Environmental Taxes and Productivity: Lessons from Canadian Manufacturing*

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Abstract

This paper investigates how environmental taxes affect manufacturing productivity by examining British Columbia's revenue-neutral carbon tax. I develop a new hypothesis, "Productivity Dividend Hypothesis," to show that environmental taxes can positively affect productivity by recycling tax revenues to reduce corporate income taxes. This particular revenue-recycling increases investments and could raise productivity more than environmental taxes lower productivity by diverting resources from production. I empirically test this hypothesis using detailed confidential plant-level data. I find that the carbon tax lowers productivity, although this is slightly offset by the revenue-recycling. For some plants, the policy led to a net gain in productivity.

Key Words: Environmental tax; manufacturing; productivity

JEL Codes: D22, H23, L6, Q5

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1. Introduction

Implementing environmental policy is a challenging task as some worry that environmental benefits are uncertain and, if any, come at the cost of economic growth and jobs. Among various policy instruments available, environmental taxes have gained popularity, especially in Europe, due to its ability to raise revenues.[1] Such revenues are used to reduce the existing distortionary taxes, thereby stimulating economic growth. In the wake of the Paris Agreement, many more jurisdictions are considering some types of carbon pricing policy to reduce emissions. Policymakers then face a challenge in deciding how to use the revenues. To guide policymakers on this issue, this paper investigates how environmental taxes affect manufacturing productivity when the tax revenues are recycled. I answer such an important question by examining the revenue-neutral carbon tax in British Columbia.

Investigating the productivity effect on the manufacturing sector is important for three reasons. First, the manufacturing sector has been contributing to economic growth of many countries and is still one of the largest sectors in the economy around the world.[2] Second, the manufacturing sector plays an essential role in future innovation because its R&D expenditure is large. The technological advancement in manufacturing positively affects the rest of the economy. Third, policymakers and the public worry that manufacturing businesses would suffer greatly from additional costs imposed by the carbon tax. This is because the manufacturing sector is an emission-intensive and trade-exposed industry.

British Columbia (BC) implemented a carbon tax on July 1st, 2008, applying it to the purchase of all fossil fuels for all consumers. It is the first and most comprehensive carbon pricing policy in North America. The policy provides unique features that one can take advantage of to clearly identify the productivity effect of the policy. First, the policy was implemented only five months after its announcement. This surprise and quick implementation gave no room for polluting plants

[1] See Bosquet (2000) for the list of European countries with different types of environmental taxes.

[2] For example in BC, manufacturing sector comprises 10 percent of the provincial GDP, and it is a major contributor to exports. In terms of jobs, 20 percent of jobs are in the manufacturing sector and their wages are 15 percent higher than the provincial average (Heartwell, 2012).

to adjust their operations to minimize the tax burden prior to the implementation. Second, the tax rate was set at a relatively high rate, which provided strong incentives for plants to adjust operations to reduce their emissions. Third and most importantly, all of the tax revenue raised was used to reduce personal and corporate income taxes and provide lump-sum transfers to low-income households. In this paper, I particularly focus on the importance of the reduction of corporate income taxes on productivity.

My empirical strategy is motivated by a simple model of the total factor productivity (TFP) residual. By incorporating abatement investment decisions into the model, I develop a new hypothesis to show that environmental taxes can positively affect productivity by recycling tax revenues to reduce corporate income taxes (CIT). The model shows that there are two distinct channels through which a revenue-neutral carbon tax affects plant's productivity. First, the model predicts that taxing energy diverts some productive resources away from production to regulatory compliance, lowering productivity. At the same time, it could induce more investment in abatement, enhancing productivity. The productivity effect of this "carbon tax effect" is determined by these two effects.

Second, recycling revenues from the carbon tax to lower the rate of the CIT positively affects productivity. This comes from the fact that the "revenue-recycling effect" ameliorates the distortionary nature of the CIT system, increasing the productivity-enhancing investments. When this revenue-recycling effect raises productivity more than the carbon tax lowers productivity by diverting resources from production, a revenue-neutral carbon tax can lead to a net gain in productivity. I name this hypothesis the "Productivity Dividend Hypothesis" (PDH). Furthermore, if revenue-neutral carbon taxes also reduce emissions, such policies offer a double dividend. I name this the "Productivity Double Dividend (PDD) Hypothesis."

I test the PDH using detailed confidential plant-level production data linked with firm-level administrative tax data. This linked data allows me to decompose the productivity effect into the carbon tax and revenue-recycling effects and identify each effect separately. I identified both effects, not only by comparing plants in BC with plants in the rest of Canada (ROC) before and after the implementation of the carbon tax, but also by comparing plants based on plant characteristics.

The carbon tax effect is estimated using the plant-level carbon tax expenditure intensity. Using the data on the fuel-specific energy expenditure, I calculated how much each plant paid for the carbon tax relative to its value-added. If plants in BC with high carbon tax expenditure intensity experience a larger decline in productivity relative to other plants in BC with low carbon tax expenditure intensity, this productivity decline can be interpreted as the effect of the carbon tax. The revenue-recycling effect is estimated using the data on taxable income. I compare plants whose parental firm is in a loss position with plants whose parental firm is making a positive profit. If the latter plants experience a larger increase in productivity relative to the former plants, this productivity increase can be interpreted as the effect of the revenue-recycling. This is because a reduction of the CIT rate is irrelevant for plants whose parental firm is in a loss position.

Using this strategy, the productivity effect is estimated by a propensity-score-weighted (PSW) difference-in-difference (DID) estimator, allowing for different treatment intensity across plants. This method augments the conventional DID estimator by allowing the treatment to be continuous and constructing estimates for the counterfactual from the ROC plants that resemble the BC plants. I first estimate the propensity scores using a rich set of observable pre-treatment plant characteristics, such as energy expenditures by various fuel types. I then use these propensity scores as weights to re-weight the distributions of the control plants in the estimation so that the plants from BC and ROC are similar in the pre-treatment period. Larger weights are given to plants that are more similar to plants in BC. In addition, I exploit the panel structure of the data by including various fixed effects to control for possible unobserved confounding factors, such as commodity price shocks, provincial geographic characteristics, and plant-specific managerial ability.

Using this approach, I find that BC's revenue-neutral carbon tax had a statistically significant negative carbon tax effect and positive revenue-recycling effect on manufacturing plant's productivity. On average, the carbon tax effect reduced productivity annually by 1.2% while the revenue-recycling effect increased productivity by 0.2%, offsetting the negative carbon tax effect by approximately 20%. The policy led to a net loss in productivity by 1%. Yet, once I allow for heterogeneity, some plants experienced a net gain in productivity. These plants are the ones with a positive taxable income, but little carbon tax expenditure. For those plants, the productivity dividend hypothesis was supported. These findings provide an evidence that recycling tax revenues through the reductions of the CIT rates can alleviate some negative productivity impacts from the carbon tax, and may lead to a net gain in productivity.

To put this in context, one can interpret these declines in productivity in terms of output (value-added). Assuming that inputs are held constant, on average, output fell annually by $150,000 in response to the policy.[3] Without the CIT reduction, the output would have declined by $160,000, implying that recycling tax revenues through the reduction of CIT helped save plant's output by $10,000. By aggregating plant-level estimates, the finding suggests that BC's manufacturing output fell by $440 million annually while the CIT reduction had saved output by $25 million.

This paper makes several contributions. Firstly, this paper develops a new hypothesis to evaluate novel predictions related to the double dividend hypothesis of environmental tax reforms. The traditional double dividend hypothesis suggests that the revenue-neutral substitution of the environmental tax for existing distortionary taxes leads to welfare or employment gains (Goulder, 1995).[4] The PDH introduces a new possibility that revenue-recycling could also enhance productivity in addition to welfare and employment.

Furthermore, this paper estimates the revenue-recycling effect of an environmental tax, providing the first empirical test of the double dividend hypothesis in terms of productivity. No study in the literature has ever separately estimated both the carbon tax and revenue-recycling effects. The empirical approach used in this paper can be applied to estimate these two effects of environmental taxes in general.

Secondly, this paper contributes to the broader literature on the productivity impacts of environmental policies.[5] There are two types of environmental policies, command-and-control and

[3] This is calculated as taking the average of plant-level output effects. The plant-level output effect is calculated as the difference between the counterfactual output ($= Y_i/(1 - \%\Delta\text{TFP}_i)$), e.g., if the productivity effect is -0.2% with $1 million observed output, the counterfactual output is $1.002 million.

[4] The effect could also be zero.

[5] See Koźluk and Zipperer (2015) and Dechezlepretre and Sato (2017) for the survey of this literature.

market-based policies. Early studies have mostly focused on the former policy, e.g., the US Clean Air Act, and found that environmental regulations hamper productivity in narrowly defined sub-industries within the manufacturing sector.[6] More recently, Greenstone, List and Syverson (2012) have conducted a large-scale study of the 1970 US Clean Air Act Amendments using the plant-level data covering the entire US manufacturing sector. They found that plants in regulated counties experienced a decline in TFP by 4.8%.

While this literature is relatively extensive, there is little work examining the productivity effect of market-based policy, e.g., carbon pricing policies. Commins et al. (2011) and Lutz (2016) have both investigated the European Union Emission Trading System (EU-ETS) while Martin, de Preux and Wagner (2014) examined the UK energy tax. What is different about the market-based policy is that it provides incentives for polluters to respond to the policy in a flexible fashion. Commins et al. found that the first phase of the EU-ETS negatively affected European manufacturing firms' TFP.[7] On the other hand, Lutz found the EU-ETS had a positive productivity effect during the first phase, but no effect during the second phase on German manufacturing firms.[8] Martin, de Preux and Wagner also found no effect of the energy tax on UK manufacturing plants. Although the empirical evidence is limited, the productivity effects of the carbon pricing policies seem to be much less detrimental than those of command-and-control policies. This may be exactly due to the incentives encouraged by the policy for innovations and investments to improve the input efficiency. This paper adds to this literature by showing that such incentives can also be provided by recycling the tax revenues raised by the policy. Thus, this paper shows the importance of estimating both the carbon tax and revenue-recycling effects.

Thirdly, this paper improves upon previous studies by constructing a measure of TFP more

[6] One exception is Berman and Bui (2001). They examined a stricter air quality regulation imposed on the Los Angeles Air Basin and found a positive productivity effect in oil refineries. Although their empirical estimate was positive, it was statistically insignificant, and its confidence interval ranged from 19% to −9%. This result is consistent with the results found in Greenstone, List and Syverson (2012). Their estimate for the refinery sector was also statistically insignificant and its confidence interval ranged from 2% to −3%.

[7] The credibility of this study's finding has been questioned by many papers as their treatment variable is defined at the sector-level. Their estimates may be severely biased due to the measurement errors and confounding sector shocks.

[8] The first phase of the EU-ETS was an experimental phase when the price of allowances were zero due to the excess supply. Thus, the second phase might be seen as the actual policy.

accurately. I do this by employing a semi-parametric estimation method proposed by Ackerberg, Caves and Frazer (2015) – henceforth ACF. I further revised the ACF method by following De Loecker (2007) and Lutz (2016). I allow TFP to endogenously reflect on important plant heterogeneity that is related to behavioral responses to carbon tax, such as energy efficiency. In addition, this paper further improves the measure of TFP by using direct capital input data. This addresses an issue in estimating the production function when there is a measurement error in capital input Collard-Wexler and De Loecker (2016)

The remainder of the paper is structured as follows. Section 2 describes the design of the BC carbon tax. Section 3 defines the Productivity Dividend Hypothesis (PDH). I provide a simple model to explain the PDH. Section 4 presents the research design while section 5 explains the data. The empirical findings are presented in section 6. Section 7 discusses the counterfactual experiment where the tax revenue is recycled entirely through the CIT reduction. Finally, section 8 concludes. Detailed descriptions of TFP calculation, quantity-based TFP construction, data, and additional robustness checks are in the Appendix.

2. Background of the BC Carbon Tax

The Ministry of Finance formally announced the implementation of carbon tax in their February 2008 budget plan. Only five months later, the tax was implemented on July 1st, 2008. The announcement surprised the public given the past political actions taken by the Liberal government (Harrison, 2013). The tax was originally criticized by northern and rural communities, arguing that tax burden might fall on them unfairly due to their colder climate. Even with some negative reactions, polls indicated that a majority of voters in BC supported the introduction of carbon tax. Thus far, despite the regime change from the Liberal Party to the New Democratic Party after the 2017 general election, the carbon tax has survived since the announcement and implementation.

The BC carbon tax is levied on the carbon content of all fossil fuels initially at \$10/t CO_2e. The rate increased by \$5/t CO_2e annually until it reached \$30 in 2012, making it the highest carbon tax in the world (Murray and Rivers, 2015). The rate was kept at $30 until 2018 when it increased to $35 on April 1. It will continue to annually increase by $5 and reach $50 in 2021 (Ministry of Finance, 2017). These increases are set to meet the carbon pricing requirements in the Pan-Canadian Framework on Clean Growth and Climate Change. This framework is a collective plan set out by the federal government to reduce emissions in Canada. British Columbia joined this framework in 2016. Under this framework, the carbon tax rate is required to be at $50 by 2022. The BC carbon tax rate will reach this requirement in 2021 and will be kept at $50 for 2022.

As each fuel has a different carbon content, the rate is adjusted accordingly. For example, the carbon tax increased the price of gasoline by 2.34 cents per liter, rising gradually to 6.67 cents per liter in 2012 (Ministry of Finance, 2010). Increasing the tax rate gradually allows consumers to adjust their fuel usage slowly and minimize the financial burden from the tax.

In designing carbon pricing policy, certain exemptions are often made to avoid potential negative impacts to the economy.[9] The exemptions are considered to address the concerns raised by the public and policymakers about losing competitiveness of regulated industries. At the same time, such compromises could be costly and lead to welfare losses due to the tax base erosion and increases of dead-weight loss (Böhringer and Rutherford, 1997). On the other hand, the BC carbon tax was designed initially with no exemptions, making the tax base broad.[10]

One of the unique aspects of the BC carbon tax is the revenue-neutrality. It is meant not only to minimize the potential adverse impact on the economy, but also to gain more support from the business community. Although business leaders expressed their support for the tax when they were approached by the Premier's office in late 2007, their support was contingent on the revenue-neutrality. According to the Budget and Fiscal Plan (Ministry of Finance, 2015), the carbon tax raised about $1.2 billion revenue annually since 2012 when the tax rate has stopped increasing at

[9] For example, manufacturing and horticulture sectors are entirely exempted from the energy tax in Sweden while various transport sectors are exempt from the carbon tax in Norway (see Ekins and Speck (1999) for more examples of exemptions in Europe).

[10] In March 2012, a carbon tax relief was granted to commercial greenhouse growers to protect the competitiveness of agricultural industries against producers in the United States and Mexico (Murray and Rivers, 2015). A temporary relief of $7.6 million was provided in 2012, and then the relief program was made into a permanent program in 2013. As of January 1, 2014, the purchase of colored gasoline and colored diesel fuel used for farm purposes are exempted. For further information, see http:www.gov.bc.ca/agri/.

\$30/t CO_2e. These revenues are used to reduce the rate of personal and corporate income taxes and provide lump-sum transfers to low-income households. In detail, the personal income tax was reduced by 5 percent over the first two years for the two lowest income brackets (i.e., those earning less than \$70,000 per year) while the general and small corporate income taxes were reduced from 12 to 10 percent and 4.5 to 2.5 percent over the first three years, respectively (Ministry of Finance, 2008).[11] In addition, a one-time Climate Action Dividend of \$100 per adult was provided in the initial year to help begin the transition to a lower carbon lifestyle. To respond to the concerns raised by northern and rural communities, as of the 2011 tax year they are given a further benefit of \$200.

Although the government had designed this policy to be revenue-neutral, tax credits have been exceeding tax revenues since its implementation, an average excess of \$128 million over the first six years. The government has no intention of making the policy a part of the province's stimulus package. This discrepancy simply stems from failing to accurately estimate the expected revenue from the carbon tax. The estimated revenues have been lower than anticipated since the implementation due to the much higher decline in consumption of fossil fuels. Although the policy has been revenue-*negative*, given that the excesses account only for less than 1 percent of BC's total tax revenue, I treat it as revenue-neutral in this analysis to be consistent with the intention of the BC government.

3. The Productivity Dividend Hypothesis

In this section, I briefly explain how revenue-neutral carbon tax affects productivity of manufacturing plants. A simple model motivates my empirical method discussed in Section 4.

Consider a partial equilibrium model with an iso-elastic demand for manufacturing goods:

$$x = p^{-\sigma} B \tag{3.1}$$

[11] These made BC's corporate and personal income taxes the lowest in Canada. In fact, BC has tied with Alberta and New Brunswick for the lowest corporate tax rate, and has had the lowest personal income tax rate in Canada, but for only those earnings up to \$119,000 (Elgie and McClay, 2013).

where B is a constant representing aggregate quantity and price indexes, and p is the price for the manufacturing goods.

Following Copeland and Taylor (1994), I assume there is a joint production technology for manufacturing plants:[12]

$$x = A(1-\theta)F(K, L) \tag{3.2}$$

$$Z = \varphi(\theta)F(K, L) \tag{3.3}$$

where x is manufacturing output and Z is emission.[13] I assume that capital (K) and labor (L) are used to produce the potential output, $F(K, L)$. We can think of x to be the net output because some are allocated to abatement. $\varphi(\theta)$ is an abatement function, satisfying $\varphi(0) = 1, \varphi(1) = 0$, and $d\varphi/d\theta < 0$. $\theta \in [0, 1]$ is a fraction of inputs allocated to abatement. This means that the level of emission decreases with abatement, but at the cost of output.

Now following Forslid, Okubo and Ulltveit-Moe (2018), I express the abatement function of Copeland and Taylor (1994) as follows::

$$\varphi(\theta) = \frac{(1-\theta)^{1/\alpha}}{\Omega(I_A)} \tag{3.4}$$

with $0 < a < 1$, and $\Omega(I_A)$ is the abatement augmenting technology, which is a function of abatement investment, I_A. It satisfies $d\Omega(I_A)/dI_A > 0$ and is the reciprocal of the amount of emission produced per output.[14] This can be interpreted as a technological parameter for the abatement activity, i.e., an increase in $\Omega(.)$ is an improvement in the abatement technology. Eq.(3.4) reflects that plants can reduce their emissions by increasing θ or increasing the abatement investment. From Eq.(3.2), TFP can be expressed as $A(1-\theta)$. This implies that TFP increases with less resources

[12]This is a joint production as producing one unit of output (F) produces x unit of emission, i.e., $x = AF(K, L)$ and $z = x$ if there is no abatement.

[13]Technically, the input augmenting technology, A, is applied to all inputs including emission. Thus, $AZ = \varphi(\theta)AF(K, L)$.

[14]This parameter is 1 in Copeland and Taylor (1994) as they assume one unit of gross output produces one unit of emission.

allocated to the abatement activities.

By solving plant's problem, I show below how a revenue-neutral carbon tax affects the term, $(1-\theta)$. Using Eq.(3.2) and Eq.(3.3), output can be shown to be:

$$x = A\big(\Omega(I_A)Z\big)^{a} F(K, L)^{1-a} \tag{3.5}$$

With this formulation, one can think of Z as an input and re-interpret it as energy.[15] Further, let $e \equiv Z/x$ be energy intensity. Substituting $Z = ex$ into Eq.(3.5), and then solving for x yields:

$$x = A^{1/1-\alpha}\big(\Omega(I_A)e\big)^{\alpha/(1-\alpha)} F \tag{3.6}$$

This shows that $A(1-\theta) = A^{1/1-\alpha}\big(\Omega(I_A)e\big)^{\alpha/(1-\alpha)}$. There are four decision processes that a plant goes through. First, the plant chooses how much to invest in abatement given the optimal pricing rule. Second, it sets its optimal pricing rule given abatement investments. Third, it chooses how much to abatement. Lastly, it chooses how much capital and labor to use to produce output. Thus, I solve backward to find an expression for plant's TFP, specifically $\Omega(I_A)$ and e, as a function of the carbon tax and corporate income tax (CIT).

Cost minimization

The minimum cost of producing a unit of F can be found by solving the following problem:

$$c^F(\tilde{r}, \tilde{w}) = \min_{(k,l)} \Big\{\tilde{w}l + \tilde{r}k : F(k, l) = 1\Big\} \tag{3.7}$$

[15] A concept of abatement in Copeland and Taylor (1994) is relevant here although regulation they consider is either emission tax or emission standard. Once I interpret Z as energy and θ as a fraction of inputs allocated to energy-saving activities, such as R&D expenditure allocated to energy-saving technology, the formulation of Copeland and Taylor (1994) is still valid. Tombe and Winter (2015) argue that "one might loosely interpret abatement as any costly activity that lowers the use of emissions-relevant energy, such as substitution between different fuel types." For this reason, investment in energy-saving technology, fuel switching, and factor substitution can all be interpreted as abatement in the definition of Copeland and Taylor (1994).

where $\tilde{r} \equiv (1-\lambda_k t^c)r$ and $\tilde{w} \equiv (1-t^c)w$. r and w are the prices of capital and labor, respectively. t^c is the CIT rate. Following McKenzie and Ferede (2017), I assume that labor cost is fully deductible for the tax purpose while only a portion $\lambda_k \geq 0$ of the capital cost is deductible.

λ_k is a highly stylized representation of many CIT systems, intending to reflect the distortionary features of the CIT with regard to capital. The typical case would be $\lambda_k < 1$ because the real cost of capital is not fully deductible. This is because only the nominal cost of debt finance is fully deductible. $\lambda_k > 1$ is also possible when the tax system subsidizes capital.[16] When $\lambda_k = 1$, the full opportunity of cost of capital is deducted, and the CIT is a tax on economic profit (i.e., the CIT is not distortionary).

I assume that $F(k,l) = k^\beta l^{1-\beta}$. Then the cost function can be shown as:

$$c^F(\tilde{r}, \tilde{w}) = \kappa_\beta \tilde{r}^\beta \tilde{w}^{1-\beta} \tag{3.8}$$

where $\kappa_\beta \equiv \beta^{-\beta}(1-\beta)^{\beta-1}$. Next, the plant determines how much to abate by solving the following cost minimization problem:

$$c^x(\tilde{\tau}, c^F) = \min_{(z,F)} \left\{ \tilde{\tau} z + c^F(\tilde{r}, \tilde{w})F : A\big(\Omega(I_A)z\big)^\alpha F^{1-\alpha} = 1 \right\} \tag{3.9}$$

where $\tilde{\tau} \equiv (1-t^c)\tau$. τ is the carbon tax inclusive energy price.[17] I assume that energy cost is fully deductible for the tax purpose. Solving the cost minimization problem yields the conditional input function for energy and cost function:

$$z = \frac{1}{A\Omega(I_A)^\alpha} \left(\frac{\alpha}{1-\alpha} \frac{c^F}{\tilde{\tau}} \right)^{1-\alpha} \tag{3.10}$$

$$c^x(\tilde{\tau}, c^F) = \kappa_a A^{-1} \Omega(I_A)^{-\alpha} {c^F}^{1-\alpha} \tilde{\tau}^\alpha \tag{3.11}$$

[16] $\lambda_k > 1$ is possible due to accelerated depreciation, investment allowances, investment tax credits, etc (McKenzie and Ferede, 2017).

[17] Here I am abstracting away from any changes in the tax-exclusive energy price. Thus, all the changes in the carbon tax inclusive energy price are due to the changes in the carbon tax rate. Henceforth, I call τ carbon tax.

where $\kappa_a \equiv \alpha^{-\alpha}(1-\alpha)^{\alpha-1}$. Then, using the definition of energy intensity, Eq.(3.10) can be plugged into Eq.(3.6) as $Z/x = z = e$, and I can express TFP as a function of the abatement technology, carbon tax, and CIT:

$$\text{TFP} = A \underbrace{\left(\frac{\alpha}{1-\alpha}\right)^{\alpha} \left(\Omega(I_A)\frac{c^F}{\tilde{\tau}}\right)^{\alpha}}_{(1-\theta)} \tag{3.12}$$

This shows that the abatement technology plays an important role in the productivity effect of the revenue-neutral carbon tax.

Profit maximization

Next, the plant sets the pricing rule given the abatement investment, and then chooses how much to invest in abatement given the pricing rule.

Pricing rule

Profit maximization by a monopolistic competitive manufacturing plant yields a pricing rule:

$$p = \frac{\sigma}{\sigma-1}\frac{c^x}{1-t^c} \tag{3.13}$$

Using Eq.(3.1) and Eq.(3.13), plant's profit can be expressed as:

$$\pi = B(1-\sigma)^{\sigma-1}\sigma^{-\sigma}(1-t^c)^{-\sigma}{c^x}^{1-\sigma} - (1-t^c)I_A \tag{3.14}$$

Here, similar to labor cost, I assume that the abatement investment cost is fully deductible.[18]

Optimal abatement investment

Finally, I derive an expression for I_A as a function of τ and t^c. Following Forslid, Okubo and Ulltveit-Moe (2018), I assume that $\Omega(I_A) = I_A^{\rho}$ with $\rho > 0$. Plugging Eq.(3.11) into Eq.(3.14),

[18] Alternatively, I can also allow the abatement investment cost to be not fully deductible like capital cost. See Appendix A for more.

and then maximizing plant's profit with respect to abatement investment I_A yield:

$$I_A = A^{\frac{\sigma-1}{\gamma}} \Gamma^{\frac{1}{\gamma}} \tau^{-\frac{\alpha(\sigma-1)}{\gamma}} \left(\frac{1-\lambda_k t^c}{1-t^c} \right)^{-\frac{\beta(1-\alpha)(\sigma-1)}{\gamma}} \tag{3.15}$$

where $\Gamma \equiv \alpha\rho B\sigma^{-\sigma}(\sigma-1)^{\sigma}\left(\kappa_\alpha\kappa_\beta^{1-\alpha}\right)^{1-\sigma}\left(r^{\beta}w^{1-\beta}\right)^{(1-\alpha)(1-\sigma)}$ and $\gamma \equiv 1-\alpha\rho(\sigma-1) > 0$.[19] Before plugging Eq.(3.15) back into Eq.(3.12) to discuss the productivity effect of the abatement investment, it is worth interpreting Eq.(3.15). Notice that when the costs of capital investments are fully deductible, i.e., $\lambda_k = 1$, Eq.(3.15) becomes independent of the CIT. This is simply because when the CIT is levied on the pure profit, there is no distortion in the capital investment market.

Eq. (3.15) shows that the abatement investment is a decreasing function of carbon tax. However, Forslid, Okubo and Ulltveit-Moe (2018) point out that the effect of carbon tax on the abatement investment is ambiguous because carbon tax indirectly affects the abatement investment through the market competition, i.e., through Γ. If the plant's competitors pay more carbon tax, then it provides the plant an incentive to invest more in abatement.

On the other hand, the abatement investment is a decreasing function of the CIT.[20] This implies that the reduction of the CIT rate has a positive effect on the abatement investment.[21]

Finally, plugging Eq.(3.15) into Eq.(3.12) yields:

$$\text{TFP} = A^{1/\gamma} \underbrace{\tilde{\Gamma}\, \tau^{-\frac{\alpha}{\gamma}}}_{\text{Carbon tax}} \underbrace{\left(\frac{1-\lambda_k t^c}{1-t^c} \right)^{-\frac{\mu}{\gamma}}}_{\text{Revenue-recycling}} \tag{3.16}$$

where $\tilde{\Gamma} \equiv \left(\frac{\alpha}{1-\alpha}\right)^{\alpha}\Gamma^{\frac{\alpha\rho}{\gamma}}\left(\kappa_\beta r^{\beta}w^{1-\beta}\right)^{\alpha}$ and $\mu \equiv \alpha\beta(\rho(\sigma-1)-1)$.

Besides the Hick-neutral technology parameter, A, Eq.(3.16) shows that there are two channels through which revenue-neutral carbon tax affects TFP.[22] First, paying tax on energy purchased has

[19] In order to satisfy the second order condition of the profit maximization problem, γ has to be positive. See Appendix A for the verification.

[20] See Appendix A for the verification.

[21] In addition, lowering the CIT rate increases investments in general. Lowering the user costs of capital encourages plants to invest more. This may make plants more productivity through the increase in A.

[22] In addition, one could also imagine that plants might substitute away from fuels to non-fuel inputs in response to the carbon tax. This channel could be linked to the changes in α. However, given that α is affecting Eq.(3.16) in much

a direct effect on TFP. I refer to it as the carbon tax effect. Eq.(3.16) shows that the carbon tax effect on productivity is ambiguous as carbon tax also affects abatement investment through the market competition, Γ, hence positively affecting TFP.[23] There are two opposing channels within this carbon tax effect, a positive effect from the increases in abatement investment and a negative effect from the resource diversion.

Second, a decline in the CIT rate indirectly affects TFP. I refer to it as the revenue-recycling effect. Eq.(3.16) shows that the revenue-recycling effect increases TFP when $1 \leq \rho(\sigma - 1)$. This means that the reduction of the CIT will likely to have a positive impact on TFP when the abatement technology improves faster with the abatement investment, and the goods are more substituable. The revenue-recycling effect positively affects TFP through reducing the distortion in the capital market created by the CIT. Notice again that when the costs of capital are fully deductible, Eq.(3.16) becomes independent of the CIT. This suggests that the revenue-recycling effect of carbon tax on productivity comes entirely from the distortionary nature of the CIT.

With these two effects, it is clear that the productivity effect of the revenue-neutral carbon tax could go either direction. Yet, it could positively affect plant's TFP. To summarize my model predictions, I develop an (empirically testable) hypothesis:

Hypothesis I: Recycling tax revenues by reducing corporate income tax rates increases productivity-enhancing investments.

Hypothesis II: If the revenue-recycling increases productivity more than the carbon tax lowers productivity by diverting resources away from production, the policy achieves a net productivity gain.

I name this two-part hypothesis the "Productivity Dividend Hypothesis" (PDH). The first part of

more complex fashion, I assume that α is constant in this paper. I also abstract away from the TFP effect through wage (w and rental rate (r). As the incidence of the CIT may fall onto labor in terms of wages, the reduction of the CIT rate may also positively affect plant's TFP through a higher wage. On the other hand, rental rate is unlikely to respond to the policy because it is determined at the world market (e.g., small open economy assumption).

[23] This model prediction can also be related to the Porter hypothesis, i.e., carbon tax positively affects productivity through increases in investment.

the PDH is only about the revenue-recycling effect. One may need to test whether the revenue-recycling through the CIT reduction increases investments, and thus productivity. In this paper, I test whether the revenue-recycling has a positive productivity effect. Then when the positive revenue-recycling effect exceeds or completely offsets the negative carbon tax effect, the policy supports the PDH.[24]

Furthermore, as this has an obvious connection to the double dividend hypothesis of environmental tax reforms, when a policy achieves both emission reduction and productivity enhancement, such a policy offers a double dividend. I call this the ”Productivity Double Dividend (PDD) Hypothesis.” This hypothesis is similar to the employment double dividend hypothesis when the second dividend is employment gains. Although these are defined specifically with carbon taxes, this can be applied to any environmental taxes that recycle the tax revenues via the tax substitutions as well.

In the next section, I take Eq.(3.16) to data and estimate the productivity effect of the BC carbon tax to test the PDH. A TFP equation can be approximated with a linear function as:

$$\text{TFP}_{it} = \beta_1 \tau_{it} + \beta_2 (1 - t_{it}^c) + \epsilon_{it} \tag{3.17}$$

where τ_{it} is the carbon tax rate and $(1 - t_{it}^c)$ is the net-of-the CIT rate for plant i at time t. β_1 captures the carbon tax effect and β_2 captures the revenue-recycling effect through the reduction of the CIT rate. However, I do not observe plant-level carbon tax rate or CIT rate because these taxes are only levied at provincial-level. Thus, I take advantage of rich data and interact these provincial tax rates with plant-level characteristics to approximate τ_{it} and $(1 - t_{it}^c)$. I discuss the detail in the next section.

[24]There is one another case when a policy can achieve a net productivity gain. That is when both carbon tax and revenue-recycling effects are positive. When the carbon tax effect is positive, that provides a support for the Porter hypothesis. The combination of the Porter hypothesis and the positive revenue-recycling effect can also support the PDH.

4. Research Design

I. Empirical Framework

This section discusses the econometric design to estimate the effect of the BC carbon tax on manufacturing plants' productivity. I employ a difference-in-difference (DID) estimator, i.e., comparing the plants in BC with plants in the rest of Canada (ROC). The simple model illustrated that the productivity effect depends on the carbon tax and CIT rates, affecting the decisions on resource allocations including abatement investment. With available data, I augment the DID estimation with the information from the model, using plant-level heterogeneity to proxy plant-level policy exposures.[25] I estimate the following equation:

$$\ln \text{TFP}_{ijpt} = \beta_1 \text{CTax}_{ipt} + \beta_2 \text{Recycling}_{ipt} + X_{pt} + \phi_i + \lambda_{jt} + \epsilon_{ijpt} \tag{4.1}$$

where $\ln \text{TFP}_{ijpt}$ is the log of TFP for plant i in industry j in province p at time t, which is estimated using the semiparametric estimation method proposed by Ackerberg, Caves and Frazer (2015).[26] This method addresses the problem of endogeneity in the input decisions and is argued to be the most robust among other estimation methods (Van Biesebroeck, 2007). I define $\text{CTax}_{ipt} \equiv \left(\sum_f \text{Fuel}_i^f \times \text{CTax}_{pt}^f\right)/\text{VA}_i$ and $\text{Recycling}_{ipt} \equiv \mathbb{1}(\text{TI}_i > 0) \times (1 - \text{CIT}_{pt})$. Let Fuel_i be an average consumption of fuel f for plant i from the pre-policy period (2004-2007), CTax_{pt}^f be a fuel-specific carbon tax variable (e.g., for gasoline, 0 if $t =$ pre-carbon tax period for BC plants, 2.34 cents/liter if $t = 2008$, 3.51 if $t = 2009$, 4.45 in $t = 2010$, 5.56 if $t = 2011$, and 6.67 if $t = 2012$ for BC plants. 0 for ROC plants at all t), and VA_i be a pre-policy average value-added for plant i. TI_i is a pre-policy average taxable corporate income for plant i.[27] CIT_{pt} is BC's corporate

[25] This augmentation is similar to Yamazaki (2017).

[26] See Appendix B.I for further details on the construction of TFP measure. De Loecker (2007) and Lutz (2016) further extend the OP/LP/ACF method by allowing determinants of production to enter the productivity process. Such determinants include the export status (De Loecker, 2007), R&D status (Doraszelski and Jaumandreu, 2013), and the EU-ETS (Lutz, 2016).

[27] If a plant is owned by a multi-plant firm, $\text{TI}_i \equiv s_i \times \text{TI}_e$ with $\sum_{i \in e} s_i = 1$ where s_i is the output share of plant i within firm e and TI_e is the taxable income for firm e.

income tax rate. $\mathbb{1}(\text{TI}_i > 0)$ is an indicator function that takes one when average taxable income during the pre-policy period is strictly positive.[28] X_{pt} is a control variable at province-level, such as provincial GDP. ϕ_i are plant fixed effects that capture time-invariant plant heterogeneity while λ_{jt} are industry-specific time fixed effects that controls for industry specific shocks at given year. Finally, ϵ_{ijpt} is an error term that captures idiosyncratic changes in productivity.

The Recycling_{ipt} term allows me to test the first part of the PDH while the first two terms together test the second part of the PDH of the BC carbon tax. The first term measures the carbon tax effect (β_1) while the second term measures the revenue-recycling effect (β_2). The carbon tax effect is the productivity effect coming directly from taxing the energy purchased. Calculating the fuel-specific carbon tax expenditure allows me to exploit the plant-level variation in the financial tax burden. I hypothesize that the higher CTax_{ipt} is, the larger the tax burden is for this plant. β_1 can also measure the productivity effect of the carbon tax without the reduction of the corporate income tax. The revenue-recycling effect is the productivity effect coming from the reduction of the CIT rate. Interacting the positive taxable corporate income indicator with the net-of-the CIT rate allows me to observe how much of the financial benefits a plant receives from the revenue-recycling of this carbon tax. This is based on a logic that plants with non-positive taxable income would not receive any benefits from the revenue-recycling. This allows me to exploit the plant-level variation in the financial benefit of the policy.

The coefficients of interest are β_1 and β_2. In particular, the approximate percentage change in productivity for plant i at time t in response to the carbon tax is calculated by $\alpha_{it} \equiv 100 \times (\hat{\beta}_1 \Delta\text{CTax}_{ipt} + \hat{\beta}_2 \Delta\text{Recycling}_{ipt})$.[29] The estimated coefficient $\hat{\beta}_1$ and $\hat{\beta}_2$ are estimated from across plant × province comparisons over time.

To properly estimate the productivity effect, the underlying identification assumption requires that there be no factors other than the carbon tax creating differences in changes in productivity

[28] I also test the robustness of the estimates using different thresholds and find similar results, presented in Table C.2 in Appendix C.

[29] As the estimation equation is in the semi-elasticity (log-linear) form, the exact percentage change in productivity is calculated by $100 \times \left(e^{\hat{\beta}_1 \Delta\text{CTax}_{ipt} + \hat{\beta}_2 \Delta\text{Recycling}_{ipt}} - 1\right)$.

between plants in BC and plants in other provinces. This assumption will be violated if the government of BC concurrently implements other policy induced by the carbon tax that affects all plants in BC differently while no other provinces implement a similar policy. Another important identification assumption is the common trends. This assumption requires that the changes in productivity for plants in BC (treatment group) and other provinces (control group) would follow the same time trend in the absence of the carbon tax. This implies that the plants in BC and ROC are similar and thus would experience the same level of productivity effect if they are all subject to the carbon tax. Although including the fixed effects and time-varying control variables can control for various confounding factors, the estimates will be biased if treated and control plants are inherently different, especially in the pre-treatment period.

To ensure the similarity between treated plants (BC) and control plants (ROC), I take advantage of the rich data and estimate Eq.(4.1) with weights based on propensity scores – PSW-DID estimator. More weights are given to control plants that resemble treated plants. The weight of one is given to the treated plans while the weights, $\frac{p_i(X)}{1-p_i(X)}$, are given to the control plants.[30] The propensity scores are estimated using a probit model. The observable pre-treatment plant characteristics that are related to the carbon tax are used as predictors of the treatment assignment.[31] A full list of covariates used for estimating the propensity scores is presented in Table C.1 in Appendix C.[32] Re-weighting plants based on this rich set of observable pre-treatment characteristics allows me to compare similar treated and control plants in many dimensions and credibly isolate the effect of the policy on manufacturing productivity.

[30] $p_i(X)$ is the estimated probability for plant i being treated conditioning on the covariates, X. The weights are normalized such that their average is equal to one among control plants.

[31] Only the period of 2004-2006 is used to estimate the propensity score. This is because by using all pre-treatment years, the common trend assumption will hold by construction, which is not meaningful. I leave out 2007 to see if the common trend assumption will still hold despite matching only on the 2004-2006 period.

[32] I also included a square term of the covariates to improve the balancing (Caliendo and Kopeinig, 2008; Dehejia and Wahba, 2002).

5. Data Sources

To test the productivity dividend hypothesis, two of Statistics Canada's confidential dataset are linked, the Annual Survey of Manufactures (ASM) and General Index of Financial Information (GIFI). The ASM is an annual survey that contains information on manufacturing activities for all manufacturing locations in Canada.[33] I obtain information on output, employment, and intermediates (raw materials and energy consumptions) from the ASM. What is missing from the ASM is information on capital, which I obtain from the GIFI.[34] The GIFI is an extensive list of financial statement items, which businesses use to file their T2 corporate income tax return. One advantage of the GIFI is that unlike other studies that must rely on the perpetual inventory method or a proxy to construct a capital stock variable, it provides a direct measure of capital input. This helps to address an issue in estimating the production function when there is a measurement error in input variables.

From the ASM-GIFI linked data, I take advantage of the rich data and obtain necessary variables to employ the PSW-DID method in estimating Eq.(4.1), such as energy expenditure by fuel types (e.g., electricity, gasoline, natural gas, etc), taxable corporate income, plant age, export, and etc.

There are about 77,000 plants (10,000 plants in BC and 65,000 plants in ROC), 86 sub-industries (4 digit NAICS level), 13 regions (10 provinces and 3 territories), and 9 years (2004-2012) in the data.[35]

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[33] Although the ASM is a survey data, over the sample period it is essentially a census with data on smaller firms being filled with administrative records. The further details of the ASM are provided in http://www23.statcan.gc.ca/imdb/p2SV.pl?Function=getSurvey&Id=504733.

[34] The further details of the GIFI are provided in https://www.canada.ca/en/revenue-agency/services/forms-publications/publications/rc4088/general-index-financial-information-gifi.html.

[35] Although the survey has been conducted annually since 1917, there was a major change to its survey design in 2004. To preserve the consistency in the data, I decided to only use the 2004-2012 period. For further information about the changes in the survey, see http://www23.statcan.gc.ca/imdb/p2SV.pl?Function=getMainChange&Id=3060.

Estimated TFP

Before I present the main results, I provide summary statistics of the estimated TFP. Figure 1 plots the trend of TFP for BC and ROC. Overall trends are increasing for both BC and ROC over the sample period, except there is a noticeable decline for BC in 2008. Many might argue that this could be due to the global financial crisis that took place at the same time as the implementation of the BC carbon tax. If so, we should expect to see a similar decline for ROC as well. However, we actually observe the opposite, i.e., TFP increased at 2008 for ROC. This is one suggestive evidence that the BC carbon tax might have contributed to this difference in TFP between BC and ROC.

In addition, to credibly identify the productivity effect of the policy, the pre-policy TFP trend between plants in BC and plants in ROC must be parallel. It is clear from Figure 1 that they are. After normalizing the trends, the trends start to deviate from each other at the same year as the implementation of the policy. I calculated differences in TFP between BC and ROC before and after the policy, presented in Table 1. This simple calculation shows that manufacturing productivity declined by 8% in response to the carbon tax in BC. Now with this suggestive finding, I present the main results using the more rigorous econometric technique to identify the productivity effect of this policy.

6. Results

The results are presented in the following subsections. Section 6.I presents estimates of Eq.(4.1) to test the PDH while the rest of the subsections presents the results from robustness checks, heterogeneous effects, and dynamic effects. All analyses employ the propensity-score-weighted DID estimator.

I. Carbon Tax and Revenue-recycling Effects

The results of three specifications based on Eq.(4.1) are reported in column 4 through 6 of Table 2. Each column reports coefficients estimated using a different level of the industry by year fixed effects, 2-digit NAICS by year, 3-digit NAICS by year, and 4-digit NAICS by year, respectively. These estimates are identified with clustered standard errors (clustered on provinces × industries). In the last row, I present the F statistics from the joint test for the significance of β_1 and β_2 together, i.e., H_0: $\beta_1 = \beta_2 = 0$.

Before I discuss the results from estimating Eq.(4.1), I briefly explain the importance of Eq.(4.1). An alternative to Eq.(4.1), one can employ a simpler version of Eq.(4.1), which has a similar taste to a conventional DID estimator:

$$\ln \text{TFP}_{ijpt} = \beta \text{CTax}_{pt} + X_{pt} + \phi_i + \lambda_{jt} + \epsilon_{ijpt} \tag{6.1}$$

where CTax_{pt} be a carbon tax variable (i.e., for BC plants 0 if $t =$ pre-carbon tax period, 10 if $t =$ 2008, 15 if $t =$ 2009, ..., 30 if $t =$ 2012 and 0 for ROC plants) and the rest is defined as in Eq.(4.1). While this approach is intuitive and straightforward, it is difficult to isolate the productivity effect for a casual interpretation, especially when many other macroeconomic events happened around the same time as the implementation of the BC carbon tax. Although some confounding factors can be captured by the fixed effects, any factors that are different across provinces and over time would bias the estimation. To mitigate this issue, I directly exploit plant-level variations in the policy exposures in Eq.(4.1). This also provides me more variations to clearly identify the effects.

The results based on Eq.(6.1) are reported in the first three columns of Table 2. These robust point estimates suggest that, on average, the carbon tax decreases productivity annually by 6% during the sample period. Although the direction of the productivity effect is consistent with the results from estimating Eq.(4.1), the magnitude is much larger when plant heterogeneity in policy exposures is ignored. This illustrates the importance of plant heterogeneity in estimating the productivity effect using Eq.(4.1).

Now I discuss the main results. A clear pattern emerged from these results, presented in the last three columns of Table 2. The results provide a support for the first part of the PDH – the revenue-recycling effect positively affects productivity. Based on the coefficients from column 6 of Table 2, on average, the carbon tax effect reduced productivity annually by 1.2% while the revenue-recycling effect increased productivity by 0.2%, leading to a net loss in productivity by 1%.[36] This finding suggests that, on average, the revenue-recycling effect alleviated the negative effect from the carbon tax by approximately 20%. For some plants the policy generated a net gain in their productivity (Figure 2), supporting the PDH. To sum, recycling the tax revenues can alleviate some of the adverse effect of this policy on plants' productivity, and may even lead to a net productivity gain.

Another way to interpret the results is to translate these percentage changes in productivity to the changes in output (value-added). With the plant-level estimated productivity effect, on average, the output is reduced annually by $150,000 in response to the policy.[37] Although the reduction of the CIT rates helped plants save the output, on average, by $10,000, the carbon tax reduced output by $160,000.[38]

To discuss the aggregate effect, I aggregated the plant-specific output effects. The finding suggests that BC's manufacturing output declined by $440 million while it would have declined by $465 million without the CIT reduction. Thus, the CIT reduction has saved output by $25 million.

[36]As the distribution of the estimated productivity effect is left-skewed, the mean and median productivity effects differ. In terms of median, the carbon tax effect reduced productivity by 0.6% while the revenue-recycling effect increased productivity by 0.2%, leading to a net loss in productivity by 0.4%. To maintain the confidentiality in conformity with Statistics Canada's Statistics Acts, I define median as a range between the 49th and 51st percentile.

[37]This is calculated as taking the average of plant-level output effects. The plant-level output effect is calculated as the difference between the counterfactual output ($= Y_i/(1-(\alpha_i/100))$, e.g., if the productivity effect is -0.2% with $1 million observed output, the counterfactual output is $1.002 million.) and the observed output. As the distribution of plant-level output is heavily right-skewed, the median might be more informative. In terms of median, the output is reduced by $4,300.

[38]In terms of median, the carbon tax effect reduced output by $5,800 while the revenue-recycling effect increased output by $1,500. In the net, output declined by $4,300.

II. Robustness Checks

In this subsection, I probe the robustness of the estimates. Overall, I found little evidence that undermines the results reported in Section 6.I.[39]

Excluding Contaminated Control Plants

Identifying the productivity effects relies heavily on an assumption that the control plants are not affected by the treatment. Violating such an assumption would bias my estimates. There are several ways that the treatment impacts could spill over to the control plants. I attempt to rule out these possibilities in the estimation by restricting the sample. All the results for the robustness check below should be compared to the results of base specifications (column 6 of Table 2), presented in column 1 of Table 3.

First, if a firm owns multiple plants across provinces, the firm can minimize the tax burden by shifting production away from plants located in BC to plants located in the rest of Canada. Operational adjustments within a firm with plants across BC and ROC are easier and would be more likely to occur than across plants that do not share a common owner. To eliminate such adjustments in the estimation, I restricted the sample only to single-plant firms. The estimation result is reported in column 2 of Table 3. Although the coefficient on the revenue-recycling effect is no longer statistically significant, the signs of the coefficient on both carbon tax and revenue-recycling effects are preserved. F-statistics from the joint test suggests that the carbon tax and revenue-recycling effects are statistically important together. These results imply that the possibility of the PDH still exists due to the positive revenue-recycling effect. However, the PDH might be unlikely for this particular group as the negative carbon tax effect is much larger than the base case. I further examine this in Section 6.III to see whether there is a heterogeneous effect between single-plant firms (plants) and multi-plant firms.

[39]In Appendix C, I also performed a placebo test, treating one of non-BC provinces as a pseudo treatment group. Of fourteen coefficients (two coefficients for seven provinces), the carbon tax effect for AB was statistically significant at 1 percent and negative while the carbon tax effect for ON and NS were significant at 5 percent and 10 percent, respectively, but positive. None of the coefficients for the revenue-recycling effect were statistically significant. However, in contrast to BC, no province had a pattern of sign and significance in line with the model.

Second, a plant could move production entirely away from BC to ROC to avoid the tax burden. If such adjustments were to occur, I suspect that the plant would relocate to a neighboring province, such as Alberta, to minimize the costs. To examine how this might affect the estimation, I dropped plants in Alberta from the sample. The result is reported in column 3 of Table 3. Similar to the single-plant only case, the signs of both carbon tax and revenue-recycling effects are preserved, and the coefficients are statistically significant together. The coefficient on the carbon tax effect is much closer to the base case than the single-plant only case.

In constructing the control group, plants from Québec (QC) are included in the sample. As QC has implemented its own carbon tax, the estimates might be underestimated or overestimated when control plants from QC are compared with the BC plants.[40] I dropped plants in QC to eliminate a potential effect of the QC carbon tax that might bias the estimated effects of the BC carbon tax. The result is reported in column 3 of Table 3 and look similar to no AB-plants case.

Price Effects

One of the difficulties in conducting a productivity analysis is that output is measured in revenue, not quantity. The exact problem with this is that plants may increase their price in response to the policy. I argue that this price effect may not be a major issue in this paper 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. Nonetheless, I test this price effect by constructing the quantity-based TFP (TFPQ) and compare that with my revenue-based TFP (TFPR). I explain in detail how I construct TFPQ in Appendix B.II.

The results, presented in Table 4, suggest that the productivity effect of this policy is reasonably similar regardless of the choice of TFP measures. The signs and sizes of both carbon tax and revenue-recycling effects using TFPQ are similar to those of my base estimation with TFPR.

[40] Québec introduced a carbon tax in 2007 at the rate of \$3.5/t CO_2e. Alberta also implemented a carbon levy in 2007. But only facilities that emit more than 100,000 tonnes of greenhouse gas emission a year are subject to pay \$15 a tonne. As the levy is only targeted to the small fraction of industries, I do not expect to see productivity adjustments that are identifiable from this policy.

Unlike other studies that also compared the productivity effects between TFPR and TFPQ (e.g., Greenstone, List and Syverson (2012); Tanaka, Yin and Jefferson (2014)), the difference in the productivity effect between TFPR and TFPQ identified in this paper is substantially small. This confirms my prior expectation that the price effect is not a major concern in this context.

III. Heterogeneous Effects

The analyses to this point have focused on the average effects of the revenue-neutral carbon tax on plant productivity. It is more realistic that the size of the productivity effects varies across different plants. Some plants are likely to be more affected by this policy than others. These differences might be attributed to the differences in plants' characteristics. To investigate such heterogeneous responses, I group plants in three dimensions. First, I allow the productivity effect to differ across large, medium, and small plants based on the size of their output. This is particularly important as the public worries that small plants might be disproportionately affected by the policy due to their inability to adjust. Second, following up on the robustness check section, I test whether the productivity effect differs between the single-plant firms and multi-plant firms. Third, I separately estimate the productivity effect for young and old plants. This is based on a hypothesis that young plants are relatively more efficient and productive than old plants, allowing them to adjust to the policy more efficiently. The results from these heterogeneous effect analyses are reported in Table 5.

There are several interesting results worth discussing. First, the coefficient on the carbon tax effect for small plants is statistically insignificant while that on the revenue-recycling effect is statistically significant and positive. This suggests that small plants may be benefiting from the revenue-recycling of this policy without incurring the substantial costs from the policy. This may increase the chance to support the PDH for these small plants. This finding could also imply that the public concern about these small businesses may be unwarranted. On the other hand, large plants are experiencing the statistically significant negative impact from the carbon tax effect and positive impact from the revenue-recycling effect, resulting in the net decline in their TFP.

The remaining results are consistent with my prior expectations. As shown in the robustness checks, single-plant firms are more negatively affected by the carbon tax effect than multi-plant firms. What is interesting here is that the revenue-recycling effect is statistically significant only for the multi-plant firms although the signs of the point estimates are the same between these firms. These findings suggest that it is not the small plants that are affected more negatively, but rather single-plant firms. It also suggests that the the negative carbon tax effect identified in the baseline case is mainly coming from the single-plant firms while the positive revenue-recycling effect from the baseline case is mainly coming from the multi-plant firms.

Similarly as expected, old-plants are more (negatively) affected by the policy than young plants. This finding may imply that there are rooms for productivity improvements of old plants if the policy is designed to encourage them to invest and modernize their production technology. A surprising finding here is that young plants are not affected by the policy at all. At least their point estimates for both carbon tax and revenue-recycling effects are statistically insignificant.

IV. Dynamic Effects

All the specifications above assume that plants respond to the policy contemporaneously. While this may be true, it is also likely that some adjustments, such as investments, may take some time and their impact on productivity may be pronounced later. This may be, especially, true for the market-based policy, such as carbon tax, because it provides incentives for plants to respond. It may take some time for plants to best respond to such incentives, hence affecting productivity with lags. I explore the possibility of such long-term responses by adding one and two years of lagged carbon tax and revenue-recycling effects in Eq.(4.1). One cautionary note here is that I would argue that what I discuss here is suggestive for the long-term responses because the time span used in this paper is too short to be considered long-run.

The results are presented in Table 6. Column 1 is taken from column 6 of Table 2, which should be used as a basis for comparison. One of the most interesting findings here is that there is a one-year lag positive carbon tax effect, shown in column 2. When the one-year lag of carbon tax and revenue-recycling effects are included, the contemporaneous carbon tax effect became more negative than the estimate without the lag. The one-year lag carbon tax effect is statistically significant and positive. The contemporaneous and one-year lag indirect revenue-recycling effects are both positive; however, they are not statistically significant. Including both one and two years of lag generates similar results as the estimates with one-year lag despite their lack of statistical significance. These findings suggest that this may be an evidence for both the PDH and Porter hypothesis in the long-run.

7. Discussion

All the analyses above has shown that recycling the carbon tax revenue via reducing the rates of corporate income tax positively affects productivity. However, at the current rates, the net productivity effect was negative. During the 2008-2012 period, on average 50% of the tax revenue was recycled back to the economy by the reduction of the CIT. The other half was recycled by the reduction of the personal income tax and the lump-sum transfer to low-income households. Instead of recycling the tax revenues this way, one can recycle the revenues entirely through the reduction of the CIT. This may increase the size of the positive revenue-recycling effect, increasing the chance of supporting the PDH. To explore this possibility, I take the estimates from column 6 of Table 2 and then increase the reduction rates of the CIT.[41] The results are presented in Figure 3.

As expected, the distribution of productivity effects slightly shifts to the right, increasing the positive region. The number of plants who experienced the net gain in their productivity is approximately tripled from the baseline. Yet, the average net productivity effect is negative (-0.8%). One interesting finding from this counterfactual experiment is that when the carbon tax rate is at $10/t

[41] To do this, I made a few assumptions. First, I assume that the total carbon tax revenue raised does not change between the actual reduction rates and the counterfactual reduction rates of the CIT. Second, the amount of corporate taxable income does not change between the actual and counterfactual. With these two assumptions, I calculated the counterfactual reduction rates of the CIT. I do this by taking the ratio between the level of the total carbon tax revenue recycled and the level of the revenue recycled via the reduction of the CIT rates. Then I multiply the ratio to the actual reduction rates of the CIT to obtain the counterfactual reduction rates. I set the counterfactual reduction rates to be as follows: 3.3 percentage point reduction in 2008, 3.5 percentage point reduction in 2010, and 4.4 percentage point reduction in 2011.

CO_2e, the median net productivity effect is positive (on the order of 0.06%). These findings emphasize that the economic impacts of a policy depends heavily on how the revenues are returned to the economy because it is possible to design a policy that support the productivity dividend hypothesis.

8. Conclusion

Theoretical research hypothesizes that environmental taxes can achieve both emission reductions and welfare (employment) gains. The non-environmental benefits of such policies come from recycling tax revenues to reduce rates of distortionary taxes. This paper developed a new hypothesis – the "Productivity Dividend Hypothesis" – and empirically showed that recycling revenues has a potential to improve productivity.

The model I present in this paper suggests that taxing energy purchases diverts productive resources away from production, reducing productivity. On the other hand, reducing corporate income tax rates encourages productivity-enhancing investments. If the latter is larger than the former, the carbon tax can generate a net gain in productivity.

Using a unique micro-level data on manufacturing activities and corporate income tax, I find that the BC carbon tax had the negative carbon tax effect and positive revenue-recycling effect on plants' productivity. However, the net effect of this policy was negative. On average, the carbon tax effect reduced productivity annually by 1.2% while the revenue-recycling effect increased productivity by 0.2%, leading to a net loss in productivity by 1%. In the aggregate, the declines in productivity by the carbon tax correspond to output reductions by $465 million while the CIT reduction saves output by $25 million, resulting in a net loss by $440 million. These findings suggest that recycling tax revenues alleviates some of the adverse effects of the policy on plants' productivity, but not all. Given that the complete offset is not the exact intention of the revenue-recycling, it is expected to see some plants' productivity falling while others experience productivity enhancement.

How are these negative productivity effects compared to the benefits of the policy? Aggregate emission from the manufacturing sector in BC has declined by 4% relative to the manufacturing sector in the rest of Canada after the implementation of the policy.[42] The reduction of productivity by 1% seems reasonably small.[43] Thus, the public concern regarding emission reductions being achieved at the cost of economic growth may be unwarranted.

One caveat of this paper is that the negative productivity effect I identified in this paper is mainly a short-term response. As I pointed out in my simple model, investing in abatement (energy-saving activities) plays an important role in generating a positive effect on productivity. However, the potential efficiency improvements from this investment may not be immediately reflected in one's productivity. It is possible that plants suffer from carbon tax in the short-run while managing to become more efficient and productive than before the implementation of the policy in the long-run. The results presented in Section 6.IV supports this claim although more data is required to fully analyze the long-term effect.

Finally, I conclude this paper by emphasizing the importance of the revenue-neutrality of carbon tax policy. This paper, for the first time, provided evidence that recycling revenues through the reduction of corporate income taxes can alleviate the adverse effects of the policy, possibly leading to productivity enhancement. The empirical exercise conducted in this paper to test the "Productivity Dividend Hypothesis" can be tested more broadly for any environmental taxes that attempt to keep the policy revenue-neutral by the tax substitutions. Furthermore, an empirical investigation of the "Productivity Double Dividend Hypothesis" of environmental taxes would also bring fruitful contributions to both the literature and public policy.

[42] This is calculated by using the facility-level emission data from Environment and Climate Change Canada. https://www.canada.ca/en/environment-climate-change/services/climate-change/greenhouse-gas-emissions/facility-reporting/data.html

[43] This is not to say that this reduction of emission is solely due to the policy.

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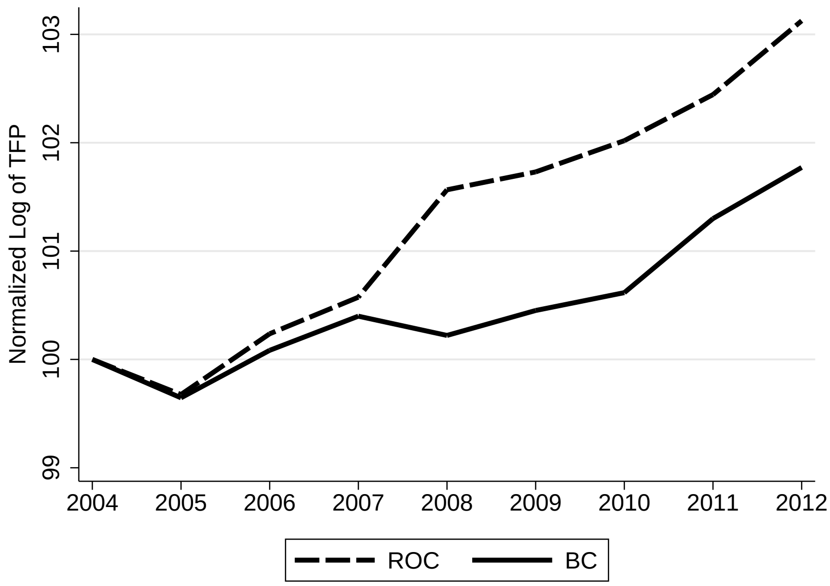

Figure 1: Trends of TFP

Note: This figure plots the trends of TFP for BC and ROC. ROC (Adjusted) is the same as ROC, but added the pre-policy average gap of TFP between BC and ROC.
Source: Author's calculation.

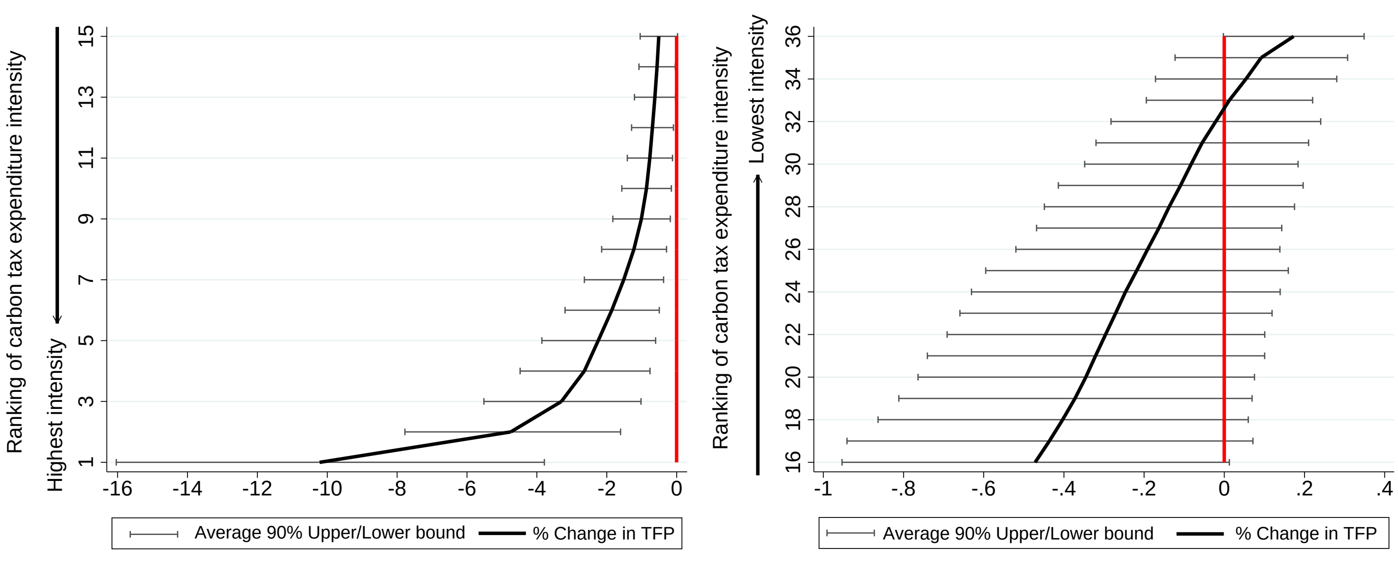

Figure 2: Distribution of Estimated Productivity Effects

Note: This figure plots the plant-level estimated TFP effects. To hide the maximum and minimum, the plant-level TFP effects and its corresponding upper and lower bounds are ranked and then averaged over 100 plants in the order.
Source: Author's calculation.

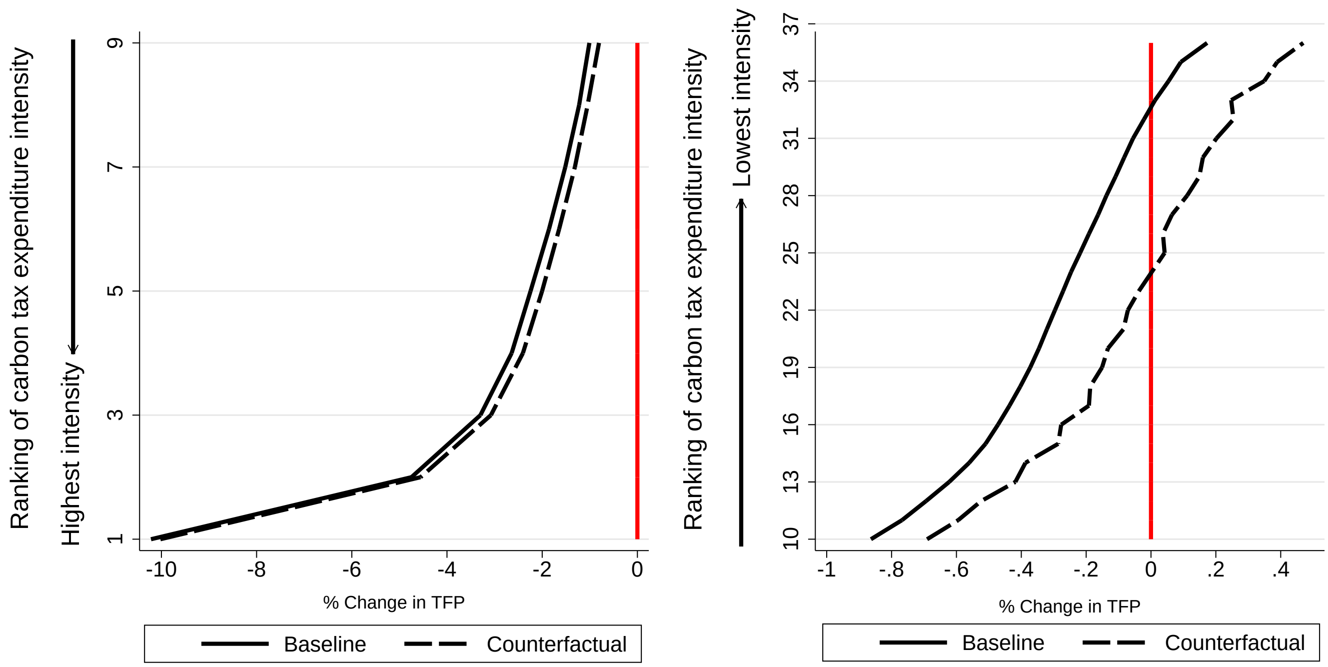

Figure 3: Comparison of the Distributions of Productivity Effects

Note: This figure plots the plant-level estimated TFP effects (baseline) and counterfactual TFP effects.
Source: Author's calculation.

Table 1: Manual Difference-in-difference (DID)

	Pre	Post	Difference
BC	9.86	9.94	0.08
	(0.79)	(0.84)	
ROC	9.85	10.01	0.16
	(1.45)	(0.83)	
DID			-0.08

Note: Standard deviations are in the parenthesis. The value for DID is calculated by taking the difference of time-differences for BC and ROC.

Table 2: Impact of the Carbon Tax on Plant Productivity

	(1)	(2)	(3)	(4)	(5)	(6)
CTax_{pt}	-0.0038**	-0.0034***	-0.0031***			
	(0.002)	(0.001)	(0.001)			
CTax_{ipt} (β_1)				-5.13	-8.21***	-7.35***
				(4.47)	(2.22)	(2.8)
Recycling_{ipt} (β_2)				0.155*	0.135*	0.13*
				(0.08)	(0.07)	(0.07)
Industry × time						
2-digit	Y			Y		
3-digit		Y			Y	
4-digit			Y			Y
N	237476	237476	237476	237331	237331	237331
R^2	0.65	0.67	0.67	0.65	0.67	0.67
F-statistics				3.1	9.7	6.5

Notes: Dependent variable is log of TFP. CTax_{pt} is a carbon tax variable (i.e., for BC plants 0 if t = pre-carbon tax period, 10 if $t = 2008$, 15 if $t = 2009$, ..., 30 if $t = 2012$ and 0 for ROC plants.); $\text{CTax}_{ipt} \equiv \left(\sum_f \text{Fuel}_i^f \times \text{CTax}_{pt}^f\right)/\text{VA}_i$; Fuel_i is an average consumption of fuel f for plant i from the pre-policy period (2004-2007); CTax_{pt}^f is a fuel-specific carbon tax variable (e.g., for gasoline, 0 if t = pre-carbon tax period for BC plants, 2.34 cents/liter if $t = 2008$, 3.51 if $t = 2009$, 4.45 in $t = 2010$, 5.56 if $t = 2011$, and 6.67 if $t = 2012$ for BC plants. 0 for ROC plants at all t);VA_{ip} is a pre-policy average value-added for plant i; $\text{Recycling}_{ipt} \equiv \mathbb{1}(\text{TI}_i > 0) \times (1 - \text{CIT}_{pt})$; TI_i is a pre-policy average taxable corporate income for plant i; CIT_{pt} be BC's corporate income tax rate; $\mathbb{1}(\text{TI}_i > 0)$ is an indicator function that takes one when average taxable income during the pre-policy period is strictly positive. All specifications includes plant FE and provincial GDP as a control. Industry by time fixed effects is included in each specification at the different aggregation-level, 2-digit NAICS by time, 3-digit NAICS by time, and 4-digit NAICS by time, respectively. To account for serial correlations and within sub-industry correlations, standard errors are clustered by 3-digit NAICS industry × province, reported in parentheses. The last row presents the F-statistics from the joint test for the significance of β_1 and β_2 together, i.e., H_0: $\beta_1 = \beta_2 = 0$.
*** Significant at the 1 percent level, ** Significant at the 5 percent level, * Significant at the 10 percent level.

Table 3: Testing the Robustness of the Estimates

	(1) Base	(2) Single	(3) No AB	(4) No QC
CTax_{ipt} (β_1)	-7.35***	-17.31***	-6.93**	-6.85**
	(2.8)	(5.5)	(2.8)	(2.9)
Recycling_{ipt} (β_2)	0.13*	0.06	0.04	0.06
	(0.07)	(0.18)	(0.07)	(0.060)
N	237331	183463	214020	177893
R^2	0.67	0.69	0.68	0.68
F-statistics	6.5	5.6	4.4	3

Notes: Dependent variable, CTax_{ipt} and Recycling_{ipt} are all defined as in Eq.(4.1). All specifications includes plant FE, industry (4-digit NAICS) by time FE, and provincial GDP as a control. To account for serial correlations and within sub-industry correlations, standard errors are clustered by 3-digit NAICS industry × province, reported in parentheses. Single means plants that are singly owned while AB and QC stand for Alberta and Québec, respectively. The last row presents the F-statistics from the joint test for the significance of β_1 and β_2 together, i.e., H_0: $\beta_1 = \beta_2 = 0$.
*** Significant at the 1 percent level, ** Significant at the 5 percent level, * Significant at the 10 percent level.

Table 4: Productivity Effects using TFPQ

	(1) TFPR	(2) TFPQ	(3) TFPQ	(4) TFPQ
CTax_{ipt}	-7.35***	-7.2	-11.8***	-10.5**
	(2.8)	(6.7)	(3.4)	(4.3)
Recycling_{ipt}	0.13*	0.24*	0.21**	0.2*
	(0.07)	(0.12)	(0.1)	(0.1)
Industry × time				
2-digit		Y		
3-digit			Y	
4-digit	Y			Y
N	237331	237331	237331	237331
R^2	0.67	0.66	0.67	0.68
F-statistics	6.5	3.07	8.8	6.02

Notes: Dependent variable is log of quantity-based TFP (TFPQ). CTax_{ipt} and Recycling_{ipt} are defined as Eq.(4.1). The result from the main estimation reported in column 6 of Table 2 is reported in column 1 as TFPR. All specifications includes plant FE and provincial GDP as a control. Industry by time fixed effects is included in each specification at the different aggregation-level, 2-digit NAICS by time, 3-digit NAICS by time, and 4-digit NAICS by time, respectively. To account for serial correlations and within sub-industry correlations, standard errors are clustered by 3-digit NAICS industry × province, reported in parentheses. The last row presents the F-statistics from the joint test for the significance of β_1 and β_2 together, i.e., H_0: $\beta_1 = \beta_2 = 0$.
*** Significant at the 1 percent level, ** Significant at the 5 percent level, * Significant at the 10 percent level.

Table 5: Effects of the BC Carbon Tax by Different Plant Characteristics

	Plant size			Firm structure		Plant age	
	Large	Medium	Small	Single-plant	Multi-plant	Old	Young
CTax_{ipt}	-7.23**	-8.75	4.16	-17.42***	-1.57	-8.18***	-8.58
	(2.28)	(6.40)	(21.85)	(4.11)	(2.40)	(2.17)	(16.58)
Recycling_{ipt}	0.18**	-0.35**	0.48**	0.13	0.15*	0.14*	0.13
	(0.09)	(0.16)	(0.06)	(0.08)	(0.05)	(0.07)	(0.19)
N	200677			237331		237331	
R^2	0.65			0.67		0.67	
F-statistics (CTax)	8.6			11		7.34	
F-statistics (Recycling)	6.2			2.04		1.86	
F-statistics (All)	7.6			7.29		5.69	

Notes: Plant size is determined by output. A plant is large if its output is above the 70th percentile, medium if its output is between the 35th and 65th percentiles, and small if its output is below the 25th percentile. Under Firm structure, I compare plants that are singly owned with plants whose parental firm owns multiple-plants. For Plant age, I compare plants that are less than 5 year old at 2007 with plants that are older than 5 year old. The former plants are defined as young plants while the latter plants are defined as old plants. All specifications includes plant FE, industry (3-digit NAICS) by time FE, and provincial GDP as a control. To account for serial correlations and within sub-industry correlations, standard errors are clustered by 3-digit NAICS industry × province, reported in parentheses. The last three rows present the F-statistics from the joint test for the significance of βs together, e.g., H_0: $\beta_1^{\text{Large}} = \beta_1^{\text{Medium}} = \beta_1^{\text{Smal}} = 0$.
*** Significant at the 1 percent level, ** Significant at the 5 percent level, * Significant at the 10 percent level.

Table 6: Dynamic Effects – Allowing for Lags

	(1)	(2)	(3)
CTax_{ipt}	-7.4***	-12.9***	-7.2**
	(2.8)	(5.5)	(2.8)
CTax_{ipt-1}		9.1**	2.4
		(4.0)	(7.1)
CTax_{ipt-2}			3.13
			(8.01)
$\mathrm{Recycling}_{ipt}$	0.13*	0.12	0.14
	(0.07)	(0.09)	(0.12)
$\mathrm{Recycling}_{ipt-1}$		0.02	0.06
		(0.08)	(0.14)
$\mathrm{Recycling}_{ipt-2}$			-0.12
			(0.13)
N	237331	197751	163658
R^2	0.67	0.7	0.73
F-statistics (All)	6.5	3.26	0.89

Notes: Dependent variable, CTax_{ipt}, and $\mathrm{Recycling}_{ipt}$ are defined as Eq.(4.1). All specifications includes plant FE, industry (4-digit NAICS) by time FE, and provincial GDP as a control. To account for serial correlations and within sub-industry correlations, standard errors are clustered by 3-digit NAICS industry × province, reported in parentheses. The last row presents the F-statistics from the joint test for the significance of β_1 and β_2 together, i.e., H_0: $\beta_1 = \beta_2 = 0$. *** Significant at the 1 percent level, ** Significant at the 5 percent level, * Significant at the 10 percent level.

Appendices

Appendix A Model

Here I present a more general treatment of the model shown in the text by assuming that only a portion$\lambda_A > 0$ of the abatement investment cost is deductible. In the text, I assume that $\lambda_A = 1$.

With λ_A, the profit function is expressed as follows:

$$\pi = B(1-\sigma)^{\sigma-1}\sigma^{-\sigma}(1-t^c)^{-\sigma}c^{x^{1-\sigma}} - (1-\lambda_A t^c)I_A \tag{A.1}$$

Solving the profit maximization problem yields:

$$I_A = \Gamma^{\frac{1}{\gamma}} A^{\frac{\sigma-1}{\gamma}} \tau^{-\frac{\alpha(\sigma-1)}{\gamma}} (1-\lambda_k t^c)^{-\frac{\beta(1-\alpha)(\sigma-1)}{\gamma}} (1-t^c)^{\frac{1+\beta(1-\alpha)(\sigma-1)}{\gamma}} (1-\lambda_A t^c)^{\frac{-1}{\gamma}} \tag{A.2}$$

Abatement investment function

Here I show that Eq.(A.2) is a decreasing function of carbon tax and a decreasing function of corporate income tax in more detail.

To show that Eq.(A.2) is an increasing function of carbon tax, I take the second derivative of the profit function (Eq.(A.1)):

$$\pi'' = B(1-\sigma)^{\sigma-1}\sigma^{-\sigma}(1-t^c)\big(\kappa_\alpha A^{-1} c^{F^{1-\alpha}} \tilde{\tau}^{\alpha}\big)^{\sigma-1}\big(\alpha\rho(\sigma-1)\big)(-\gamma)I_A^{-(\gamma+1)} \tag{A.3}$$

In order for the second order condition of the profit maximization to be satisfied, $\pi'' < 0$, which implies that $\gamma > 0$.

Then, Eq.(A.2) is an increasing function of carbon tax as:

$$I_A = \Phi\, \tau^{-\frac{\alpha(\sigma-1)}{\gamma}} \tag{A.4}$$

where Φ is the rest of non-carbon tax variables and parameters in Eq.(A.2).

Next, showing that Eq.(A.2) is a decreasing function of the CIT rate is a bit more involved as t^c shows up in multiple places. Given that $\lambda_A \in [0, 1]$, I consider the two extreme cases, 1) $\lambda_A = 0$, and 2) $\lambda_A = 1$.

When $\lambda_A = 0$,

$$I_A = \Gamma^{\frac{1}{\gamma}} A^{\frac{\sigma-1}{\gamma}} \tau^{-\frac{\alpha(\sigma-1)}{\gamma}} (1 + \text{METR})^{-\frac{\beta(1-\alpha)(\sigma-1)}{\gamma}} (1 - t^c) \tag{A.5}$$

where $1 + \text{METR} = \frac{1-\lambda_k t^c}{1-t^c}$, and METR is the marginal effective tax rate.[1] Eq.(A.5) is a decreasing function of the CIT as long as the METR is an increasing function of the CIT, which is true when $\lambda_k < 1$.[2]

When $\lambda_A = 1$,

$$I_A = \Gamma^{\frac{1}{\gamma}} A^{\frac{\sigma-1}{\gamma}} \tau^{-\frac{\alpha(\sigma-1)}{\gamma}} (1 + \text{METR})^{-\frac{\beta(1-\alpha)(\sigma-1)}{\gamma}} \tag{A.6}$$

Similarly, Eq.(A.6) is a decreasing function of the CIT as long as the METR is an increasing function of the CIT.

As I show that the abatement investment is a decreasing function of the CIT in both cases, the abatement investment is a decreasing function of the CIT regardless of the value of λ_A as long as $\lambda_k < 1$.

TFP function

Plugging Eq.(A.2) into Eq.(3.12) yields:

$$\text{TFP} = A^{1/\gamma} \underbrace{\tilde{\Gamma} \tau^{\frac{-\alpha}{\gamma}}}_{\text{Carbon tax}} \underbrace{\left(\frac{1 - t^c}{1 - \lambda_A t^c}\right)^{\frac{\alpha\rho}{\gamma}} \left(\frac{1 - \lambda_k t^c}{1 - t^c}\right)^{-\frac{\alpha\beta(\rho(\sigma-1)-1)}{\gamma}}}_{\text{Revenue-recycling}} \tag{A.7}$$

Here I show that the sign of carbon tax and revenue-recycling effects in Eq.(A.7).

[1] See Mckenzie (2016) for a more detail explanation of the METR.

[2] $\lambda_k > 1$ means capital is subsidized.

Carbon tax effect

Similar to the abatement investment function, the sign of the carbon tax effect is ambiguous due to the presence of $\tilde{\Gamma}$ in Eq.(A.7).

Revenue-recycling effect

To determine the sign of the revenue-recycling effect, I consider the two extreme cases as before, , 1) $\lambda_A = 0$, and 2) $\lambda_A = 1$.

When $\lambda_A = 0$,

$$\text{TFP} = A^{1/\gamma}\tilde{\Gamma}\tau^{\frac{-\alpha}{\gamma}}(1+\text{METR})^{\frac{\alpha\beta(1-\rho(\sigma-1))}{\gamma}}(1-t^c)^{\alpha\rho} \tag{A.8}$$

Eq.(A.8) is a decreasing function of the CIT if $1 \leq \rho(\sigma-1)$. If $1 > \rho(\sigma-1)$, Eq.(A.8) can still be a decreasing function of the CIT when the speed of the decrease of $(1-t^c)^{\alpha\rho}$ is larger than the speed of the increase of $(1+\text{METR})^{\frac{\alpha\beta(1-\rho(\sigma-1))}{\gamma}}$ with the CIT.

When $\lambda_A = 1$,

$$\text{TFP} = A^{1/\gamma}\tilde{\Gamma}\tau^{\frac{-\alpha}{\gamma}}(1+\text{METR})^{\frac{\alpha\beta(1-\rho(\sigma-1))}{\gamma}} \tag{A.9}$$

Similarly, Eq.(A.9) is a decreasing function of the CIT if $1 \leq \rho(\sigma-1)$.

In both cases, TFP is a decreasing function of the CIT if $1 \leq \rho(\sigma-1)$. This means that the reduction of the CIT will likely to have a positive impact on TFP when the abatement technology improves faster with the abatement investment, and the goods are more substituable.

Appendix B Data

I Construction of Total Factor Productivity

In this appendix, I describe the details of the data and method used for the construction of the total factor productivity and its method. First, I explain the data below.

To estimate plant-level total factor productivity, two confidential micro-level data are merged, the Annual Survey of Manufactures (ASM) and General Index of Financial Information (GIFI). The ASM is an annual survey that contains information on manufacturing activities for all manufacturing locations in Canada. The GIFI is an extensive list of financial statement items, which businesses use to file their T2 corporate income tax return.

[Add Table Here][3]

Annual Survey of Manufactures

Output (Y_{it}): Plant output is total value of shipments of manufacturing goods minus raw material expenditure. It is deflated to 2007 dollars using industry-specific price indexes from the Canadian Productivity Accounts.

Labor (L_{it}): I use the number of total employees, which are the sum of production workers and non-production workers.

Energy (E_{it}): Energy is total of energy expenditures.

General Index of Financial Information

Capital (K_{it}): Capital is the book values of tangible assets, deflated to 2007 dollars using industry-specific price indexes from the Canadian Productivity Accounts.

Total Factor Productivity: Plant-level TFP is the log residual from a semiparametric production function estimation. I explain the details of the method below.[4]

Consider a plant with a Cobb-Douglas value-added production function:[5]

$$Y_{it} = A_{it} L_{it}^{\beta_l} K_{it}^{\beta_k} E_{it}^{\beta_e} \tag{B.1}$$

[3]A table summarizing the variables discussed in this appendix as well as other variables used in the propensity score estimation will be added here once the table is vetted by Statistics Canada.

[4]Although I explain each step of the modified ACF method one by one here, I used the user-written package, *prodest*, available in stata to implement these procedures. I am grateful for the creators of the package, Gabriele Rovigatti and Vincenzo Mollisi, for their help in modifying the ACF method using their package.

[5]I implicitly assume that a gross output production function is Leontief in the raw materials, i.e., $GO = G(F(K, L, E), M)$.

Taking logs yields:

$$y_{it} = \beta_0 + \beta_l l_{it} + \beta_k k_{it} + \beta_e e_{it} + \epsilon_{it} \tag{B.2}$$

where lowercase symbols represent the logs of variables and $\ln(A_{it}) = \beta_0 + \epsilon_{it}$. To estimate the production function using the algorithm introduced by Ackerberg, Caves and Frazer (2015) – henceforth ACF method, ϵ_{it} is separated into two components, ω_{it} and η_{it}.

$$y_{it} = \beta_0 + \beta_l l_{it} + \beta_k k_{it} + \beta_e e_{it} + \omega_{it} + \eta_{it} \tag{B.3}$$

where ω_{it} is the unobserved productivity and η_{it} is the idiosyncratic error term. This method assumes each input is determined at a different time. Capital is determined at $t-1$ while labor and energy are determined at $t-b$ where $b \in (0,1)$. These differences in decision timing are what make the identification of the input coefficients possible. Now raw material input (M_{it}) is used as a proxy to express the unobserved productivity with observables. Unlike the rest of variables, raw material is determined at t. Assume that:

$$m_{it} = m_{it}(\omega_{it}, l_{it}, k_{it}, e_{it}, \boldsymbol{z_{it}}) \tag{B.4}$$

While the original ACF method assumes that m_{it} depends only on the unobserved productivity, capital, and labor, this formulation is problematic when the objective is to estimate the productivity effect of environmental regulations. This is because there could be a selection bias arising from only productive plants engaging in the energy-saving activities. There could also be another simultaneity bias because the energy-saving decisions depends on a prior expectation of its own productivity. To address this issue, the vector of the determinants of productivity, $\boldsymbol{z_{it}}$, is included in m_{it}. Following De Loecker (2013) and Lutz (2016), $\boldsymbol{z_{it}}$ consists of export status, R&D status, energy intensity, and carbon tax dummy.

By assuming that m_{it} is strictly positive and monotonic in ω_{it}, m_{it} can be inverted to express the unobserved productivity as a function of observables:

$$\omega_{it} = h_t(l_{it}, k_{it}, e_{it}, m_{it}, \boldsymbol{z_{it}}) \tag{B.5}$$

Then, substituting Eq.(B.5) into Eq.(B.3) yields:

$$y_{it} = \beta_0 + \beta_l l_{it} + \beta_k k_{it} + \beta_e e_{it} + h_t(l_{it}, k_{it}, e_{it}, m_{it}, \boldsymbol{z_{it}}) + \eta_{it} \tag{B.6}$$

The first stage of ACF method involves estimating Eq.(B.6) using a semi-parametric method, treating $h_t(l_{it}, k_{it}, e_{it}, m_{it}, \boldsymbol{z_{it}})$ non-parametrically. A (4th-order) polynomial function, $\phi_t(.)$, in all its variables is often imposed as:

$$y_{it} = \phi_t(l_{it}, k_{it}, e_{it}, m_{it}, \boldsymbol{z_{it}}) + \eta_{it} \tag{B.7}$$

Although estimating Eq.(B.7) does not identify any input coefficients, it is still important as it nets out η_{it} and yields $\widehat{\phi}_t$, which is used in the second stage.

Here I assume that the unobserved productivity follows the first-order Markov process:

$$\begin{aligned} \omega_{it} &= E[\omega_{it} | \boldsymbol{J_{it-1}}] + \xi_{it} && \text{(B.8)} \\ &= E[\omega_{it} | \omega_{it-1}, \boldsymbol{z_{it-1}}] + \xi_{it} && \text{(B.9)} \\ &= g(\omega_{it-1}, \boldsymbol{z_{it-1}}) + \xi_{it} && \text{(B.10)} \end{aligned}$$

where $\boldsymbol{J_{it-1}}$ is the information set at time $t-1$. From the first stage, I have:

$$\widehat{\omega}_{it-1} = \widehat{\phi}_{it-1} - \beta_l l_{it-1} - \beta_k k_{it-1} - \beta_e e_{it-1} \tag{B.11}$$

Substituting Eq.(B.10) and Eq.(B.11) into Eq.(B.3) yields:

$$\begin{aligned} y_{it} = \quad & \beta_0 \quad + \beta_l l_{it} + \beta_k k_{it} + \beta_e e_{it} \\ + \quad & g'(\widehat{\phi}_{it-1} - \beta_l l_{it-1} - \beta_k k_{it-1} - \beta_e e_{it-1}, \boldsymbol{z_{it-1}}) + \xi_{it} + \eta_{it} \end{aligned} \tag{B.12}$$

Then three moment conditions are used to identify β_l, β_k, and β_e.

$$E(\xi_{it} + \eta_{it}, k_{it}) = 0 \tag{B.13}$$

$$E(\xi_{it} + \eta_{it}, l_{it-1}) = 0 \tag{B.14}$$

$$E(\xi_{it} + \eta_{it}, e_{it-1}) = 0 \tag{B.15}$$

Finally, with the unbiased and consistent estimate of all input coefficients, $\widehat{\beta_l}, \widehat{\beta_k}, \widehat{\beta_e}$, plant-level TFP is calculated as a residual:

$$\text{tfp} = y_{it} - \widehat{\beta_0} - \widehat{\beta_l} l_{it} - \widehat{\beta_k} k_{it} - \widehat{\beta_e} e_{it} \tag{B.16}$$

I estimate Eq.(B.16) for each of 21 sub-sectors (at 3-digit NAICS) within manufacturing industry separately. The estimation results for all inputs are presented in Table B.1. I also test to see if the production function exhibits constant return to scale. For the confidential reason, some results are suppressed. Although the test rejects constant return to scale production function for 19 out of 21 sectors, all the return to scales is close to one.

Table B.1: Production Function Estimation

NAICS	311	312	313	314	315	316	321	322	323	324	325
Labor	***	***	***	***	***	***	0.853***	0.841***	0.841***	***	***
							(0.004)	(0.002)	(0.004)		
Capital	***				***		0.01***	0.006**	-0.0007	***	
							(0.002)	(0.003)	(0.002)		
Energy	***	***	***	***	***	***	0.185***	0.236***	0.098***	***	***
							(0.004)	(0.003)	(0.0016)		
Return to scale	1.02	1.099	1.158	1.056	0.994	1.021	1.047	1.084	0.938	0.993	0.965
N	27,771	2,354	2,457	3,934	8,535	1,681	20,001	5,714	18,265	2,128	12,573
χ^2	27.5	44	3855	181	2	23	102	421	190	0.05	21
P-value	0	0	0	0	0.16	0	0	0	0	0.82	0

NAICS	326	327	331	332	333	334	335	336	337	339
Labor	0.81***	0.7***	0.89***	0.82***	0.88***	1.01***	0.96***	0.935***	0.96***	0.94***
	(0.004)	(0.006)	(0.003)	(0.002)	(0.003)	(0.004)	(0.003)	(0.0025)	(0.003)	(0.004)
Capital	0.0004	-0.01***	0.003	0.004***	0.002	0.012***	0.0045	0.008**	0.0042	0.008**
	(0.003)	(0.003)	(0.005)	(0.002)	(0.002)	(0.003)	(0.003)	(0.003)	(0.003)	(0.0035)
Energy	0.15***	0.21***	0.19***	0.19***	0.16***	0.061***	0.11***	0.15***	0.12***	0.07***
	(0.005)	(0.0076)	(0.004)	(0.004)	(0.004)	(0.005)	(0.005)	(0.004)	(0.004)	(0.003)
Return to scale	0.97	0.9	1.08	1.02	1.04	1.08	1.07	1.08	1.09	1.02
N	15,121	14,286	3,995	44,330	27,695	10,089	6,150	12,080	19,820	25,527
χ^2	86	150	251	21	91	413	190	349	563	21
P-value	0	0	0	0	0	0	0	0	0	0

Notes: 3-digit NAICS codes are listed and its corresponding sector name is: Food (311), Beverage and tobacco product (312), Textile mills (313), Textile product mills (314), Clothing (315), Leather and allied product (316), Wood product (321), Paper (322), Printing and related support activities (323), Petroleum and coal product (324), Chemical (325), Plastics and rubber product (326), Non-metallic mineral product (327), Primary metal (331), Fabricated metal product (332), Machinery (333), Computer and electronic product (334), Electrical equipment, appliance and component (335), Transportation equipment (336), Furniture and related product (337), and Miscellaneous (339). The results for 311-316 and 324-325 are suppressed for privacy reason. The last two columns present statistics (the Chi-squared and p-value) from the hypothesis test for the constant return to scale, i.e., H_0: $\beta_l + \beta_k + \beta_e = 1$. The coefficient and standard error for some industries are suppressed to maintain confidentiality in conformity with Statistics Canada's *Statistics Act*.
*** Significant at the 1 percent level, ** Significant at the 5 percent level, * Significant at the 10 percent level.

II Constructing the quantity-based TFP (TFPQ)

In this appendix, I summarize how I construct the quantity-based TFP (TFPQ) using the approach proposed by Hsieh and Klenow (2009). This approach derives an expression for TFPQ from the revenue-based TFP (TFPR) without needing to obtain the plant-specific output prices.

The basic model is based on a standard model of monopolistic competition with heterogeneous plants. Single final good Y is produced by a representative firm in a perfect competitive final output market with Cobb-Douglas production technology:

$$Y = \prod_{s=1}^{S} Y_s^{\theta_s}, \quad \sum_{s=1}^{S} \theta_s = 1 \tag{B.17}$$

The final good producer maximizes:

$$\max_{Y_s} \quad PY - \sum_{s=1}^{S} P_s Y_s = P \prod_{s=1}^{S} Y_s^{\theta_s} - \sum_{s=1}^{S} P_s Y_s \tag{B.18}$$

and the first-order condition (FOC) is:

$$\frac{\theta_s}{Y_s} P \prod_{s=1}^{S} Y_s^{\theta_s} = P_s \quad \Rightarrow \quad P_s Y_s = \theta_s P Y \tag{B.19}$$

Industry output Y_s is itself a CES aggregate of M_s differentiated products:

$$Y_s = \left[\sum_{M_s} Y_{si}^{\frac{\sigma-1}{\sigma}} \right]^{\frac{\sigma}{\sigma-1}} \tag{B.20}$$

The demand for these industries is given by maximizing:

$$\max_{Y_{si}} \quad P_s Y_s - \sum_{M_s} P_{si} Y_{si} = P_s \left[\sum_{M_s} Y_{si}^{\frac{\sigma-1}{\sigma}} \right]^{\frac{\sigma}{\sigma-1}} - \sum_{M_s} P_{si} Y_{si} \tag{B.21}$$

and the FOC is:

$$P_{si} = \frac{\sigma}{\sigma - 1} P_s \left[\sum_{M_s} Y_{si}^{\frac{\sigma-1}{\sigma}} \right]^{\frac{1}{\sigma-1}} \frac{\sigma - 1}{\sigma} Y_{si}^{\frac{-1}{\sigma}} \tag{B.22}$$

$$= P_s Y_s^{\frac{1}{\sigma}} Y_{si}^{\frac{-1}{\sigma}} \tag{B.23}$$

Then, multiple both sides by Y_{si} yields:

$$P_{si} Y_{si} = P_s Y_s^{\frac{1}{\sigma}} Y_{si}^{\frac{\sigma-1}{\sigma}} \tag{B.24}$$

Then, raise both sides by $\sigma/(\sigma - 1)$ yields:

$$Y_{si} = \left(P_s Y_s^{\frac{1}{\sigma}} \right)^{\frac{-\sigma}{\sigma-1}} (P_{si} Y_{si})^{\frac{\sigma}{\sigma-1}} \tag{B.25}$$

Finally, Foster, Haltiwanger and Syverson (2008) defines TFPQ as:

$$TFPQ_{si} \equiv A_{si} = \frac{Y_{si}}{K_{si}^{\alpha_s} L_{si}^{1-\alpha_{si}}} \tag{B.26}$$

Although we do not have neither P_{si} nor Y_{si} directly from the data, using (B.25) (i.e., expressing Y_{si} as a function of $P_{si} Y_{si}$) helps me derive the following:

$$A_{si} = \kappa_s \frac{(P_{si} Y_{si})^{\frac{\sigma}{\sigma-1}}}{K_{si}^{\alpha_s} L_{si}^{1-\alpha_{si}}} \tag{B.27}$$

where $\kappa_s = (P_s Y_s)^{-\frac{1}{\sigma-1}} / P_s$. Then,

$$\ln A_{si} = \ln \kappa_s + \frac{\sigma}{\sigma - 1} \ln P_{si} Y_{si} - \alpha_s k_{si} - (1 - \alpha_s) l_{si} \tag{B.28}$$

This equation requires only an assumption about the elasticity of substitution between plant value added, σ. It requires neither the plant-level output price nor the plant-level output. Following Hsieh and Klenow (2009), I set $\sigma = 3$ as estimates of the substitutability of competing manufacturers in the trade and industrial organization literature typically range from 3 to 10. In estimating TFPQ, I ignore the industry-common term, κ, because this does not vary across plants within the same sub-industry. Given that I estimate TFPQ for each sub-industry separately, this term does not affect the plant-level TFPQ within the same sub-industry. With $\sigma = 3$, estimating TFPQ is as simple as scaling down the revenue-based value-added by 2/3 and re-run the Ackerberg, Caves and Frazer algorithm.

Appendix C Additional Tables and Figures

Table C.1: A full set of variables used for estimating the propensity scores

TFP	Taxable income
Output	Labor
Capital	Intermediates
Production workers	International export
Non-production workers	Intra-provincial export
R&D	Wage for production worker
Wage	Salaries for non-production worker
Utility bill	Electricity
International export intensity	Gasoline
Intra-provincial export intensity	Diesel fuel
4 digit NAICS ID	Natural gas
Plant age	Coal
Total expenditure	Light fuel oil
Revenue	Heavy fuel oil
Profits	Liquefied petroleum gases
# of subsidiary	Others energy

Note: All energy related variables are expenditures.

Table C.2: Checking Robustness of Revenue-recycling effect

	(1)	(2)	(3)
CTax_{ipt}	-7.349***	-7.349***	-7.351***
	(2.801)	(2.801)	(2.803)
Recycling_{ipt} ($\text{TI}_i > 0$)	0.130*		
	(0.0683)		
Recycling_{ipt} ($\text{TI}_i > \$230$)		0.131*	
		(0.0681)	
Recycling_{ipt} ($\text{TI}_i > \$1,679$)			0.133*
			(0.0681)
N	237,331	237,331	237,331
R^2	0.673	0.673	0.673

Notes: Dependent variable and CTax_{ipt} are defined as Eq.(4.1). The definition of Recycling_{ipt} is altered, and its result is presented in each column. Column (1) is taken from column (4) of Table 2. In column (2), I changed the threshold for Recycling_{ipt} from zero to approximately \$230, which is the 1st percentile of plants whose taxable income is positive. I further change the threshold of Recycling_{ipt} in column (3) to \$1,679 (5th percentile). All specifications includes plant FE, industry (4-digit NAICS) by time FE, and provincial GDP as a control. To account for serial correlations and within sub-industry correlations, standard errors are clustered by 3-digit NAICS industry × province, reported in parentheses.
*** Significant at the 1 percent level, ** Significant at the 5 percent level, * Significant at the 10 percent level.

Table C.3: Placebo Tests by Implementing Fake Carbon Tax in Other Provinces

	(1) AB	(2) NS	(3) NB	(4) QC	(5) ON	(6) MB	(7) SK
CTax	-0.0507***	12.22*	-1.204	2.629	1.479**	6.703	3.069
	(0.0107)	(6.227)	(2.305)	(2.085)	(0.632)	(7.327)	(2.663)
Recycling	-0.00427	0.249	0.121	0.0332	0.0694	0.181	0.110
	(0.137)	(0.227)	(0.107)	(0.0436)	(0.0528)	(0.114)	(0.143)
N	206,760	206,765	206,774	206,772	206,775	206,766	206,775
R^2	0.678	0.702	0.687	0.689	0.927	0.678	0.672

Notes: Provincial abbreviation is as follows: Alberta (AB), Nova Scotia (NS), New Brunswick (NB), Québec (QC), Ontario (ON), Manitoba (MB), and Saskatchewan(SK). All specifications includes plant FE, industry (3-digit NAICS) by time FE, and provincial GDP as a control. To account for serial correlations and within sub-industry correlations, standard errors are clustered by 3-digit NAICS industry × province, reported in parentheses.
*** Significant at the 1 percent level, ** Significant at the 5 percent level, * Significant at the 10 percent level.