in this paper.

emission data, Pretis finds that the BC carbon tax did not have a (statistically) significant effect on emissions, arguing that the carbon tax rate was too low for the policy to have any impacts. Our paper explains the weakness of the use of the DID method with the aggregate-level data in estimating the emission effect of this particularly policy. With other major macro economic shocks (e.g., the financial crisis) and concurrent policies implemented in other provinces, it is difficult to isolate the casual impact of this policy using DID method. We provide empirical results suggesting that DID method cannot isolate the effect of the BC carbon tax. To address the empirical issues of the previous studies, we offer a comprehensive evidence on the effectiveness of carbon taxes by directly exploiting the plant-level variations in the exposure to the policy (i.e., plant-level emission intensity) and design a triple difference estimation.

The remainder of the paper is organized as follows. Section 2 provides an overview of the BC carbon tax and its features. Section 3 presents the theoretical framework. The description of the data and empirical methodology are presented in Section 4. Section 5 presents the estimation results and robustness checks. Section 6 concludes.

2. Overview of the BC carbon tax

The BC's Liberal government announced the new climate policy agenda in its throne speech in February 2007. The target of the policy was to reduce BC's GHG emissions by 33 percent (i.e., 10 percent below the 1990 level) by 2020. Additionally, all electricity generators were required to have zero emissions by 2016. Two months after the throne speech, the BC government announced its intention to join five U.S. states in developing a regional cap and trade system called the Western Climate Initiative. This announcement was completely unexpected because the Liberal government had been previously criticized by environmentalists for supporting off-shore oil and gas explorations, a large decline in its environmental budget, and proposals for two new coal-fired electricity power plants (Harrison, 2012). Those in the business community with close ties to the Liberal government were taken by surprise. Jock Finlayson, the executive Vice President of the BC Business Council, said:

> *The throne speech was a huge surprise, not just to my organization but to everybody in the corporate community. There really was not any advance notice, either through public statements or even through back channels. I actually dropped my coffee cup, full of coffee, when I was watching the live broadcast. (Harrison, 2012).*

The carbon tax rate initially began at \$10 per tonne of CO_2 equivalent (tCO_2eq), and increased by \$5 annually, reaching \$30 in 2012. The tax at \$10/tCO_2eq represented an increase of 2.4 cents per liter for gasoline, and a \$20.8 increase per ton for coal. These numbers rose to 7.2 cents per liter for gasoline (equivalent to 4.4% of the final price) and \$62.4 per ton of coal (equivalent to 55% of the final price) at the tax rate of \$30/tCO_2eq. All fossil fuels purchased within BC are covered by the tax, and it covers 77% of total provincial emissions (Murray and Rivers, 2015).[9] The BC carbon tax is comprehensive and includes all plants in BC.[10]

The tax was designed to be revenue neutral. The revenue is returned to consumers and businesses through: a direct transfer to low-income individuals (a one time \$100 Climate Action Dividend per adult in the initial year), a decline in income taxes (around 2% reduction in 2008 and 5% reduction in 2009 for those who have annual income of less than \$70,000), a decline in general corporate income taxes (from 12 to 10 percent), and a reduction in small corporate income taxes (from 4.5 to 2.5 percent in the first three years after the implementation of the policy). According to the budget and fiscal plan for 2013, the carbon tax raised about \$1.2 billion in revenues for 2012-2013 and returned about \$1.4 billion to consumers. The excess amount returned is around 15% of the carbon tax's total revenue, but is less than 1% of BC's total budget (Ministary of Finance, 2013).

3. Theoretical Framework

We adopt a simple version of the model developed by Aichele and Felbermayr (2015) to identify channels through which a carbon tax may affect emissions. We then use this model to motivate our identification strategy. We changed their model in three ways. First, we abstract from the trade in intermediate goods and focus only on trade in the final goods. Second, the market structure of manufacturing good is perfect competition rather than monopolistic competition. Third, we assume a fix number of firms rather than an endogenous number of firms.[11] These assumptions are made for simplicity. Consider K provinces, indexed by i, $j = 1, ..., K$, which differ only with respect to their carbon pricing policies. Only one province introduces a carbon tax while there is no carbon tax in other provinces. Each province consumes a homogeneous good H_i and a manufacturing good M_i. α denotes the expenditure share of manufacturing good. M_i is a Cobb-Douglas composite of manufacturing varieties from s sectors, indexed $s = 1, ..., S$. μ^s denotes the expenditure share of sector s. Consumers have constant elasticity of substitution (CES) preferences over

[9] The uncovered emissions are associated with emissions produced by landfill facilities, non-combustion emissions from agriculture sector, most of fugitive emissions, and industrial emissions that do not come from burning fossil fuels.

[10] There is no manufacturing industry that is exempted from the carbon tax. The agriculture sector was exempted from the tax after 2012, which is not included in our analysis because the focus of this paper is on manufacturing plants.

[11] We also assume that firms and plants are interchangeable in this section.

quantities of varieties that are imported or produced domestically.

$$U_i = H_i^{1-\alpha} M_i^{\alpha}, \quad M_i = \prod_{s=1}^{S} (M_i^s)^{\mu^s}, \quad M_i^s = \left(\sum_{j=1}^{K} N_j (q_{ij})^{\frac{\sigma-1}{\sigma}} \right)^{\frac{\sigma}{\sigma-1}} \tag{3.1}$$

where σ is the elasticity of substitution and N_j is the number of varieties produced in each province. Solving the utility maximization problem gives the price of each variety and the demand for that variety in each province.

$$q_{ij}^s = \frac{N_j \alpha \mu^s I}{P_i^{1-\sigma}} (p_{ij}^s)^{-\sigma} (\tau)^{-\sigma}, \quad P_i^s = \left(\sum_{j=1}^{K} N_j (p_{ij}^s)^{1-\sigma} \right)^{\frac{1}{1-\sigma}}, \quad p_{ij}^s = \tau_{ij} p_j^s \tag{3.2}$$

where q_{ij} and p_{ij} are the province i's consumer demand for varieties of goods produced in province j and its price, respectively. P_i^s is the sectoral price index in province i, p_j^s is the price of a variety produced in province j, τ_{ij} is the iceberg trade cost for a variety produced in province j and consumed in province i, and $\alpha \mu^s I$ is the share of income spent on each manufacturing sector.

The homogeneous good is produced under perfect competition using only labor with a marginal productivity of one. We assume the production is diversified in all provinces, which means wage rates are equal to one. The manufacturing goods in each sector are produced under perfect competition and constant return to scale. For simplicity, we assume a fixed number of firms in each sector, and each sector produces a distinct variety using labor and fossil fuels. The unit cost function is Cobb-Douglas, which depends on the wage rate and fuel prices.

$$c_i^s = t_i^{\beta^s} w_i^{1-\beta^s} = t_i^{\beta^s} \tag{3.3}$$

where the second equality is the result of $w_i = 1$. t_i are fuel prices in each province. Fuel prices are assumed to differ across provinces only due to a carbon tax. β^s denotes the factor cost shares of fossil fuels in each sector. The profit of each firm is $(p_i^s - t_i^{\beta^s}) q_i^s$. Under a competitive market, price equals marginal cost:

$$p_i^s = t_i^{\beta^s}$$

Substituting the equilibrium price into the goods market clearing condition results in provinces' sectoral production level.

$$q_i^s = \alpha \mu^s I (t_i)^{-\beta^s \sigma} \sum_{j=1}^{K} \frac{N_j}{P_j^{1-\sigma}} (\tau_{ij})^{-\sigma} \tag{3.4}$$

The total income and the sectoral price are exogenous to firms. Inserting the equilibrium price in Eq.(3.2) for q_{ij} yields an expression for the quantity of province i's total sectoral imports, Q_{ij}, from province j:

$$Q^s_{ij} = \frac{N_j \alpha \mu^s I}{P_i^{1-\sigma}} (t_j)^{-\beta\sigma} (\tau_{ij})^{-\sigma} \tag{3.5}$$

In this simple model, I abstract from any trades of intermediate goods and only focus on the trades in final goods. The results are, however, similar to the inclusion of the trades of intermediate goods.[12]

In the next step, we show how emission levels, emission-intensity, and output levels change due to the introduction of a carbon tax in one province. From Shephard's lemma, the emission-intensity of a sector is given by the derivative of the unit cost function with respect to the price of emissions, which is the carbon tax.

$$\eta^s_i = \frac{dc^s_i}{dt_i} = \beta^s_i (t_i)^{\beta^s_i - 1} \tag{3.6}$$

Following Antweiler et al. (2001) the sectoral emissions can be decomposed into technique and scale effects. The technique effect represents changes in sectoral emissions because of changes in the emission-intensity of each industry or firm. Industries or firms can substitute away from energies with high emissions content to the ones with low emissions content (e.g., switch from coal to natural gas). The scale effect reflects the change in emissions due to a change in the volume of sectoral output. Sectoral emissions can be written as the multiplication of sectoral emission intensity and sectoral output.

$$E^s_{ij} = \eta^s_j \times Q^s_{ij} \qquad\qquad i, j \in \{1, ..., K\} \tag{3.7}$$

where Q^s_{ij} and E^s_{ij} are the quantity and embodied emissions of imports of province i from province j, respectively. Totally differentiating Eq.(3.7) yields:

$$dE^s_{ij} = \underbrace{Q^s_{ij} \frac{d\eta^s_j}{dt_i} dt_i}_{\text{Technique Effects}} + \underbrace{\eta_j \frac{dQ^s_{ij}}{dt_i} dt_i}_{\text{Scale Effects}} \tag{3.8}$$

Suppose that only province i (i.e., BC) introduces a carbon tax (i.e., $dt_j = 0$ and $dt_i > 0$). Based on Eq.(3.4), the domestic production in each province is directly related to the carbon tax in that province, and through the sectoral price index, indirectly depends on the carbon tax in other

[12] An interested reader can refer to Online Appendix of Aichele and Felbermayr (2015) to view the model with the inclusion of the trades of intermediate goods and monopolistic competition market structure.

provinces. It can be shown that:

$$\frac{dq_i}{dt_i} = f(\gamma_i, t_i) \lesseqgtr 0 \tag{3.9}$$

$$\frac{dq_j}{dt_i} = f(\tau_{ij}, \gamma_i, t_i) > 0 \tag{3.10}$$

where γ_i is the change in corporate income tax in province i. Corporate income taxes(CIT) declined by 2 percentage points after the introduction of the BC carbon tax. The reduction in the CIT leads to higher capital investment and higher output. The carbon tax, however, reduces the output of firms. These two opposing effects lead to an ambiguous impact of the BC carbon tax on the output of firms. The negative output effect is larger for high emission-intensive plants than low emission-intensive plants, but the magnitude of increased output due to the CIT cut is also larger for high emission-intensive plants since these plants are more capital-intensive. The output level in other provinces increases in response to the carbon tax in BC. The magnitude of this change is a decreasing function of bilateral trade costs, an increasing function of the BC carbon tax rate, and a decreasing function of the reduction in the BC CIT rate. Thus, we expect to see a small or no change on the output level of provinces that have very limited trade with BC. Similar equations can be derived for the volume of imports and exports in each province.

Using Eq.(3.6), we can find the change in the emission-intensity with respect to the carbon tax. Each firm's emission intensity only depends on its own province's carbon tax.

$$\frac{d\eta_j}{dt_i} = 0 \qquad\qquad \frac{d\eta_i^s}{dt_i} = (\beta_i^s - 1)\frac{\eta_i}{t_i} < 0 \tag{3.11}$$

Firm's emission-intensity declines as the carbon tax rate increases since η_i and t_i are positive and β_i^s is less than one. The magnitude of this response (in the absolute value) is larger for high emission-intensive firms when compared to low emission-intensive firms, which can be shown by taking a second derivative of Eq.(3.11) with respect to the emission intensity.[13] Eq.(3.9), and (3.10) determine all the required parameters in the Eq.(3.8) for finding the total change in sectoral emissions. In this section we showed that high emission-intensive plants are more affected by the BC carbon tax. Therefore, we expect to see a larger reduction in emissions from high emission-intensive plants. In the next section, we use these theoretical findings to design our estimation strategy.

[13]The change in the natural log of emission due to the carbon tax is also higher for high emission-intensive firms since the natural log of emission is a monotonic transformation of emission.

4. Empirical Analysis

4.1. Research Design

The goal of this paper is to estimate the causal effect of the BC carbon tax on GHG emissions from manufacturing plants.[14] Manufacturing plants account for about 15% of Canada's total GHG emissions. There are three reasons why we choose manufacturing plants for this study. First, data on emissions from manufacturing plants is available in detail, whereas there is no high-quality emission data available for other sectors. Second, manufacturing plants mainly use fossil fuels with high embodied emissions such as coal and natural gas. Therefore, we expect the carbon tax to have larger impacts on manufacturing plants, i.e., these plants are more likely to respond to the carbon tax. In contrast, the transportation sector accounts for about 25% of total GHG emissions. However, gasoline and diesel have low embodied emissions, i.e., the carbon tax imposes a very small charge on consumers. Thus, the response of transportation sector to the carbon tax may be small and not identifiable. Third, there is a large variation in the emission intensity and total emissions of manufacturing plants. Focusing on the manufacturing plants allows us to capture this extra source of variation across plants and design a more accurate estimation strategy (i.e., triple difference estimation).[15]

The carbon tax in BC imposes extra costs on plants that use fossil fuels. The magnitude of this extra cost depends on two factors. First, plants with a high emission intensity pay a high tax per unit of output. Second, large plants pay a high tax in the absolute value because they emit more. Therefore, a low emission-intensive plant, but with a large level of output, may pay a higher tax in the absolute term relative to a high emission-intensive plant with a small level of output. However, based on summary statistics, high emission-intensive plants are, on average, much larger in terms of their output.[16] This supports the approach followed in this paper, which considers low emission-intensive plants as less-affected group. If the emission intensity is low enough, the tax burden of the carbon tax is negligible relative to other types of costs. This allows us to treat low emission-intensive plants as the control group in the analysis.[17] We also consider plants outside BC as untreated because they are not subject to the carbon tax. Based on these notions, we exploit three sources of variation to estimate the causal effect of the BC carbon tax on GHG emissions from manufacturing plants.

[14] The list of manufacturing industries that is provided in Appendix B at the 3-digit NAICS industry code.

[15] Although the oil and gas sector accounts for 25 percent of total emissions, all active plants have high emission intensity. Therefore, there is less variation across plants that can be captured to identify the effect of interest.

[16] Low emission-intensive plants, on average, pay \$3,000 carbon tax per year, while high emission-intensive plants, on average, pay \$100,000 carbon tax per year.

[17] For an average plant below the 70$^{\text{th}}$ percentile in emission intensity, the carbon tax imposes a charge less than 0.05 percent of the plant's total costs.

Table 1: The Tax Burden of the BC Carbon Tax for Various Industries

Industry	Emission Intensity Tons/$1000	Tax paid as Percentage of output
5 Most Emission Intensive		
Pulp and paper	1.588	3.18
Cement and concrete	1.179	2.36
Non-metallic mineral	0.605	1.21
Primary metal manufacturing	0.447	0.89
Petroleum and coal product	0.351	0.70
5 Least Emission Intensive		0.00
Aerospace product	0.013	0.03
Tobacco manufacturing	0.011	0.02
Electronic product	0.010	0.02
Other transportation equipment	0.006	0.01
Computer and peripheral equipment	0.005	0.01
Average in Manufacturing	0.15	0.30
Median in Manufacturing	0.04	0.08

Note: This shows the top and bottom five industries in terms of their emission intensities, as well as the average and median emission intensity among all industries. We multiply the average tax rate during the 2008-2012 period (i.e., \$20/tCO_2e) by industries' emission intensity in 2007 to calculate the average cost imposed on industries.

Source: CANSIM Table, Statistics Canada

The first source of variation is time. The BC carbon tax was unexpectedly announced in February 2008 and was implemented shortly after (five months after its announcement) in July 2008. The unexpected announcement eliminates the possibility of anticipatory responses before the implementation of the carbon tax.[18]

The second source of variation originates from the difference in emission intensity across plants. Table 1 shows the top and bottom five industries in terms of their emission intensities, as well as the average and median emission intensity among all industries. We multiply the average tax rate during the 2008-2012 period (i.e., \$20/tCO_2e) by industries' emission intensity in 2007 to calculate the average cost imposed on industries. There is a substantial variation in the emission intensity, and for 50 percent of industries, the carbon tax burden is less than 0.1 percent

[18]We do examine the anticipatory response effect of the policy using flexible estimation method, presented in Section 5.2.

of their output value. Even though all plants have the same incentive to reduce emissions at the margin, the low tax burden per unit of output for small emitters creates little incentive to invest in reducing emissions. However, low emission-intensive plants may still have the incentive to reduce their emissions if they pay a considerable amount of tax (i.e., if plants' output level is high enough). Especially if fuel switching requires only a fixed cost (e.g., a fixed cost to buy new machinery that works with electricity rather than coal and natural gas), then plants' incentives to invest depends only on the absolute value rather than the per unit cost of the carbon tax. Summary statistics, however, show that low emission-intensive plants pay much less carbon tax in the absolute term relative to high emission-intensive plants. This fact suggests that even in the case of a fixed cost for fuel switching, high emission-intensive plants have a much larger incentive to reduce their emissions.

The third source of variation is across provinces. Plants outside BC are not subject to the carbon tax and can be used as control plants. The results from the theoretical model, however, show that the carbon tax in BC can alter the output level in other provinces. The magnitude of this change depends on the bilateral trade cost. The control group being (indirectly) affected by the policy violates the stable unit treatment value assumption (SUTVA). To test the severity of this concern, we performed a robustness test by using only provinces that have very low trade flows with BC.[19]

These three sources of variations allow us to compare plants in three dimensions by employing a triple difference estimation method. To illustrate the importance of the triple difference estimation, we briefly point out the inability to isolate the effect of the BC carbon tax from other concurrent shocks (e.g., 2008 global recession) when we do not use the triple difference estimation here.[20]

The simplest way to observe the policy response of plants is to compare the emission level of each plant in BC before and after the policy implementation. This comparison would control for any unobserved time-invariant factors that affect plants' emissions. Some examples of these time-invariant characteristics are location and market access, fuel abundance in a city or province, and proximity to coal mines. This does not, however, warrant identification of the effect of interest. A before-after comparison would estimate the causal effect of the carbon tax if there were no other concurrent policy or economic shocks, and in the absence of secular trends in emissions. However, the economic recession started in 2008, about the same time as the implementation of the carbon tax, which negatively affected the output and emissions of all plants in BC. Therefore, a before-after comparison of plants in BC would not be able to distinguish the effect of the carbon tax from the effect of the recession.

[19]The baseline estimation results presented in the later section are robust to this sample difference. The results of this robustness check is not presented; however, they are available upon a request.

[20]We discuss this in more detail in Appendix A.

To identify the emission effect of the policy while controlling for the time-variant factors, one can take one step further and design a difference-in-differences (DID) estimation to isolate the effect of the carbon tax. The DID estimation can capture some of the time-variant factors that were problematic in the before-after comparison; however, we argue that it is not enough.

One way to implement a DID estimation is to compare the changes in emission before and after the policy among high and low emission-intensive plants within BC, dropping all observations outside BC. This DID estimation can control for the time-variant factors that are common among plants in BC. However, if such factors have differential effects across high and low emission-intensive plants, the DID estimation will be biased.

Alternatively, one can design a DID estimation by comparing the changes in emission before and after the policy only among high emission-intensive plants across provinces, dropping all of the low emission-intensive plants from the analysis. This DID estimation can capture the differential effect among high and low emission-intensive plants, but cannot capture the differential effect across provinces. For example, if the economic recession had different impacts across provinces, it would bias the estimation.

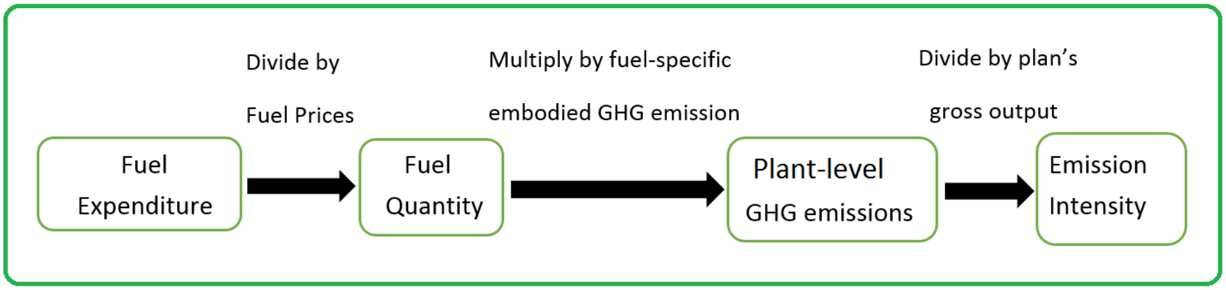
To address these identification issues above, one can employ a triple difference method, which we use in this paper. This compares the differential change in emissions for plants with high and low emission intensity in BC before and after implementation of the carbon tax, to the same differential change in the counterfactual plants in provinces outside of BC. This can address the identification issues mentioned above and allows us to isolate the effect of the BC carbon tax from the effect of the recession, or of other confounding factors that vary either at the sector or at the province level.

4.2. Data

To identify the causal effect of the BC carbon tax on GHG emissions, we build plant-level indices for emission intensity and trade flows across provinces. To do so, we use the Annual Survey of Manufacturing (ASM) dataset, a uniquely accessed plant-level data set which includes: plant-level fuel purchases, shipment destinations, sales, final products, plant location, and plant total production costs. While limited to the manufacturing plants, the ASM dataset allows us to calculate plant-level emissions and emission intensity that cannot be done with other known available datasets. To construct our measure of GHG emissions, we collect fuel prices[21] for various cities in all provinces over time and then divide fuel purchases by fuel prices to determine the fuel quantities that are used in each plant. Finally, using the embodied GHG emission of each fuel

[21] Fuel prices for gasoline, diesel, propane, light fuel oil, and heavy fuel oil is retrieved from Natural Resource Canada (2016), prices for natural gas is retrieved from Statistics Canada (2015), and prices for coal is retrieved from Natural Resource Canada (2012).

Figure 1: Steps for calculating emission intensity



type,[22] we calculate GHG emissions at the plant-level and divide by the plant's output value to find the emission intensity. This is the first-ever comprehensive plant-level dataset for GHG emissions in Canada.[23] These steps are shown in a simple flowchart in Figure 1.

Quick (2014) shows that estimating emissions by fuel consumption is a more accurate way to determine GHG emissions when compared to using observed emissions from emissions monitoring systems. Linn et al. (2015) show that these two alternative measures of emissions are very consistent with each other and the results are not statistically different. In sum, previous research suggests that the lack of emissions data in the ASM dataset is not of concern with regards to our analysis and our method of estimating GHG emissions should be more accurate than using self-reported emissions or at least consistent with it.

Based on summary statistics, 68 percent of all manufacturing plants report their energy expenditure by fuel types.[24] Because not all plants report their energy expenditure, we exclude some plants from the analysis. There are three reasons why some plants do not report their energy expenditures: 1) plants were not active in the relevant years; 2) plants did not fill the fuel expenditure section of the survey; 3) those plants are administrative plants and not manufacturing plants, and so they do not use any fuels. There is no correlation between the size of plants and missing data for energy expenditure. Therefore, if plants that did not report their energy expenditure were not active for a reason other than carbon tax, or are not systematically different from other plants, there

[22] The embodied GHG emissions by fuel type are available at Environment Canada website.

[23] GHG emissions at the plant-level in Canada only exists for large emitters that emit more than 50,000 tons of CO_2 equivalent. The constructed GHG emissions from large plants in our dataset is consistent with this existing large facility emissions dataset.

[24] The fact that for each fuel we use the average price in major cities in each province, is a potential source of concern. This average price can be different from the exact price that each plant faces, because plants may have different contracts and strategies for buying their fuel. This difference creates a certain degree of error in measuring plant-level GHG emissions. However, if the measurement error does not vary systematically with the treatment (i.e. is not systematically larger or smaller for plants that are more exposed to the policy and only after the BC tax is introduced), it will only increase the noise in the data, inflating the standard errors, but it would not undermine our ability to identify the effect of interest.

will be no selection problem that undermines the identification strategy. The sample is restricted to include plants that appear in the dataset at least once before and once after implementation of the BC carbon tax.

Another concern is that the ASM dataset does not include electricity generation plants. The electricity generation in BC is primarily from hydro, which has negligible emissions and would not be of concern in our analysis. Furthermore, plants are taxes only for their direct purchases of fossil fuels; therefore, we focus only on direct GHG emissions from manufacturing plants and abstract from indirect emissions from electricity consumption.

4.3. Empirical Specification

We estimate the following equation:

$$\ln E_{lipt} = \beta(EI_l \times D_t \times K_p) + \alpha_l + \lambda_{l't} + \phi_{it} + \delta_{pt} + \epsilon_{lipt} \tag{4.1}$$

where $\ln E_{lipt}$ is the log of GHG emissions from plant l of industry i in province p at year t. EI_l is the average emission intensity for plant l from the pre-policy period because the emission intensity after 2008 would be an outcome variable and would change due to the carbon tax. D_t is a dummy for the post-policy period, which is equal to one after 2008 and is equal to zero otherwise. K_p is a dummy variable that takes the value of one for BC and zero for all other provinces. α_l is the plant fixed effect that captures plant specific time-invariant characteristics, as well as industry and province time-invariant characteristics that affect GHG emissions. $\lambda_{l't}$ is the high emission-intensive plant by time fixed effect. We denote l' as a group of plants whose EI_l is greater than a threshold. We use the 70^{th} percentile of emission intensity in the whole sample as the threshold. This fixed effect captures any high emission-intensive plant-specific time shocks. ϕ_{it} are industry by year fixed effects that capture any industry-specific time shocks. δ_{pt} are province by year fixed effects that capture any province-specific and nationwide time shocks. ϵ_{ipt} is the idiosyncratic error term.

β is the coefficient of interest. It shows the average effect of the BC carbon tax on GHG emissions from treated plants during the 2008-2012 period. The identifying assumption is that there are no high emission-intensive-by-province specific shock to GHG emissions that are contemporaneous to the adoption of the BC carbon tax. In other words, there should not be any other factor aside from the BC carbon tax that changes the GHG emissions of (more) treated plants differently than those of untreated (or less treated) plants. This assumption fails if, for instance, there is an economic shock that affects high emission-intensive versus low emission-intensive plants, differently across provinces. We exclude Alberta and Québec as control provinces because they implemented similar policies in 2007.

There was a significant change in the price of natural gas in BC in 2009 and 2014. This study focuses on the period from 2004 to 2012 period; so the price change in 2014 is out of scope and not a concern. The price change in 2009 may be a concern. In the triple difference design we control for industry specific shocks at the 2-digit NAICS code. Therefore, if the impact of the change in natural gas price is not different between the high-emission-intensive and low-emission-intensive plants, our estimation method isolates the impact of the policy from the effect of change in the natural gas price.

5. Results

5.1. Baseline Estimates for BC plants

As mentioned earlier in the empirical research design, two different forms of DID can be used to identify the causal effect of interest. One is to compare high and low emission-intensive plants within BC and the other one is to compare high emission-intensive plants in BC and outside BC before and after the policy. We found some empirical evidence suggesting that these two DID approaches are not able to isolate the effect of the BC carbon policy from the 2008 economic recessions and other concurrent sectoral and provincial shocks. First, we compare high and low emission-intensive plants using only plants within BC and performed placebo estimations in other provinces (See Table B.1 in Appendix B). This specification would reflect the effect of interest in the absence of a secular trend in emissions at the sector level. The coefficient shows that the BC carbon tax reduced the GHG emissions of high-emission-intensive plants in BC by 22 percent relative to the low-emission-intensive plants. In this specification, we do not, however, allow for sector-specific time shocks.

In Appendix A, we mathematically show that this DID estimation within BC cannot isolate the effect of the carbon tax if the recession had a different effect across sectors. Further, we find empirical evidence that the recession had different impacts across sectors. We run placebo regressions in other provinces, where we introduce a carbon tax at the same time period as the BC carbon tax (i.e., the year 2008). For example, we introduce a placebo carbon tax in Ontario in 2008 and run a DID regression comparing high and low emission-intensive plants in Ontario. We do similar placebo regressions in Québec and Alberta. If the DID estimation within BC is able to isolate the effect of the carbon tax, then we expect to see no significant effect in all other provinces using the similar method. The results, however, show that the estimated coefficient from the DID estimation within each province is strongly negative and statistically significant. This suggests that there was a shock common to most provinces in 2008 that affected high emission-intensive plants more severely than low emission-intensive ones. This common shock can be attributed to the economic recession, which started in 2008.

Second, we compare high emission-intensive plants in BC with those in the rest of Canada. In this specification, we do not need to worry about differential time trends across high and low emission-intensive plants, but we cannot control for province-specific time shocks. The coefficient shows that GHG emissions from manufacturing plants in BC declined by 8 percent due to the carbon tax. This specification would reflect the causal effect of interest in the absence of any concurrent shock or policy change at the province level. There are several reasons that these assumptions may not be true. For instance, some provinces like Alberta and Québec implemented similar policies in 2007. Moreover, the economic recession could affect provinces differently because provinces have different industry compositions, have access to different international markets, and because some provinces are natural resource-based economies (i.e. Alberta, Saskatchewan, and Manitoba encounter less impact from the recession).

We also show, in Appendix A, that this comparison cannot isolate the effect of the carbon tax if the recession had a different impact across provinces. We also find empirical evidence suggesting differential effects of the recession across provinces. We run placebo regressions in other provinces, where we introduce a placebo tax in Ontario, Québec, Manitoba, Saskatchewan, and Alberta. If the DID estimation across provinces (i.e., comparing only high emission-intensive plants across provinces) was able to isolate the effect of the BC carbon tax, then we expect no significant effect in other provinces using the same method. The coefficient of interest is negative for Ontario and positive for Manitoba, Saskatchewan, and Alberta. These results suggest that this comparison also cannot isolate the effect of the BC carbon tax. Alberta, Saskatchewan, and Manitoba, which are resource-based economies, withstood the impacts of the economic recession better. This fact is consistent with the positive coefficient for these provinces. The results of these placebo tests are presented in Table B.2 in Appendix B.

We then use a triple difference method to deal with the identification issue regarding DID estimations. This specification allows for province, industry, and high emission-intensive plant specific time effects. These fixed-effects can capture any differential effect of the economic recession across provinces, industries, and sectors. The results of four specifications based on Eq.(4.1) are reported in Table 2. First two columns report coefficients estimated using the data at the plant-level whereas last two columns report coefficients estimated using the semi-aggregated data. We aggregate the data to the city-by-sector (6-digit NAICS) level to address a measurement error in the dependent variable. As we are using the constructed emission data based on fuel expenditures from a survey-based dataset, there is a concern of measurement error in the dependent variable (i.e., plants GHG emissions), as well as in the independent variable (i.e., emission-intensity of plants).[25]

[25] Measurement error in the dependent variable is less of concern because it only reduces precision in estimating the

Table 2: Baseline Estimates for Emissions

	(1)	(2)	(3)	(4)
$EI_l \times D_t \times K_p$	-0.20	-0.15	-0.26**	-0.23**
	(0.16)	(0.16)	(0.10)	(0.10)
Plant	Y	Y		
City × sector			Y	Y
Industry × time		Y		Y
Measurement error correction			Y	Y
N	117445	117445	41548	41548
R^2	0.90	0.91	0.93	0.93

Notes: Dependent variable is log of plant-level emission. EI_l is the average emission intensity for plant l from the pre-policy period. D_t is a dummy for the post-policy period, which is equal to one after 2008 and is equal to zero otherwise. K_p is a dummy variable that takes the value of one for BC and zero for all other provinces. Sector refers to the 6-digit NAICS industry while industry refers to the 2-digit NAICS industry. All specifications include high emission intensive plant by time FE, and province by time FE. To account for serial correlations and within sub-industry correlations, standard errors are clustered by province by industry (at 2-digit NAICS), reported in parentheses.
*** Significant at the 1 percent level, ** Significant at the 5 percent level, * Significant at the 10 percent level.

To deal with the measurement error, we follow a similar approach as Chowdhury and Nickell (1985). They show that dividing the sample into different groups and taking the average within each group would reduce the measurement error to a large extent. We take the average of plants' emission intensity during the 2005-2007 period, as well as taking the average of plants' emission intensity within the same industry and city.[26] We expect that taking the average in two dimensions reduces the measurement error to a large extent. This approach also allows us to reduce the measurement error in the dependent variable, which improves the precision of estimating the standard errors. The downside of this approach is that we cannot control for confounding factors at the plant-level. We are, however, still able to control for such factors common to industries and locations.

In all columns, we control for high emission-intensive plant by time fixed-effects[27], and province

standard error, but the coefficient would be unbiased. The measurement error in emission intensity is more of concern because it causes attenuation bias, as it biases the estimates downward. For more details regarding measurement errors in panel data refer to Griliches and Hausman (1986). I use plants' emission intensity prior to 2008 meaning that the measurement error would not be correlated with the treatment variable.

[26]We take the average over time and across plants within the same 6-digit North America Industry Classification System (NAICS) code and the same city. Each industry-by-city group contains about 3 plants.

[27]Plants with emission intensity higher than 70 percentile are considered high emission-intensive plants. Results

by time fixed-effects. Plant fixed-effects are included in the first two columns while city by sector (6-digit NAICS) fixed-effects are included in the last two columns. Industry (at 2-digit NAICS) by time fixed-effects are included in column 2 and 4. Standard errors are clustered at the level of province by industry (2-digit NAICS).[28] The sample covers from 2004 to 2012 and includes only plants that appear in the data set at least once before and once after implementation of the carbon tax.

All specifications show negative signs with the similar magnitudes, implying that the carbon tax had a negative impact on the manufacturing emission in BC. As expected, addressing the measure error by the data-aggregation improved the precision of the estimations so that the coefficients from column 3 and 4 are negative and statistically significant. Although adding the industry by time FEs reduced the size of the coefficient slightly, the point estimates are robust to the inclusion of such FEs. These point estimates suggest that at the average tax rates (at \$20/tCO_2e), the carbon tax reduced the manufacturing emission by approximately 2 percent.[29]

5.2. Robustness Check

5.2.1. Anticipatory Effect

Plants might have anticipated the BC carbon tax and changed their behavior prior to the implementation of the policy. The BC carbon tax was announced unexpectedly, but plants might still get informed prior to the announcement. To test for the presence of an anticipatory response, we use an event-study method to investigate the evolution of the emission effects during the sample period, treating 2007 as the base year.[30] The emission effect should be zero for all years during the pre-policy period (2004-2007) in order to have no anticipatory effect. The results from this event-study method are shown in Figure 2. The point estimates for the pre-policy period are all close to zero (i.e., precisely estimated zero), which confirms that there was no anticipatory response to the BC carbon tax. It is clear from the figure that the emission effects are declining after the implementation of the policy.

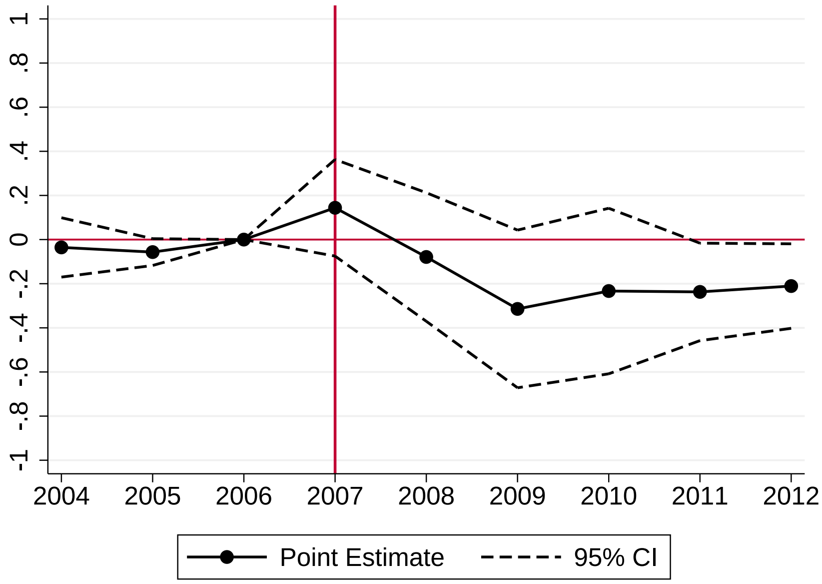
are robust to using 50 and 60 percentile.

[28] We also cluster the standard errors at the province level as well as province by 3-digit NAICS industry level, and results are similar. Mackinnon and Webb (2019) show that under-clustering (i.e., clustering at the 3-digit NAICS industry by province) suffers from a severe over-rejection, implying that ignoring the within-province correlation is worse than having too few cluster groups (i.e., clustering at the province level). Thus, we cluster at the 2-digit NAICS industry by province.

[29] This 2 percent reduction is calculated by $100 \times \left(e^{(\hat{\beta}\,\overline{EI}_i} - 1\right)$ where $\overline{EI}_i$ the average emission intensity among the BC plants. We also calculated the upper and lower bounds for the emission effect, which are 0.22 and 3.5 percent reduction, respectively.

[30] This method is also referred to as a flexible estimation.

Figure 2: Regression Result from Event-study Method for Emissions



Note: This figure plots the point estimates from the event-study method estimation, treating 2007 as the base year (indicated by red solid line). Y-axis is the percentage change in emission while x-axis is year.
Source: Author's calculation.

5.3. Mechanism: Scale vs. Technique effects

As we discussed in Section 3, emissions can decrease by either an improvement of technology (technique effect), a reduction in output (scale effect), or both. This suggests that the 2 percent reduction in emission found in the previous section could be solely due to the scale effect, which would further imply that the emission reduction would necessarily come at the cost of manufacturing output. We explore this possibility by investigating the effect of the carbon tax on the manufacturing output. The result of estimating Eq.(4.1) with the log of output being the dependent variable is shown in Table 3.

Contrary to the prior expectation described above, Table 3 shows an interesting and appealing result, i.e., the estimated coefficient is statistically significant and positive. This suggests an increase of the manufacturing output in response to the policy. The point estimate shows that, at the average tax rates (at \$20/tCO_2e), the output increases by 0.8 percent.[31]

If the scale effect is positive, emissions can decline only through the improvement of technology.[32] There are two possible channels through which this particular policy can generate this

[31] This 0.8 percent increase is calculated using the same method as the emission effect, and its upper and lower bounds are 1.1 and 0.5 percent, respectively.

[32] We also estimated Eq.(4.1) with the plant-level emission intensity being the dependent variable and found a statistically significant negative result.

Table 3: Baseline Estimate for Output Effect

	(1)
$EI_l \times D_t \times K_p$	0.097***
	(0.018)
N	41548
R^2	0.96

Notes: Dependent variable is log of plant-level output. EI_l is the average emission intensity for plant l from the pre-policy period. D_t is a dummy for the post-policy period, which is equal to one after 2008 and is equal to zero otherwise. K_p is a dummy variable that takes the value of one for BC and zero for all other provinces. It includes high emission intensive plant by time FE, province by time FE, industry (2-digit NAICS) by time FE, and city by sector (6-digit NAICS) FE. The measurement error correction is also applied to this specification. To account for serial correlations and within sub-industry correlations, standard errors are clustered by province by industry (2-digit NAICS), reported in parentheses. *** Significant at the 1 percent level, ** Significant at the 5 percent level, * Significant at the 10 percent level.

positive technique effect. The first is that the carbon tax can directly provide an incentive for plants to invest in an energy-saving technologies. This is because plants may wish to lower the long-run financial costs of paying the carbon tax.

The second channel is through the reduction of the corporate income taxes (CIT). As a CIT is essentially a tax on capital, reducing its rate would improve a distortion in plants' decision on capital. This could incentivize plants to invest. What is different from the first channel is that this channel can also explain the positive output effect found in this paper because plants may also invest in productivity-enhancing technologies. As lowering the user costs of capital provides incentives for all types of capital, not just energy-saving related capital, these investments may allow plants to produce more with the same amount of inputs or even less inputs. This is why it is possible for plants to reduce emission while producing more. In fact, Yamazaki (2019) theoretically supports this argument by showing the importance of this revenue-recycling through a CIT reduction.

One concern here is the measure of output. The ASM does not provide the quantity of output produced, instead it records the total sales (the product of product price and quantity). The increase in output found in this section can also be due to the increase of price. Although there is no direct way to test or isolate the price effect, we argue that this may not be much of concern in this particular context because a majority of plants in the sample are heavily traded internationally. This implies that their output prices are determined at the world market, not set by individual plants. This is especially true for Canadian manufacturing plants as Canada is considered as a small open economy. Yamazaki (2019) confirms this view in the context of productivity.

Putting together the results, manufacturing plants seem to respond to a revenue-neutral carbon tax by investing in both energy-saving and productivity-enhancing technologies, which allows them to lower emissions while producing more.

6. Conclusion

Several jurisdictions implemented unilateral environmental policies such as carbon taxes to reduce their GHG emissions. After the universal climate agreement in Paris (December 2015), it is expected that more countries impose carbon policies to limit their GHG emissions. Empirical evidence on the effectiveness of such policies is, however, very limited. This paper takes advantage of a unique plant-level dataset and uses the revenue-neutral carbon tax in BC as an ideal setting to estimate the effect of this policy on GHG emissions from manufacturing plants.

We point out that conventional DID methods are not able to distinguish the causal effect of the BC carbon tax from the effect of the economic recession. To deal with this identification issue, we directly exploit a variation in emission intensity across plants, in additional to the over-time and across-province variation, and design a triple difference estimation. This method allows us to isolate the causal effect of the carbon tax on GHG emissions. We find that, at the average tax rates (\$20/tCO_2e), the BC carbon tax led to a decline in manufacturing emissions by approximately 2 percent. Furthermore, we investigate whether this decline in emission comes entirely by the negative scale effect of the policy. We find that output increased by 0.8 percent in response to the policy, suggesting that the reduction of corporate income taxes encouraged plants to invest in both energy-saving and productivity-enhancing technologies (i.e., positive technique effects) to produce more with less energy.

The appealing findings from this paper is mainly due to the revenue-neutrality feature of this policy, especially the reduction of the corporate income tax. As we mentioned, the amount of tax revenues the BC government returned to its economy was 15% more than what the BC carbon tax collected. Although we did not directly estimate the technique effect of this policy, recycling the carbon tax revenues to reduce the CIT played a major role in the emission reduction from the manufacturing sector through investments. What would be important to investigate in a future research is the long-run effect of the policy. This paper already demonstrated the importance of the technique effect for emission reductions in response to the policy. Many argue that it takes time for investments to have a substantial impact on emission reductions, productivity enhancement, or even both. Thus, investigating the long-run effect of this policy would provide a fruitful contribution to both the literature and public policy. In addition, we can understand better about the magnitude of each component of a revenue-neutral carbon tax by separately identifying the emission and output effects from the carbon tax and CIT cut.

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Appendices

Appendix A Mathematical Illustration of the Weakness of the DID Estimation

In the main text, we explain the weakness of the DID estimation. In this appendix, we explicitly show the exact bias in the DID estimation.

With our data, there are three sources of variations that can be exploited to isolate the effect of the carbon tax. First two obvious variations are temporal and regional variations, i.e., pre-policy vs. post-policy period and BC vs. the rest of Canada. The third variation comes from the fact that the exposure to the policy differ by emission intensity of plants, i.e., high emission-intensive vs. low emission-intensive plants. We show the identification issue regarding two potential DID estimations.

Suppose that Y_{0lpt} is the potential emissions from plant l, in province p, and at time t in the absence of any carbon tax. Denote Y_{1lpt} as the potential emissions of a plant in the presence of a carbon tax. One of the main assumptions of DID estimations is that the potential outcome in the no-treatment state has an additive structure. This assumption means that in the absence of the treatment, the potential outcome is determined by the sum of a time-invariant province effect and a year effect that is common across provinces.

$$E[Y_{0lpt}|p,t] = \gamma_p + \lambda_t \tag{A.1}$$

While in the main analysis we directly use the plant-level variation in emission intensity, here instead we discretize this variation by grouping plants into high emission-intensive and low emission-intensive plants.

Formally, let D_{lpt} be a dummy variable for high emission-intensive plants in BC after year 2008, let D_{lt} be a dummy variable for high emission-intensive plants in all provinces after 2008, and let D_{pt} be a dummy variable for each province after 2008. In the rest of the appendix, we exclusively refer to the two different categories of emission intensity as "sectors". Suppose that the economic recession had different impacts across provinces and sectors. Assuming that the BC carbon tax did not have any impact on low emission-intensive plants, the observed emissions, Y_{ilpt}, can be written as:

$$Y_{ilpt} = \gamma_p + \lambda_t + \rho_1 D_{lpt} + \rho_2 D_{lt} + \rho_3 D_{pt} + \epsilon_{lpt} \tag{A.2}$$

where λ_t captures the effect of the recession common for all plants, ρ_1 is the effect of the BC carbon tax on GHG emissions, ρ_2 is the effect of the recession on high emission-intensive plants relative to the low emission-intensive ones, ρ_3 is the differential effect of the recession on BC relative to the rest of Canada, and $E[\epsilon_{lpt}|l, p, t] = 0$.

One way to implement a DID estimation is to compare high and low emission-intensive plants within BC and drop all observations outside BC. This DID estimation can control for the differential effect of the recession across provinces, but cannot control for the differential effect of the recession across high and low emission-intensive plants.

$$\begin{aligned}
&E[Y_{ilpt}|l = high|p = BC, t \geq 2008] - E[Y_{ilpt}|l = high|p = BC, t < 2008] \\
&= \lambda_{t\geq 2008} - \lambda_{t<2008} + \rho_1 + \rho_2 \\
&E[Y_{ilpt}|l = low|p = BC, t \geq 2008] - E[Y_{ilpt}|l = low|p = BC, t < 2008] \\
&= \lambda_{t\geq 2008} - \lambda_{t<2008}
\end{aligned}$$

The DID would result in:

$$\begin{aligned}
&E[Y_{ilpt}|l = high|p = BC, t \geq 2008] - E[Y_{ilpt}|l = high|p = BC, t < 2008] \\
&- E[Y_{ilpt}|l = low|p = BC, t \geq 2008] - E[Y_{ilpt}|l = low|p = BC, t < 2008] \\
&= \rho_1 + \rho_2
\end{aligned}$$

The coefficient from this DID estimation would capture the effect of the carbon tax plus the effect of the economic recession.

Another way to design a DID estimation is to compare high emission-intensive plants across provinces. We drop low emission-intensive plants from the analysis. Using a similar logic, it can be shown that the coefficient from this DID would capture $\rho_1 + \rho_3$, which is the effect of the BC carbon tax plus the effect of the recession. DID estimations can identify the causal effect of the BC carbon tax only if the economic recession had exactly the same impact on all provinces and sectors (i.e., ρ_2 and ρ_3 are equal to zero).

Appendix B Additional Table

Table B.1: DID and Placebo Regressions within Provinces

	(BC)	(ON)	(QC)	(AB)
$EI_l \times D_t$	-0.22**	-0.15**	-0.16**	-0.27**
	(0.08)	(0.08)	(0.08)	(0.12)
N	5351	15877	10174	4282
R^2	0.92	0.92	0.92	0.93

Notes: Dependent variable is log of plant-level emission. D_t is a dummy for the post-policy period, which is equal to one after 2008 and is equal to zero otherwise. EI_l is a dummy variable that takes the value of one if the emission intensity for a given plant is greater than a threshold, and is zero otherwise. We use the 70^{th} percentile of emission intensity in the whole sample as the threshold. Emission intensity captures the variation of the policy impact across plants and provinces. All specifications include plant fixed-effects and industry-by-time fixed-effects. Standard errors clustered at industry-level (2-digit NAICS) are reported in parentheses.
*** Significant at the 1 percent level, ** Significant at the 5 percent level, * Significant at the 10 percent level.

Table B.2: DID and Placebo Regressions across Provinces

	(BC)	(ON)	(QC)	(MB)	(SK)	(AB)
$D_t \times K_p$	-0.086	-0.23***	0.02	0.23***	0.32**	0.28***
	(0.08)	(0.06)	(0.07)	(0.07)	(0.12)	(0.08)
N	11585	11585	11585	15877	11585	11585
R^2	0.91	0.91	0.91	0.91	0.91	0.91

Notes: Dependent variable is log of plant-level emission. D_t is a dummy for the post-policy period, which is equal to one after 2008 and is equal to zero otherwise. K_p is a dummy variable that takes the value of one for BC and zero for all other provinces. Only plants that have emission intensity greater than the 70^{th} percentile are included. All specifications include plant fixed-effects and industry-by-time fixed-effects. Standard errors clustered at industry-level (2-digit NAICS) are reported in parentheses. *** Significant at the 1 percent level, ** Significant at the 5 percent level, * Significant at the 10 percent level.

Table B.3: Manufacturing Industries at 3-digit NAICS code

311	Food manufacturing
312	Beverage and tobacco product manufacturing
313	Textile mills
314	Textile product mills
315	Clothing manufacturing
316	Leather and allied product manufacturing
321	Wood product manufacturing
322	Paper manufacturing
323	Printing and related support activities
324	Petroleum and coal product manufacturing
325	Chemical manufacturing
326	Plastics and rubber products manufacturing
327	Non-metallic mineral product manufacturing
331	Primary metal manufacturing
332	Fabricated metal product manufacturing
333	Machinery manufacturing
334	Computer and electronic product manufacturing
335	Electrical equipment, appliance and component manufacturing
336	Transportation equipment manufacturing
337	Furniture and related product manufacturing
339	Miscellaneous manufacturing