

# Environmental Regulations and the Clean-Up of Manufacturing: Plant-Level Evidence from Canada\*

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## **Abstract**

For much of the industrialized world, pollution from manufacturing has been falling despite increased output. In this paper, we provide the first estimates of the extent to which environmental regulations have contributed to this “clean-up” of manufacturing by causing: (i) the adoption of cleaner production processes, (ii) the reallocation of output across producers, and (iii) producer entry and exit. To do this, we examine a major revision to Canadian environmental policy using a novel, confidential dataset containing information on the production decisions and pollution emissions of Canadian manufacturing plants. We find regulation explains, at most, 61% of the Canadian clean-up, but the underlying mechanisms differ strikingly across pollutants. We present a stylized model featuring plant heterogeneity to illustrate how the costs of abating pollution can affect the channels through which regulation causes a clean-up.

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# 1 Introduction

The past thirty years have witnessed a marked improvement in manufacturing pollution levels across much of the world despite large increases in manufacturing activity. In the United States, for example, manufacturing emissions of most air pollutants fell by between 52%-69% from 1990 to 2008, while total real shipments from the sector rose by 35% (Levinson, 2015). In Europe, manufacturing air pollution fell by between 23-59% from 1995 to 2008, while real shipments rose by 37% (Brunel, 2016). These patterns appear to extend outside of the United States and Europe; sulphur dioxide emissions from manufacturing have been falling in a number of countries despite increases in shipments (Grether et al., 2009). These broad trends imply that, for much of the world, manufacturing is becoming cleaner.

In this paper, we ask how plant-level responses to environmental regulation have contributed to this “clean-up” of manufacturing. Regulation can cause a clean-up by changing a sector’s composition – reallocating output across plants or causing plant entry and exit – or by changing the production processes used by plants. Recent work has shown that environmental policies have affected the composition of the manufacturing sector (Henderson, 1996; Greenstone, 2002) and reduced the sector’s aggregate pollution intensity (Shapiro and Walker, 2015). However, there are no estimates of regulation’s effect on the processes used by manufacturing plants, or the degree to which each of these channels have contributed to the clean-up. This makes it difficult to determine how the composition of the economy might change in transitioning to a less-polluting economy. Addressing this is important because changes in an economy’s composition could potentially disrupt labor and product markets (see, e.g., Foster et al. (2008)), whereas changes in production processes would not. We provide the first estimates of the magnitude of each of these channels of regulation. To do this, we estimate the effects of a major revision to Canadian environmental policy on Canadian manufacturing plant entry and exit, the reallocation in output from regulated to unregulated surviving plants, and the adoption of cleaner production processes by surviving plants.

We start by examining the manufacturing clean-up in Canada using the industry decomposition developed by Levinson (2009, 2015). Based on these results, the clean-up in Canada appears to be very similar to those documented in the United States and Europe. In each case, total manufacturing emissions of most air pollutants have fallen substantially, and this is primarily because of reductions in industry pollution intensity.

The results of our decomposition suggest the clean-up of Canadian manufacturing is primarily due to within-plant changes in emission intensity, within-industry reallocations of activity across plants, and plant entry and exit. In order to understand how environmental regulation has affected these channels, we study the effects of the Canada Wide Standards for Particulate Matter and Ozone (CWS) on the emission intensity and productive activities of plants that emit pollutants directly targeted by the policy.

The CWS was created in the year 2000 as a result of an agreement between the federal government of Canada and the various provincial governments, and was the major air quality regulation in place in Canada over the period 2000-2012. The agreement was designed to ensure each region met a minimum level of air quality by establishing thresholds for the ambient concentrations of two common pollutants: fine scale particulate matter ( $PM_{2.5}$ ) and ground-level ozone ( $O_3$ ). Regions in which the ambient concentrations of either pollutant exceeded the relevant threshold in a given year were subject to more stringent regulation relative to other regions. In addition, these regulations explicitly targeted plants in a set of “targeted industries”. Under the CWS, the annual permits required by plants to operate in each province were used to impose more stringent rules on pollution emissions for plants in targeted industries and regions violating one of the CWS standards. These standards either required plants to adopt technical changes to meet industry best practices, or reduce activities generating the regulated pollutant.<sup>1</sup>

To guide our analysis, we next develop a simple theory based on a closed-economy variant of the Melitz (2003) model in which heterogenous plants face regulatory constraints similar

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<sup>1</sup>We describe the CWS in more detail in Section 3.

to those imposed under the CWS. This model has three key features. First, it allows for plant productivity differences, which have been highlighted as a key determinant of the effects of environmental regulation in the existing theoretical literature (see, e.g., Konishi and Tarui (2015) or Anouliés (2017)). Second, it allows for endogenous technology adoption by plants to capture the fact that leading technologies were used as a benchmark for the technical changes required under the CWS. Third, it allows for differences across pollutants in the cost of adopting less-polluting production processes, which we call abatement costs. This feature is important because, as we discuss in Section 3, the two pollutants we focus on carry very different abatement costs, at least in Canada: nitrogen oxide<sup>2</sup> (NO<sub>x</sub>) abatement can be accomplished at a relatively low cost, while PM<sub>2.5</sub> abatement typically requires high fixed costs (Canadian Council of Ministers of the Environment, 1998; Environment Canada, 2002).

We then test the predictions generated by this framework. We directly estimate the effects of the CWS on affected plants using a unique confidential dataset containing longitudinal information on the pollution emissions and productive activities of Canadian manufacturing plants over the period 2004-2010. We identify the effects of environmental regulation on manufacturing plants by exploiting variation in the stringency of regulation across regions, time, and industries created by the design of the CWS. As such, we adopt a triple-difference research design that embeds three margins of comparison. First, we examine the effects on plants in regulated regions, by comparing outcomes between plants in regulated and unregulated industries in years in which their region is regulated. Next, we compare outcomes between these plants in years in which their region is unregulated. Lastly, we compare outcomes between plants in regulated and unregulated industries in regions that are never regulated. This approach allows us to flexibly control for factors such as localized recessions or industry demand shocks that would otherwise confound the effects of environmental regulation.

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<sup>2</sup>Nitrogen oxide is a main contributor to O<sub>3</sub> pollution, and a main target of the CWS.

We start our assessment of the CWS by asking what effect, if any, the policy had on the level of pollution emitted by affected Canadian manufacturing plants. We begin here to establish that the CWS did contribute to the manufacturing clean-up in Canada. We find robust evidence that the CWS reduced pollution emissions from affected manufacturing plants. For the average  $PM_{2.5}$  emitting plant, the CWS is associated with a 15% reduction in  $PM_{2.5}$  emissions. Furthermore, we find that the CWS is associated with a 33% reduction in  $NO_X$  emissions from the average  $NO_X$  emitting plant.

Next, we examine the effects of the CWS on the emission intensity of affected plants. Our theory predicts that the effects of the CWS will depend on the fixed costs of abatement. If fixed costs are high, as in the case of  $PM_{2.5}$ , only relatively productive plants will adopt cleaner production processes following regulation. As a result, the CWS should have little to no effect on the emission intensity of the average plant. If the fixed costs of abatement are low, as with  $NO_X$ , then even less productive plants should respond to regulation by adopting cleaner production processes. In this case, the emission intensity of the average plant should fall in response to the CWS. Our empirical estimates support these predictions; we find the CWS did not have a significant effect on the emission intensity of the average affected  $PM_{2.5}$  emitting plant, but is associated with a 29% reduction in the  $NO_X$  emission intensity of the average affected  $NO_X$  emitting plant.

We also examine the effects of the CWS on plant output and exit. As predicted by the model, we find that the CWS was associated with a 11% reduction in output from the average affected  $PM_{2.5}$  emitting plant, but had little to no effect on the output of the average plant that emits  $NO_X$ . In addition, we find that the CWS was associated with a significant reduction in the number of plants that emit  $PM_{2.5}$ , but had little to no effect on the entry and exit of plants that emit  $NO_X$ .

Taken together, these estimates suggest that environmental regulations contributed significantly to the clean-up of the Canadian manufacturing sector. For example, our estimates for the responses of  $PM_{2.5}$  emitters suggest that the effects of the CWS explain close to 21%

of the reduction in the  $PM_{2.5}$  intensity of manufacturing. Similarly, our estimates for the responses of  $NO_X$  emitters suggest that nearly 61% of the reduction in the manufacturing sector's  $NO_X$  emission intensity can be attributed to the effects of the CWS. However, the mechanisms driving these responses vary starkly across pollutants; the  $PM_{2.5}$  clean-up was primarily driven by changing the composition of economic activity within industries, whereas the clean-up of  $NO_X$  was primarily due to within-plant reductions in emission intensity.

Our model suggests these differential responses to regulation are due to differences in the fixed cost of abating across pollutants. While we have focused on this channel given the available evidence documenting the stark differences in the costs of abating  $PM_{2.5}$  and  $NO_X$ , we do not observe these costs directly. Hence, to provide further evidence that our estimates are consistent with this mechanism, we test the heterogeneity in responses to regulation implied by our model. The effects of regulation should only vary across plants of different productivity levels if the fixed costs of abatement are high. We test this prediction by allowing the estimated effects of the CWS to differ across plants on the basis of their initial labor productivity level. The empirical results match our model's predictions. We find considerable differences across plants in the effects of the CWS on  $PM_{2.5}$  emitters, but relatively homogeneous effects on  $NO_X$  emitters. Pollution from relatively high-productivity regulated  $PM_{2.5}$  plants fell primarily due to reductions in emission intensity, whereas pollution emissions from the least-productive  $PM_{2.5}$  plants fell due to a reduction in output. In contrast,  $NO_X$  pollution intensity fell for both high and low productivity plants. These results further suggest that fixed abatement costs are a key determinant of how industry cleans up in response to environmental regulation.

Finally, we examine the effects of the CWS on several additional margins via which plants could respond to regulation, including changes in primary factor use, intermediate input use, and productivity. This allows us to test a number of alternative explanations for why we observe different responses to the CWS across pollutants. We find little evidence for these alternative explanations.

Altogether, our findings contribute to a burgeoning literature examining the sources of the clean-up of the manufacturing sector. This research began with the work by Levinson (2009) examining how trade-induced changes in industrial composition have contributed to the clean-up of US manufacturing. Levinson finds that these changes played a small role; the clean-up is primarily due to reductions in industry emission intensity.<sup>3,4</sup> Our work is most closely related to that of Shapiro and Walker (2015), who use a structural model to ask whether the clean-up of the U.S. manufacturing sector has been caused by regulation, trade, productivity growth, or other economic factors. Using this model, Shapiro and Walker conclude the effects of regulation explains most of the reduction in pollution emissions from US manufacturing. By directly estimating the effects of regulation, our analysis complements this work along two key dimensions. First, we provide causal evidence of how environmental regulations contributed to the clean-up of manufacturing by altering the emission intensities of individual plants, reallocating activity across plants, and changing entry and exit decisions. Second, we provide evidence as to the mechanisms via which plants change their emission intensities in response to environmental regulation.<sup>5</sup>

This paper also relates to work examining the effects of air quality regulation on the emissions of manufacturing plants. Fowlie et al. (2012), for example, find Southern California's RECLAIM cap-and-trade program reduced NO<sub>x</sub> emissions from manufacturing plants. In addition, Greenstone (2003) and Gibson (2016) examine the effects of the U.S. Clean Air Act, concluding regulation reduced both the growth (Greenstone, 2003) and level (Gibson, 2016) of air pollutant emissions from manufacturing plants. Our paper complements this work by determining whether changes in plant pollution in response to regulation are due to changes in the level of output produced, or changes in the emission intensity of production.

Lastly, our work also relates to a large literature examining the effects of air quality reg-

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<sup>3</sup>Brunel (2016) documents a similar pattern using European data.

<sup>4</sup>Others have argued trade may have caused surviving plants to change how they produce their goods (due, for example, to the outsourcing of inputs or the adoption of new abatement technologies), thereby leading to a reduction in plant-level pollution intensity (see Martin (2012) or Cherniwchan (2017)).

<sup>5</sup>Our work is also related to Martin et al. (2014) who tackle a related, but distinct question, in asking how the energy intensity of UK manufacturing plants were affected by a carbon tax.

ulation on the industrial activities of manufacturing plants. This literature has typically focused on the effects of regulation on plant employment, production, capital, and productivity (see, e.g. Berman and Bui (2001), Greenstone (2002), Popp (2003), Shadbegian and Gray (2006), Hanna (2010), Greenstone et al. (2012), and Walker (2013)), primarily in the context of the U.S. Clean Air Act or other U.S. policies. Our results complement these findings in three ways. First, we show that the effects of environmental regulation on industrial activity may vary across plants of different productivity levels. Second, we find that some of the adjustments to policy that have been documented elsewhere in the literature (lower output, as in Greenstone (2002); changes in productivity, as in Greenstone et al. (2012)) extend outside the US. Finally, we show that pollution emissions may fall at regulated plants even if there is no significant reduction in production.

The remainder of this paper proceeds as follows. In Section 2, we document the clean-up of the Canadian manufacturing sector. Section 3 provides a brief overview of the CWS. In Section 4 we outline our theory. Section 5 presents our data, outlines our research design and empirical specification, and presents our empirical results. Finally, Section 6 concludes.

## **2 The Clean-Up of Canadian Manufacturing**

Our goal in this paper is to determine how the effects of environmental regulation on individual plants have contributed to the clean-up of manufacturing. While the clean-up has been documented in several countries, including the United States (e.g. Levinson (2009, 2015), Shapiro and Walker (2015)), and the European Union (e.g. Brunel (2016)), there is no evidence of whether a similar trend appears in Canada. Hence, before we examine the effects of environmental regulation, we first examine whether the changes in the pollution emitted by the Canadian manufacturing sector mirror those that have occurred elsewhere.

These trends, relative to 1992 levels, are illustrated in Figure 1. The figure depicts changes in the aggregate emissions of four common pollutants from the Canadian manufacturing sector, as well as changes in aggregate manufacturing output. As it shows, Canada



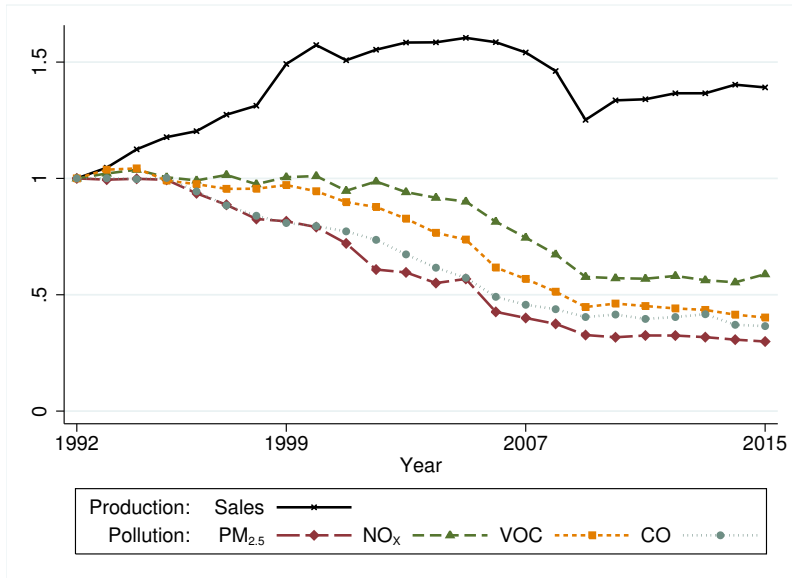


Figure 1: Production and Pollution Emissions from Canadian Manufacturing: 1992-2015

Notes: Figure depicts trends in real manufacturing sales and aggregate emissions of fine scale particulate matter (PM<sub>2.5</sub>), nitrogen oxide (NO<sub>x</sub>), volatile organic compounds (VOCs), and carbon monoxide (CO). Aggregate pollution is from Environment and Climate Change Canada's Air Pollutant Emission Inventory. Aggregate output is measured as the real value of manufacturing shipments, constructed by deflating data on industry-level nominal shipment values from Statistics Canada's CANSIM table 304-0014 using the industry price data given in Statistics Canada's CANSIM table 329-0077.

has experienced a large decline in the emission intensity of its manufacturing sector since 1992. Throughout the 1990s, manufacturing output grew substantially, but there was little change in aggregate emissions of NO<sub>x</sub> or volatile organic compounds (VOCs) and moderate reductions in particulate matter and carbon monoxide (CO) emissions. Over the early- to mid- 2000s, while the manufacturing sector stagnated, aggregate emissions of all four pollutants fell dramatically. From the late-2000s on, the sector shrank in terms of both output and pollution, with a mild recovery in output following the 2008 financial crisis, and a roughly constant level of emissions from 2010 onwards. Overall, from 1992 to 2015 real manufacturing output rose approximately 39%, while emissions fell by between 41% and 70%, depending on pollutant. These estimates imply that, on average, the emission intensity of the Canadian manufacturing sector fell by 3.5-4.7% annually.

This suggests the Canadian manufacturing clean-up was of a similar magnitude to the clean-ups that occurred in the U.S. and Europe. For example, Levinson (2015) finds the emission intensity of US manufacturing fell by 3.6-4.3% annually from 1990 to 2008. Simi-

larly, Brunel (2016) shows the emission intensity of European manufacturing fell by 4.6-7.4% annually over the period 1995-2008.

While this evidence shows the magnitudes of the clean-ups in Canada, the US, and Europe were similar, it reveals little as to whether the potential sources were the same. As such, we adopt a simple decomposition exercise first used by Levinson (2009) to study the potential sources of the clean-up.<sup>6</sup> This approach is useful because it allows us to determine if the observed reductions in aggregate emission intensity are driven by a “composition effect” created by a reallocation of economic activity from dirty pollution-intensive sectors to clean sectors with relatively low pollution intensities or by a “technique effect” created by reductions in the emission intensity of individual industries.

To make this decomposition explicit, let  $Z$ ,  $X$ , and  $E = Z/X$  denote the pollution emissions, output, and pollution intensity of the manufacturing sector, respectively. Let  $Z_i$ ,  $X_i$ , and  $E_i$  denote the same for individual manufacturing industries<sup>7</sup>, indexed by  $i$ . Manufacturing pollution intensity can then be written as  $E = \sum_i \theta_i E_i$ , where  $\theta_i = X_i/X$  denotes industry  $i$ 's share of output from the manufacturing sector. Totally differentiating yields

$$dE = \sum_i E_i d\theta_i + \sum_i \theta_i dE_i. \quad (1)$$

The first term of equation (1) is the aforementioned composition effect, while the second term is the technique effect.

We follow the approach taken by Levinson (2015) and take equation (1) directly to the data. This gives us estimates of the reduction in manufacturing pollution intensity attributable to both the composition and technique effects for PM<sub>2.5</sub>, NO<sub>x</sub>, VOCs, and CO over the period 1992-2015. These estimates are reported in Table 1. The first two columns report the percentage change in emissions and emission intensity that occurred for the sector

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<sup>6</sup>This approach traces back to work of Grossman and Krueger (1991) and Copeland and Taylor (1994).

<sup>7</sup>Due to constraints from the pollution data, our industry definitions correspond to either the three- or four-digit NAICS code.

Table 1: Decomposing Emissions from Canadian Manufacturing: 1992-2015

	$\Delta$ Aggregate Pollution (1)	$\Delta$ Aggregate Pol. Intensity (2)	Technique Effect (3)	Composition Effect (4)	Technique Effect Share (5)
PM <sub>2.5</sub>	-0.70	-0.79	-0.78	-0.01	0.99
NO <sub>x</sub>	-0.41	-0.58	-0.52	-0.06	0.90
VOCs	-0.60	-0.71	-0.67	-0.04	0.94
CO	-0.63	-0.74	-0.73	-0.01	0.99

*Notes:* Table reports estimates from a decomposition of the change in pollution intensity of the Canadian manufacturing sector from 1992 to 2015 into composition and technique effects. Estimates are from a Laspeyre’s-type index following Levinson (2015). Each row reports estimates for a different pollutant. The first two columns report the percentage change in total emissions and emission intensity from the manufacturing sector, respectively. The third and fourth columns report the reduction in aggregate emission intensity due the technique and composition effects, respectively. The final column shows the fraction of column (2) attributable to changes in the technique effect, calculated as (column (3)/column (2)).

as a whole. The third and fourth columns report the change in aggregate emission intensity attributable to the technique effect and composition effects, respectively.<sup>8</sup> The final column reports the share of the change in aggregate pollution intensity due to the technique effect.

The estimates reported in Table 1 suggest that the clean-up of the Canadian manufacturing sector can primarily be attributed to the technique effect. For example, the estimate reported in the first row indicates that during the 1992-2015 period, changes in industry emission intensity accounted for 99% of the reduction in manufacturing PM<sub>2.5</sub> intensity. This is further evidence that the Canadian clean-up is similar to those observed elsewhere; as shown by Levinson (2009, 2015) and Brunel (2016), the clean-ups of US and European manufacturing are also primarily due to the technique effect.<sup>9</sup>

## 2.1 How do Industries Clean-Up?

The evidence presented above indicates that reductions in industry emission intensities are the predominant source of the manufacturing clean-up that has been observed in Canada and elsewhere. This suggests that plant-level responses are a key determinant of the observed

<sup>8</sup>The technique effect is calculated by taking the percentage change in a Laspeyre’s-type index of  $\sum_i \theta_i dE_i$ . The composition effect is calculated as the difference between the change in manufacturing emission intensity and the technique effect.

<sup>9</sup>In addition, ?? perform a product-level decomposition, and find the clean-up in the US is primarily due to within-product reductions in pollution intensity.

reductions in manufacturing emission intensity.

To see this, it is useful to extend the logic of the decomposition exercise presented in Levinson (2009) and further decompose the technique effect into plant level responses as in Cherniwchan et al. (2017). Suppose, as above, that pollution intensity of industry  $i$  is given by  $E_i = Z_i/X_i$ . In addition, suppose each industry is composed of a continuum of plants and let  $x_i(n)$  and  $z_i(n)$  denote output and pollution from plant  $n$ , so  $e_i(n) = z_i(n)/x_i(n)$  is the emission intensity of plant  $n$  and  $\lambda_i(n) = x_i(n)/X_i$  is plant  $n$ 's share of production in industry  $i$ . Furthermore, let  $n_i$  denote the marginal plant that is endogenously determined by the industry's profitability. In this case, the emission intensity of industry  $i$  can be expressed as a weighted average of the emission intensities of each plant in the industry:  $E_i = \int_0^{n_i} e_i(n)\lambda_i(n)dn$ . The change in emission intensity of any industry  $i$  is then

$$dE_i = \int_0^{n_i} de_i(n)\lambda_i(n)dn + \int_0^{n_i} e_i(n)d\lambda_i(n)dn + [e_i(n_i) - E_i]\lambda_i(n_i)dn_i. \quad (2)$$

The first term on the right-hand side of equation (2), which we term the “process effect”, captures the changes in industry emission intensity due to plant-level changes in emission intensity created by changes in the processes used in production. As such, this term captures the direct effects of a shock; all else equal, an industry's emission intensity will fall if a shock such as environmental regulation induces plants in the industry to lower their emission intensities. The remaining two terms capture the indirect changes in industry emission intensity created by a shock. The first of these, given in the second term on the right-hand side of equation (2), captures the effects of the shock on the relative size of plants within an industry. This “reallocation effect” would arise if the shock does not affect plants uniformly; if the shock only affects a subset of plants in an industry, as is common with many environmental regulations, the resulting change in output may cause a reduction in the relative output of affected plants leading to a change in industry emission intensity, even in the absence of direct changes in plant emission intensity. Finally, the “selection effect”

given by the third term captures the change in emission intensity created by a change in the set of plants operating within the industry owing to plant entry and exit.

Equation (2) shows that regulation may cause an industry’s emission intensity to fall by causing plant-level reductions in emission intensity (the process effect), changes in the relative output of dirty and clean plants (the reallocation effect), or a change in the plants that comprise the industry (the selection effect). Yet, the majority of existing studies have examined the effects of regulations on either selection (e.g. Henderson (1996), Becker and Henderson (2000)) or reallocation (e.g. Greenstone (2002)). In what follows, we present direct estimates of the process, reallocation, and selection effects and quantify their contributions to the clean-up of Canadian manufacturing.<sup>10</sup>

### 3 Air Quality Regulation in Canada

In order to understand how environmental regulations affected pollution from manufacturing plants and quantify their contribution to the clean-up of Canadian manufacturing, we examine the effects of the Canada Wide Standards for Particulate Matter and Ozone (CWS). The CWS was the primary policy targeting particulate matter and ozone pollution throughout Canada over the period 2000-2010.<sup>11</sup> Moreover, the design of the CWS makes it an attractive setting for studying the effects of environmental regulation.

First signed in 2000, the CWS was an agreement between the federal government of Canada and the various provincial environment ministries. The intent of the CWS was to improve air quality across the country by the end of 2010 by implementing two air quality standards – one for  $PM_{2.5}$  and one for  $O_3$  – that applied to each major town or city in Canada (we call these Census Metropolitan Areas or CMAs) (Canadian Council of Ministers

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<sup>10</sup>Holladay and LaPlue (2017) present the results of a plant-level decomposition exercise similar to Equation (2) of toxic chemical emissions from the U.S. manufacturing. They show that toxic emissions fell throughout the 1990s primarily due to plant-level changes in pollution intensity, although cannot explain why pollution intensity fell.

<sup>11</sup>It was subsequently replaced with the Canadian Ambient Air Quality Standards for Fine Particulate Matter and Ozone in 2012. We end our study period in 2010 to avoid any potential contamination by this regulatory change, as the planning for this transition began in 2011.

of the Environment, 2000a).<sup>12</sup> Much like the National Ambient Air Quality Standards at the centre of the Clean Air Act Amendments (CAAA) in the United States, these standards created a target level of air quality that needed to be achieved by each CMA in Canada. These standards were common across all CMAs, and each CMA was required to meet the standards by the end of 2010.<sup>13</sup> To that end, plants in CMAs with ambient concentrations of either PM<sub>2.5</sub> or O<sub>3</sub> in excess of the relevant standard’s threshold were subject to more stringent environmental regulation than plants in relatively clean CMAs.

In addition to differentiating between regions on the basis of air quality, the CWS explicitly designated a set of “targeted industries” that were to be the focus of more stringent regulation.<sup>14</sup> These industries were chosen because they were viewed as major contributors to the air quality problems that motivated the CWS, and were common across all CMAs.

While on its surface the CWS was a relatively simple policy (manufacturing plants in targeted industries in dirty CMAs were more stringently regulated than other plants), the implementation was anything but simple. This is because regulatory authority over environmental issues in Canada is shared between the local, provincial, and federal governments (Boyd, 2003). Below, we briefly describe the broad framework used across the country, so as to clarify the core regulatory mechanisms through which the CWS was implemented.<sup>15</sup>

Broadly, the CWS was a tiered regulatory approach in which the federal and provincial

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<sup>12</sup>The agreement defines a major town or city as a Census Agglomeration (CA) or Census Metropolitan Area (CMA). A CMA must have a total population of at least 100,000 with a population in the center of the region of 50,000. A CA must have a core population of at least 10,000 (and generally have a total population less than 100,000). For detailed CA and CMA definitions, see Statistics Canada (2015). For convenience, we use the term CMA to refer to both CAs and CMAs.

<sup>13</sup>The standard for particulate matter required each CMA’s PM<sub>2.5</sub> concentration lie below  $30\mu\text{g}/\text{m}^3$  over each 24-hour period (that is, every day from midnight to midnight). Achievement of the PM<sub>2.5</sub> standard was based on the 98<sup>th</sup> percentile of each region’s 24-hour ambient concentration in a given year. The O<sub>3</sub> standard was applied as an 8-hour standard that required each CMA’s O<sub>3</sub> concentration lie below 65 parts per billion (ppb). Achievement of the O<sub>3</sub> standard was based on the 4<sup>th</sup> highest 8-hour concentration reported in a given year. In comparison, the National Ambient Air Quality Standards in the United States currently contain a 24-hour PM<sub>2.5</sub> standard set at  $35\mu\text{g}/\text{m}^3$ , and an 8-hour O<sub>3</sub> standard set at 70 ppb. For details on the US standards, see Environmental Protection Agency (2016).

<sup>14</sup>The targeted industries were pulp and paper, lumber and wood product manufacturing, electric power generation, iron and steel manufacturing, base metal smelting, and the concrete and asphalt industries (Canadian Council of Ministers of the Environment, 2000b).

<sup>15</sup>For a detailed overview of air quality regulation in Canada, see Taylor and McMillan (2014).

governments agreed on local air quality targets (the CWS standards), the federal government developed best practice and guidance documents for targeted industries (called Multi-pollutant Emission Reduction Strategies, or MERS) to provide management tools to the provincial governments (Government of Canada, 2003), and the provincial governments used new and existing regulations to meet these standards.<sup>16</sup> The main provincial mechanisms were annual provincial operation permits and licenses, which plants required to operate. Plants had to submit applications for these permits to prove compliance with certain environmental regulations<sup>17</sup> and to have any facility changes approved (see, e.g. Angle (2014, p. 290), Environment Canada (2004, p. 11), and Environment Canada (2002, p. xi)).<sup>18</sup> In most instances, facilities could effectively follow one of two paths to meet the permitting requirements: they could either adopt one or more technical changes recommended in their industry’s MERS, or reduce activities contributing to the problematic pollutant.<sup>19</sup> When local air quality was relatively clean (i.e. a region was in compliance with the CWS), the permitting constraints were laxer than when air quality was poor. This means the regulatory stringency facing a plant varied over time according to their region’s air quality. Indeed, there are examples of plants replacing relatively clean methods with less expensive, more polluting, options that were approved because local air quality had improved.<sup>20</sup>

There is reason to believe the CWS caused substantial variation in the stringency of environmental regulation. Nearly 40% of the most populated regions of the country had

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<sup>16</sup>Provincial regulations played a similar role to the State Implementation Plans submitted by each US state to the EPA under the Clean Air Act. However, the CWS allowed provinces to adopt a wide number of instruments to achieve each standard, which we discuss in the online appendix (see Section C).

<sup>17</sup>In Section C, we provide a full overview of the relevant provincial policies in place.

<sup>18</sup>For example, in Ontario facilities wishing to make even small changes, such as the replacement of natural gas burners or the installation of new generators, had to show they could do so without violating the CWS and provincial air quality regulations. All facilities, regardless of whether changes were being made, also had to show annual compliance with provincial air quality regulation. From 2000 to 2010, at least 2,800 permit applications cited particulate matter or nitrogen oxide emissions.

<sup>19</sup>For an example of a permit requiring a production limit, see <https://www.accessenvironment.ene.gov.on.ca/instruments/2000-9GFRTP-14.pdf>. For an example of a permit stipulating a particulate matter abatement device (a baghouse), see <https://www.accessenvironment.ene.gov.on.ca/instruments/7222-97RNJW-14.pdf>.

<sup>20</sup>For an example in which a low nitrogen oxide natural gas burner was replaced with a higher polluting option see <https://www.ebr.gov.on.ca/ERS-WEB-External/displaynoticecontent.do?noticeId=MTAONDQ1&statusId=MTU20TQ0&language=en>.

their regulatory status change during the period over which the CWS was in force. The regulations also appear to be associated with large changes in air quality. On average,  $PM_{2.5}$  concentrations in affected regions fell by approximately 20%, while  $O_3$  concentrations in affected regions fell by approximately 9%.<sup>21</sup>

The CWS also targeted two different pollutants, each facing different technical constraints on the abatement options available to facilities. The first pollutant,  $NO_x$ , is primarily caused by the combustion of fossil fuels. Facilities can reduce  $NO_x$  emissions at a relatively low cost by adopting efficient combustion processes<sup>22</sup> or by adopting relatively low-cost low- $NO_x$  emissions burners (see, e.g. Environment Canada (2002, p.xiii), Canadian Council of Ministers of the Environment (1998), or Environmental Protection Agency (1999a)). Indeed, Canada’s  $NO_x$  emissions guidelines for industrial boilers and heaters “are based on proven compatibility with efficient combustion operation and the use of cost-effective technology such as low  $NO_x$  burners” (Canadian Council of Ministers of the Environment, 1998, p. 3). In contrast, the second pollutant,  $PM_{2.5}$  is caused by the combustion of fossil fuels, chemical reactions, wear and tear on machinery, and the processing of lumber. Reducing  $PM_{2.5}$  emissions typically requires installing a large filtration system, such as a baghouse or electrostatic precipitator, that carries a large fixed cost (see, e.g., Environment Canada (2002, p.xiii and xvii) and Environmental Protection Agency (1998, 2002, 1999b)).<sup>23</sup>

## 4 Theory

As we described above, the CWS regulations required plants to either adopt technical changes to meet industry best practices, or reduce the activity responsible for generating the regulated pollutant. Given this regulatory structure, we develop a simple theoretical framework featuring process, reallocation, and selection effects in response to environmental regulation to help guide our empirical analysis.

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<sup>21</sup>In the online appendix (Section B.3) we present descriptive evidence of this improvement in air quality.

<sup>22</sup>This may entail either changing the temperature or the fuel-oxygen ratio at which combustion occurs.

<sup>23</sup>As a reference, engineering abatement cost estimates are between \$1,000 to \$20,000 per ton of  $PM_{2.5}$  using an electrostatic precipitator, between \$2,000 to \$100,000 per ton of  $PM_{2.5}$  using a baghouse, and between \$200 to \$1,000 per ton  $NO_x$  (low- $NO_x$  burner) (Environmental Protection Agency, 2006).



Our model is based on a closed economy version of the Melitz (2003) model in which heterogeneous plants emit pollution as a byproduct of production, and face regulations similar to those imposed under the CWS. This simple, stylized structure is intended to capture three key features of our regulatory setting. First, it features differences in productivity across plants, as recent theoretical work has emphasized the importance of these differences in determining the effects of environmental regulation (e.g. Konishi and Tarui (2015) or Anouliès (2017)). Second, it allows for endogenous technology adoption by plants following the approach developed by Bustos (2011).<sup>24</sup> This means plants differ in their technology choices even in the absence of regulation, allowing us to capture the fact that pre-regulation technology differences were used to inform the technical changes required under the CWS. Finally, our model allows for differences in abatement costs across pollutants, meaning we are able to examine how these costs affect a plant’s response to regulation.

Below, we outline the features of the model, describe its solution and highlight its key empirical predictions. For the sake of brevity, we relegate the details of the model’s solution and the derivations of the comparative statics underlying the empirical predictions to the online appendix (see Section A).

## 4.1 Setup

We consider an economy comprised of  $L$  identical consumers, each endowed with a single unit of labor. Labor is supplied inelastically and used to produce differentiated products in a single industry. Production also creates pollution as a byproduct, and this harms consumers, lowering their utility. For convenience, in what follows, we let wages be the numeraire.

The representative consumer derives utility from the consumption of goods and disutility from aggregate pollution according to  $U = [\int_0^M q(\omega)^\rho d\omega]^{1/\rho} - h(Z)$ , where  $q(\omega)$  denotes consumption of good  $\omega$ , and  $M$  denotes the measure of varieties available in the economy. It is assumed consumers ignore pollution when making their consumption decisions. As a

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<sup>24</sup>This approach has been used previously to link technological upgrading to changes in pollution levels. See, for example, Batrakova and Davies (2012), Forslid et al. (2014) or Cherniwchan et al. (2017).

result, the demand for variety  $\omega$  is given by  $q(\omega) = IP^{\sigma-1}p(\omega)^{-\sigma}$ , where  $I$  denotes consumer income,  $P = [\int_0^M p(\omega)^{1-\sigma} d\omega]^{1/(1-\sigma)}$  is the economy's price index, and  $\sigma = 1/[1 - \rho] > 1$  is the elasticity of substitution between goods.

The supply side of the economy features monopolistic competition and free entry, meaning each firm in the economy produces a unique variety. To enter, firms pay a fixed entry cost  $f_\epsilon$ , and upon entry, draw a productivity level  $\varphi$  from a common distribution  $G(\varphi)$ .<sup>25</sup> Based on the realization of  $\varphi$ , firms decide whether to exit or stay in the market, and conditional on staying, how much to produce and what technology to use in production.

Upon entering, firms are able to produce output  $x$  using a business-as-usual technology (labeled  $b$ ) that features increasing returns to scale. With this technology, the total costs of production are given by  $C_b = c_b^l(\varphi)x + f$ , where  $c_b^l(\varphi)$  is the marginal cost of producing  $x$  with technology  $b$  under regulatory regime  $l$ , which we describe further below. Moreover, the business-as-usual technology has an emission intensity of  $e_b = \kappa/\varphi$ , meaning the production of  $x$  creates  $z_b(\varphi) = [\kappa x]/\varphi$  units of pollution.

While firms are endowed with the business-as-usual technology, they can choose to upgrade their technology along one of two dimensions. First, they can adopt a state-of-the-art technology (labeled  $s$ ) that boosts labor productivity<sup>26</sup>, lowering marginal costs by a factor  $1/\alpha$ . The state-of-the-art technology also produces fewer emissions per unit of output. In this case, the emission intensity of production is given by  $e_s = \kappa/[\gamma\varphi]$ , where  $\gamma > 1$ , so total pollution from production is  $z_s(\varphi) = [\kappa x]/[\gamma\varphi]$ . Adopting the state-of-the-art technology requires that firms pay an additional fixed cost  $f_s$ , meaning total production costs with the state-of-the-art technology are given by  $C_s = c_s^l(\varphi)x + f + f_s$ , where  $c_s^l(\varphi)$  is the marginal cost of producing  $x$  with the state-of-the-art technology in regime  $l$ .

The second option for firms is to retrofit their business-as-usual technology so that it has the same emission intensity as the state-of-the-art technology. As such, the emission intensity of a retrofitted plant ( $e_r$ ) is also  $\kappa/[\gamma\varphi]$ , meaning the total level of pollution generated

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<sup>25</sup>For simplicity,  $G(\varphi)$  is assumed to be a type-I Pareto distribution such that  $G(\varphi) = 1 - \varphi^{-k}$ .

<sup>26</sup>For example, by increasing fuel efficiency, as is the case with low-NO<sub>x</sub> burners.

by production is  $z_r(\varphi) = [\kappa x]/[\gamma\varphi]$ . Retrofitting also requires firms to pay a fixed cost ( $f_r$ ). However, retrofitting does not affect labor productivity, meaning it is less costly than adopting the state-of-the-art technology, so  $f_r < f_s$ . The total costs of production for a retrofitted plant are given by  $C_r = c_r^l(\varphi)x + f + f_r$ , where  $c_r^l(\varphi)$  is the marginal cost of producing  $x$  in regulatory regime  $l$  with the retrofitted technology.

## 4.2 The No-Regulation Equilibrium

Our interest is in understanding the effects of imposing the regulatory structure created by the CWS. Hence, we begin by considering a no regulation regime (labeled  $n$ ) in which pollution is not regulated. This means labor costs are the only variable costs of production, so  $c_b^n(\varphi) = c_r^n(\varphi) = 1/\varphi$  and  $c_s^n(\varphi) = 1/[\alpha\varphi]$ .

A firm that has drawn a productivity level maximizes profits by deciding whether to stay in the market, and if they stay, choosing how much to produce and what technology to use. Given the structure of consumer preferences, this implies that producing firms set prices at a constant mark-up over marginal costs. Hence, in the absence of regulation, firms that employ business-as-usual and retrofitted technologies charge the same price:  $p_b^n(\varphi) = p_r^n(\varphi) = 1/[\rho\varphi]$ . If, instead, a firm employs the state-of-the-art technology, it charges  $p_s^n(\varphi) = 1/[\rho\alpha\varphi]$ .

Firms choose between the three available technologies to maximize profits. If firms employ the business-as-usual technology, profits are given by  $\pi_b^n = \frac{1}{\sigma}I [P\rho]^{\sigma-1} \varphi^{\sigma-1} - f$ . Profits from employing the retrofitted technology are  $\pi_r^n = \frac{1}{\sigma}I [P\rho]^{\sigma-1} \varphi^{\sigma-1} - [f + f_r]$ . Finally, profits from choosing the state-of-the-art technology are given by  $\pi_s^n = \frac{1}{\sigma}I [P\rho]^{\sigma-1} \varphi^{\sigma-1} \alpha^{\sigma-1} - [f + f_s]$ .

Lastly, note that conditional on entering and paying the fixed cost  $f_e$ , in expectation firms must earn zero profits. Using this condition solves for all endogenous variables, including industry prices, firm exit, and technology choices. The model's full solution is presented in an online appendix (see Section A).

The exit and technology choices made by firms are highlighted in Figure 2, which depicts the profits associated with adopting each technology as a function of firm productivity<sup>27</sup>.

<sup>27</sup>To linearize this figure, we show profits as a function of  $\varphi^{\sigma-1}$ , not  $\varphi$ .

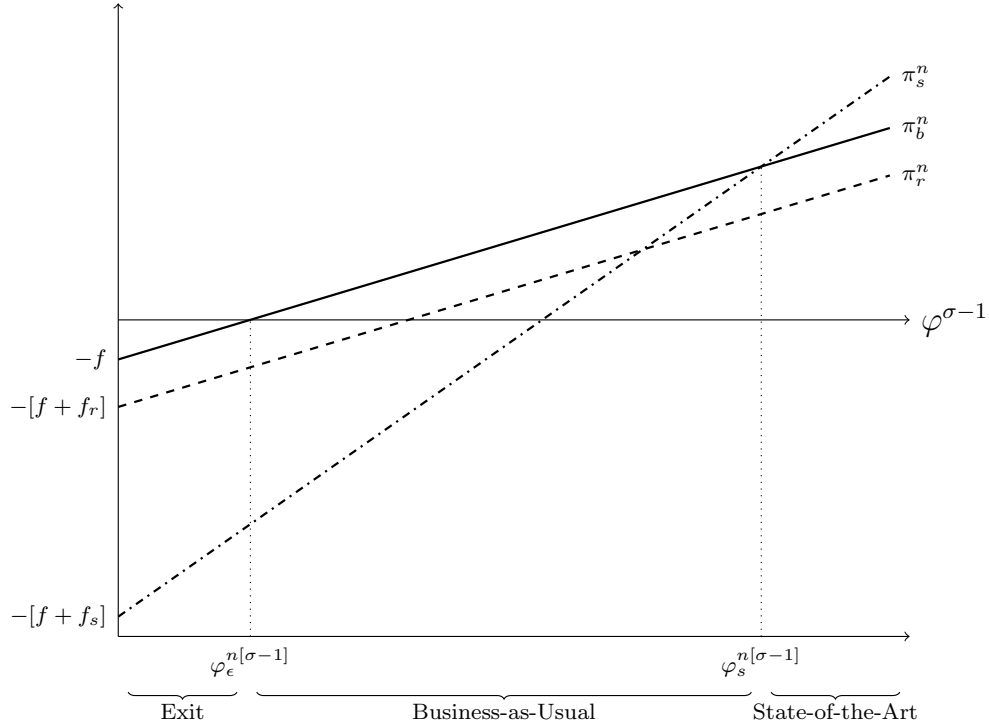


Figure 2: Technology Choices without Environmental Regulation

As the figure shows, for productivity levels below  $\varphi_\epsilon^n$  it is unprofitable for a firm to operate using any technology. Hence if a firm has a  $\varphi$  less than  $\varphi_\epsilon^n$ , it exits the market. If firms stay in the market, they choose the technology that yields the highest profit. This means that if a firm has a productivity level  $\varphi \in \{\varphi_\epsilon^n, \varphi_s^n\}$ , then it will produce using the business-as-usual technology. However, if a firm has a productivity level  $\varphi > \varphi_s^n$ , then the reduction in variable cost created by adopting the state-of-the-art technology is great enough to justify the fixed cost of adoption, meaning that these firms adopt the state-of-the-art technology.

It is also worth noting that, as Figure 2 shows, firms never choose the retrofit technology in the absence of regulation. If firms adopt the retrofit technology, the emission intensity of production falls, but this has no effect on the variable costs of production because pollution is not costly to the firm if it is not regulated. As a result, retrofitting simply lowers firm profits below what can be obtained using the business-as-usual technology by increasing the average costs of production.

### 4.3 The Effects of Environmental Regulation

To show the intuition behind the process, reallocation, and selection effects caused by a CWS-style regulation, we now consider the effects of adopting environmental regulations similar to those imposed under the CWS. We do so in a partial equilibrium context in which industry prices are held fixed at the no-regulation level. In the online appendix we solve for the full effects of regulation (see Section A).

In this regime (labeled *cws*), the government regulates pollution using a two-part regulatory rule. If a firm uses a clean production process (either the state-of-the-art technology or the retrofitted technology), it is not subject to regulation because it is operating with the lowest emission intensity currently available. As a result, the marginal costs of production for these firms are unaffected by regulation, meaning  $c_r^{cws}(\varphi) = c_r^n(\varphi) = 1/\varphi$  and  $c_s^{cws}(\varphi) = c_s^n(\varphi) = 1/[\alpha\varphi]$ . In contrast, a firm that employs a dirty production process (the business-as-usual technology) is subject to a regulatory constraint in the form of a tax  $\tau$  on each unit of pollution emitted.<sup>28</sup> Hence, regulation raises the marginal costs of production for these firms, meaning  $c_b^n(\varphi) < c_b^{cws}(\varphi) = [1 + \kappa\tau]/\varphi$ .

Given that firm prices feature a constant markup, this increase in marginal costs raises the price of output for firms producing with the business-as-usual technology. That is,  $p_b^n(\varphi) < p_b^{cws}(\varphi) = [1 + \kappa\tau]/[\rho\varphi]$ , and profits are  $\pi_b^{cws} = \frac{1}{\sigma}I [P\rho]^{\sigma-1} \varphi^{\sigma-1} [\frac{1}{1+\kappa\tau}]^{\sigma-1} - f$ . This means, holding industry prices fixed, the profit from using the business-as-usual technology falls for any level of productivity  $\varphi$ .

This partial equilibrium outcome is depicted in Figure 3, which displays the technological choices made by firms when faced with CWS-type regulation holding industry prices ( $P$ ) fixed. As the figure shows, a reduction in the profitability of using the business-as-usual technology increases the productivity level for which it is unprofitable to enter the market from  $\varphi_\epsilon^n$  to  $\varphi_\epsilon^{cws}$ . As such, firms with  $\varphi \in \{\varphi_\epsilon^n, \varphi_\epsilon^{cws}\}$  exit in response to regulation. Moreover,

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<sup>28</sup>Alternatively, we could impose a more realistic regulatory constraint, such as a production cap, without substantively affecting the results. We use a tax for analytical tractability.

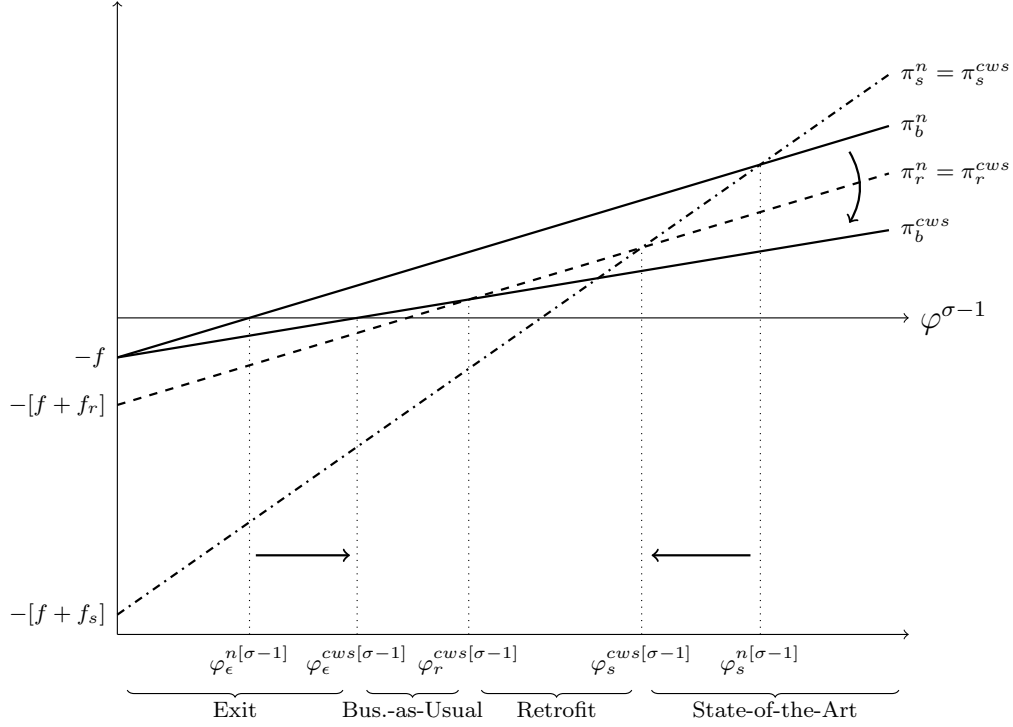


Figure 3: Technology Choices with CWS-Type Environmental Regulation

given the design of regulation, profits from using the retrofitted or state-of-the-art technology do not change. This means the increase in the variable cost of the business-as-usual technology makes technology upgrading a profitable alternative for some firms. As depicted, it is profit maximizing for firms with productivity  $\varphi \in \{\varphi_r^{cws}, \varphi_s^n\}$  to upgrade their technology in response to regulation. For these firms, the benefit of avoided tax payments outweighs the increase in fixed production costs. Similarly, firms with productivity  $\varphi \in \{\varphi_c^{cws}, \varphi_s^n\}$  adopt the state-of-the-art technology in response to regulation because it is now profit maximizing to do so.

While Figure 3 clearly highlights how environmental regulations create selection effects by causing firms to exit in response to regulation, the reallocation and process effects are not readily apparent from the figure. As such, we further explore how regulations affect firm revenues and emission intensities to make these additional effects clear.

These effects for firms that survive regulation (those with  $\varphi > \varphi_\epsilon^{cws}$ ) are displayed in Figure 4. This figure depicts the effects of environmental regulation on firm revenues (Panel

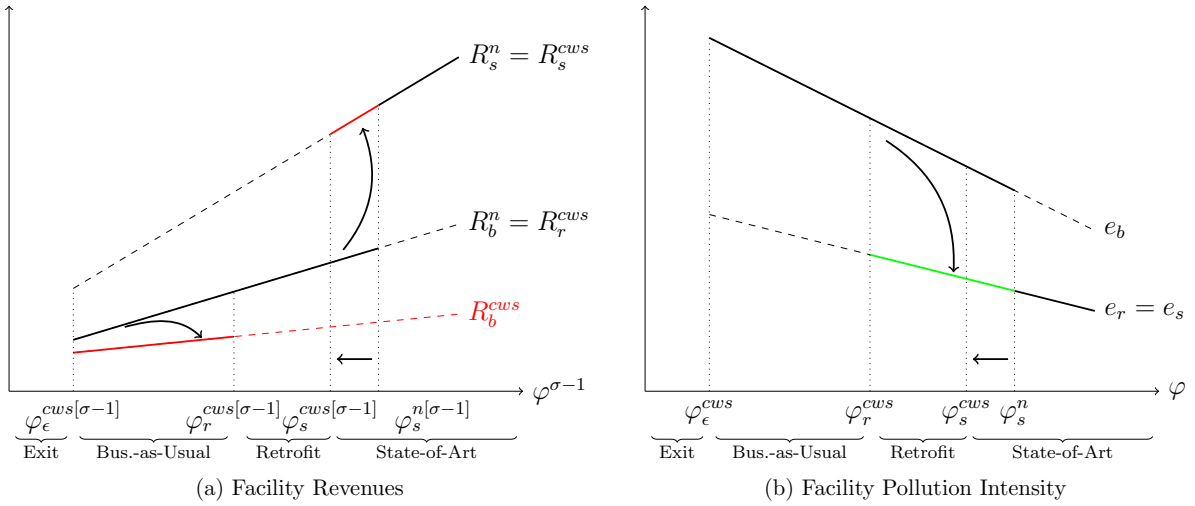


Figure 4: Revenues and Pollution Intensity for Surviving Firms with CWS-Type Environmental Regulation

(a)) and emission intensity (Panel (b)) holding industry prices ( $P$ ) fixed. Both panels show that the most productive firms, with productivity  $\varphi > \varphi_s^n$ , are unaffected by regulation, as they use a clean production technology in either regime. In contrast, regulation causes the least productive firms, with productivity  $\varphi < \varphi_r^{cws}$ , to produce less, but with the same pollution intensity. This is because they use the business-as-usual technology under either regime, and variable costs rise under regulation. Lastly, pollution intensity falls for the firms in the middle of the productivity distribution, with productivity  $\varphi \in \{\varphi_r^{cws}, \varphi_s^n\}$ . This occurs because they either retrofit or adopt state-of-the-art technology. The retrofitting firms experience no change in output, as their variable costs do not change relative to business-as-usual. However, output increases for the new state-of-the-art adopters, as both their pollution intensity and variable costs fall.

In the online appendix (see Section A) we show the full effects of a CWS-type regulation in which we allow industry prices to respond. In particular, it can be shown that regulation causes the following effects

1. If  $f_r > 0$ , then some firms exit and average revenues fall.
2. Revenues fall for firms using the business-as-usual technology. These are the least

productive surviving firms.

3. There is an ambiguous effect on revenues for all other surviving firms, but this change in revenues is bounded from below by the reduction in revenues for the business-as-usual technology firms.
4. Pollution intensity falls for all firms that retrofit or upgrade to state-of-the-art technology. These firms are in the middle of the productivity distribution.
5. There is no change in pollution intensity for firms that do not change their technology. These are at the top and bottom of the firm productivity distribution.

In addition to the above results, it can be shown that the fixed cost to retrofit ( $f_r$ ) plays an important role in determining the channels through which regulation causes an industry to clean-up. In the online appendix, we show decreasing  $f_r$  increases the measure of firms that abate in response to regulation and reduces the measure of firms that exit in response to regulation<sup>29</sup>. Thus, when  $f_r$  is very small, regulation should primarily cause an industry to clean-up through process effects. Otherwise, reallocation and selection effects will play an important role in an industry's clean-up.

## 5 Empirics

Our theoretical model provides a number of clear predictions as to how facilities would respond to the CWS. Taken together, these results imply that when the fixed costs of abatement are high, environmental regulations should primarily reduce industry emission intensity via reallocation and selection effects. In contrast, when the fixed costs of abatement are low, the industry clean-up should be driven by process effects. In this section, we explore those plant-level predictions empirically by estimating the CWS' effect on plant pollution intensity, production, and exit. We use the resulting estimates to determine how the process, reallocation, and selection effects created by the CWS have contributed to the clean-up of

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<sup>29</sup>This last result requires restricting the size of  $f_s$ .



Canadian manufacturing.

## 5.1 Research Design

Given that certain industries and regions were the primary focus of regulation, we identify the causal effects of the CWS by measuring its effects on manufacturing plants that were both located in dirty CMAs and operating in a targeted industry. We do so by using a triple-difference research design that exploits the variation in CWS regulation across time, industries and regions.<sup>30</sup>

Our design begins by comparing the average outcomes of plants in regulated CMAs while regulated (i.e. while violating one of the standards) to their average outcomes while unregulated. This allows us to control for any unobserved time-invariant industry, CMA or plant characteristics that would affect plant pollution emissions. Moreover, in the absence of any other shocks, this comparison would identify the average causal effect of the CWS on pollution emissions. Yet, such absence is unlikely; there is strong reason to believe that a simple before-and-after comparison of affected plants could also capture the effects of regional, industry, or aggregate economic shocks.<sup>31</sup> We discuss each in turn.

To address possible confounding regional shocks, we exploit the fact that each CMA contains manufacturing plants in both regulated and unregulated industries. This allows us to utilize the unregulated plants in a given CMA as a counterfactual for regulated plants in the same location. This will capture the effects of any unobserved time-varying provincial or CMA-level heterogeneity, such as changes in regional economic conditions or concurrent

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<sup>30</sup>It is worth mentioning that, while plants in dirty CMAs that were operating in a targeted industry were subject to more strict regulation and enforcement, it is possible that other plants in the country were regulated to some degree as a result of the CWS. If this is the case, then our research design produces estimates that give a lower bound on the CWS' effects on the manufacturing sector.

<sup>31</sup>Note that this raises an issue with identifying the effects of any provincial environmental regulation in Canada: who gets regulated and when are unlikely to be randomly assigned if left entirely up to regional authorities. The CWS allows us to overcome this concern by providing within-province variation in regulatory stringency. As a result, the CWS can be thought of as an instrument that allows us to identify the effects of environmental regulation on a select group of plants: those that are regulated because they are in a CMA with air quality above one of the CWS standards. Adopting the language used in the treatment effect literature, these plants are called compliers, and the CWS provides a local average treatment effect of environmental regulation for these plants.

changes in provincial policy that would otherwise confound the effects of the CWS.

The simple before-and-after comparison could also be contaminated as a result of economic shocks that affect individual industries, which could arise due to the effects of increased foreign competition created by international trade, or by revisions to federal policies that target certain sectors. To address these issues we exploit cross-CMA variation in regulation, and utilize the fact that in any particular industry, only plants in areas with poor air quality were subject to stringent environmental policy. This allows us to use the average outcomes from plants in a targeted industry in an unregulated CMA as a counterfactual for the average outcomes of plants from that industry that are located in a regulated CMA. This captures the effects of any industry specific shocks.

The cross-industry and cross-CMA variation in the stringency of environmental regulation also allows us to compare the average outcomes from regulated plants with the average outcomes from plants in non-targeted industries located in unregulated CMAs. These non-targeted plants in unregulated CMAs are not regulated under the CWS, and as such, capture the underlying aggregate trend in pollution emissions. This allows us to control for country-wide shocks, such as aggregate technological change, changes in national policy, or changes in aggregate expenditure due to the 2008 recession.

We estimate the effect of regulation on plant outcomes using the following equation:

$$y_{pict} = \beta_{PM}T_{ict}^{PM} + \beta_{O3}T_{ict}^{O3} + \rho_p + \xi_{ct} + \lambda_{it} + \varepsilon_{pict}, \quad (3)$$

where  $y_{pict}$  is the natural log of the dependent variable of interest (pollution, sales, etc), at plant  $p$ , in industry  $i$ , located in CMA  $c$ , at time  $t$ .<sup>32</sup>  $T_{ict}^j$  is an indicator of treatment for standard  $j$ , and takes a value of one for plants that are in industries targeted by the CWS for years in which their CMA exceeds threshold  $j$ .

Equation (3) also includes plant ( $\rho_p$ ), CMA-year ( $\xi_{ct}$ ), industry-year<sup>33</sup> ( $\lambda_{it}$ ) fixed effects

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<sup>32</sup>We employ the natural log transformation to address the skewness in the distribution of each variable.

<sup>33</sup>The CWS defined the targeted industries at the 3- or 4-digit North American Industry Classification System (NAICS) level. We create an industry indicator that corresponds to either the 3- or 4-digit NAICS

and an error term ( $\varepsilon_{pict}$ ). The plant fixed effects account for any unobserved plant-specific heterogeneity, as well as time-invariant industry and CMA characteristics. The CMA-year fixed effects capture any region specific shocks. The industry-year fixed effects account for any industry-wide events. Finally, the error term captures idiosyncratic changes in outcomes across plants.

The coefficients of interest in Equation (3) are  $\beta_{PM}$  and  $\beta_{O_3}$ .  $\beta_{PM}$  measures the average percentage change in outcomes for plants affected by the particulate matter standard relative to those that are not. Similarly,  $\beta_{O_3}$  measures the average percentage change in outcomes for plants affected by the ozone standard relative to those that are not. These coefficients are identified from within plant comparisons over time.<sup>34,35</sup>

Changes in plant regulatory status must be plausibly exogenous for this research design to credibly identify the effects of the CWS. There is strong reason to believe this is the case, as variation in regional air quality determines assignment to treatment. As with the CAAs in the US, regulations are determined by a nationally set air quality threshold, meaning that they are unrelated to differences in local tastes, characteristics or economic conditions (Greenstone, 2002). Moreover,  $PM_{2.5}$  and  $O_3$  are capable of being transported long distances by prevailing wind patterns, meaning that ambient pollution levels in Canada do not solely reflect local economic activity.<sup>36</sup> Indeed, transboundary pollution from the US appears to have been a concern to the federal government over this period. Shortly after the CWS was developed, Canada and the US signed an air quality agreement to address

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level. All 3-digit industries that contain targeted industries defined at the 4-digit level are grouped at the 4-digit level. The remaining industries are grouped at the 3-digit level.

<sup>34</sup>It is worth noting that regulatory enforcement is applied more stringently to plants that are in regions that currently violate a standard, and that if a region's air quality improves sufficiently, regulation will become less strict. As a result, the variation we are using is from plants in regions that cross one of the CWS thresholds over our sample period. Over our sample, some of these plants move from regulated to unregulated status. This means if plants make changes to production processes that result in permanently lower emissions, then our research design will underestimate the effects of the CWS. As our goal is to be conservative in assessing the effects of the CWS, we view this as an acceptable trade-off.

<sup>35</sup>We are able to separately estimate the effect of both standards because there are cities that exceed one, both, or none of the standards. Of all treated CMA-years in our sample, approximately 80% violated one (and only one) standard, while the remaining 20% violated both standards.

<sup>36</sup>For evidence of how wind patterns shape ambient pollution concentrations in Canada, see, for example, Brankov et al. (2003) or Johnson et al. (2007).

transboundary pollution, Canada’s contribution to which involved ensuring the CWS was met (International Joint Commission, 2002). The transboundary nature of pollution means it is unlikely a single plant can directly manipulate their treatment status.

## 5.2 Data and Measurement

Our analysis relies on a unique confidential micro-dataset that contains information on the  $PM_{2.5}$  and  $NO_X$  emission intensity of Canadian manufacturing plants. This dataset was created by merging data from two existing sources: the National Pollutant Release Inventory (NPRI) and the Annual Survey of Manufactures (ASM).<sup>37</sup> The NPRI contains information on the emissions of various pollutants from Canadian manufacturing plants. By law, any facility that emits one of the covered pollutants above a minimum threshold must report to the NPRI. The ASM was used as Statistics Canada’s manufacturing census until 2012, and it provides longitudinal information on plant sales, production costs, employment, and other plant characteristics for the majority of manufacturing plants in Canada.<sup>38</sup> Plants in these two datasets were linked by Statistics Canada, allowing us to create a longitudinal dataset containing information on  $PM_{2.5}$  and  $NO_X$  emission intensity as well as other plant characteristics over the period 2004-2010. Additional details on each data source and the construction of the dataset used in our analysis are given in the online appendix (see Section B.1).

Descriptive statistics for the key variables that we employ are reported in Table 2. Each column in Table 2 presents averages and standard deviations for a different sample corresponding to emitters of each pollutant. The first column corresponds to the set of plants that emit  $PM_{2.5}$ , the second column shows statistics for plants that emit  $NO_X$ , and the final column of the table reports summary statistics for the entire sample of plants in the ASM. The statistics in columns one and two are weighted to account for potential sample bias induced by the linking procedure used to match plants across datasets (see Section B.1 of

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<sup>37</sup>This dataset was created through a collaboration between the Economics and Environmental Policy Research Network, Environment and Climate Change Canada, and Statistics Canada.

<sup>38</sup>The ASM was discontinued in 2012 and was replaced with a repeated cross-section survey.

Table 2: Summary Statistics

	PM <sub>2.5</sub> (1)	NO <sub>x</sub> (2)	Full ASM (3)
Emissions (tonnes)	25.83 (103.43)	262.14 (646.14)	
Sales (\$1 mill.)	194.62 (890.55)	342.15 (1,305.95)	11.12 (123.56)
Value Added (\$1 mill.)	62.46 (241.82)	102.11 (346.27)	4.29 (34.34)
Employment	280.11 (634.85)	382.03 (868.68)	35.69 (125.27)
VA/Worker (\$1,000)	200.18 (243.63)	265.41 (297.06)	84.78 (166.11)
<i>N</i>	6501	3012	309541

*Notes:* Table reports averages and standard deviations of key variables examined in the main analysis. Each column reports the summary statistics for a different sample. Column (1) is the sample of PM<sub>2.5</sub> polluters, column (2) is the sample of NO<sub>x</sub> polluters, and the final column reports plant characteristics for the entire manufacturing sector. Statistics in columns 1 and 2 are weighted to account for potential sample bias induced by the match of the NPRI and ASM. All monetary values are reported in 2007 Canadian dollars.

the online appendix for further details). Each sample is an unbalanced panel; the sample for PM<sub>2.5</sub> contains 6501 plant-year observations and the sample for NO<sub>x</sub> contains 3012 plant-year observations. For comparison, the final column of the table reports summary statistics for the entire sample of plants in the ASM.

The summary statistics reported in Table 2 suggests that there are systematic differences in plants that emit different types of pollutants. For example, on average, the NO<sub>x</sub> sample emitted more pollution, produced more output, had higher employment levels, and had higher labour-productivity levels than the PM<sub>2.5</sub> sample. This potentially reflects substantial differences in how pollution is produced and abated, given that pollutants are typically produced by a few industries (Greenstone, 2002), and there are substantial differences in the fixed costs of abatement across pollutants (Canadian Council of Ministers of the Environment, 1998; Environment Canada, 2002).

Table 2 also shows that polluters represent the largest plants in the manufacturing sector. Relative to the full manufacturing sector, the sample of plants that emit either PM<sub>2.5</sub> or NO<sub>x</sub>

sell more goods (15 to 30 times on average), employ more workers (7 to 10 times), and have higher value added per worker (2 to 3 times) than the average manufacturing plant.<sup>39</sup> This is, in part, due to the reporting requirements for the NPRI; by law, plants only report if they emit at least one covered pollutant above a minimum threshold level and employ at least 10 individuals or operate an on-site generator (Environment and Climate Change Canada, 2016c). While this means we systematically exclude small facilities, our analysis covers plants that account for the majority of manufacturing pollution in Canada.<sup>40</sup>

### 5.2.1 Determining Regulatory Status under the CWS

Our analysis also requires determining which CMAs were affected by the CWS. To do so, we use local air quality information from Environment and Climate Change Canada’s National Air Pollution Surveillance Program (NAPS), which provides data on hourly monitor-level  $PM_{2.5}$  and  $O_3$  concentrations. We use this data to construct CMA-level pollution concentration measures for each year in our sample, where the measures computed are those associated with each standard.<sup>41</sup>

The variation in regulatory status created by changes in ambient air quality is illustrated in Figure 5, which shows the CMAs that changed regulatory status for the  $PM_{2.5}$  and  $O_3$  standards. In Figure 5, the red CMAs changed status under both the  $PM_{2.5}$  and  $O_3$  standards, the orange CMAs only changed status for the  $PM_{2.5}$  standard, the yellow CMAs only changed status for the  $O_3$  standard, and the green CMAs didn’t change status under either standard. As the figure shows, there was substantial variation in which CMAs changed their regulatory status over the 2000-2010 period. Of the 149 CMAs in our sample, 23% changed status under the  $PM_{2.5}$  standard, 26% changed status under the  $O_3$  standard, 11% changed status under both standards, and 60% never changed regulatory status.

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<sup>39</sup>This is still true when we consider medians instead of averages.

<sup>40</sup>In addition, the majority of  $PM_{2.5}$  and  $NO_x$  emitters use an on-site generator or boiler, which means the the employment thresholds are likely not relevant for most of these plants.

<sup>41</sup>For more details on the construction of the hourly pollution concentration measures, see Section B.1 in the online appendix.

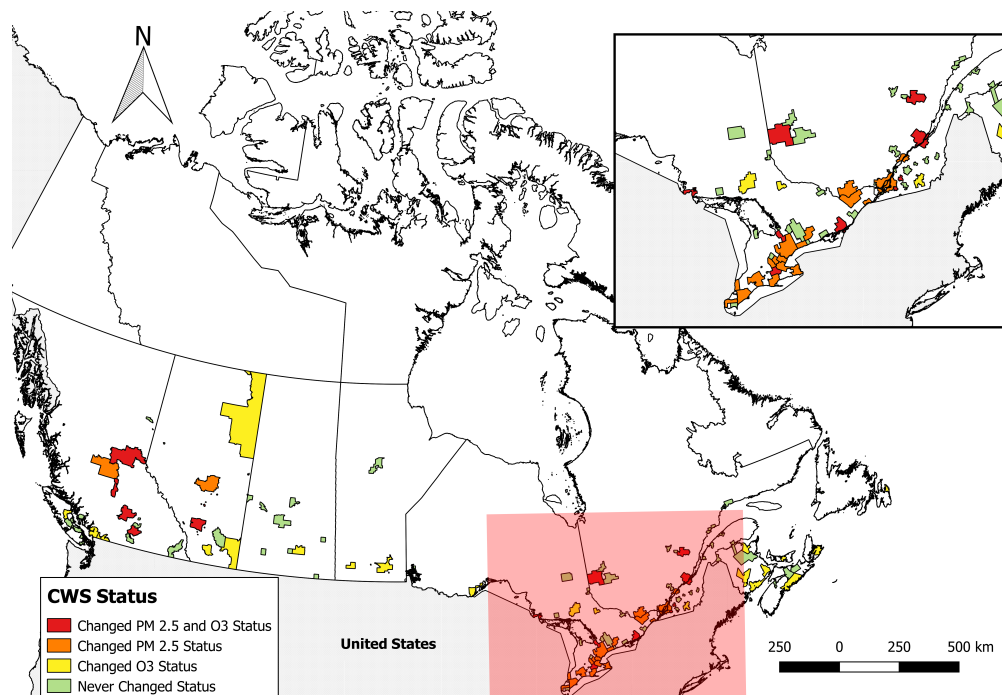


Figure 5: Regulatory Status Changes under the CWS

Notes: Figure depicts  $PM_{2.5}$  and  $O_3$  standard status changes for each CMA from 2000 to 2010. Red CMAs changed status under both the  $PM_{2.5}$  and  $O_3$  standards. Orange CMAs only changed status for the  $PM_{2.5}$  standard. Yellow CMAs only changed status for the  $O_3$  standard. Green CMAs didn't change status under either standard. The mainland United States is shown in light gray. Part of the northern Canadian Territories are trimmed for scale. The inset shows detail on the most densely populated area of Canada, colored in light red on the main map.

## 5.3 Empirical Results

### 5.3.1 The CWS and Plant Pollution Emissions

We begin our analysis by estimating the effects of the CWS on the level of pollution emitted by affected Canadian manufacturing plants.<sup>42</sup> We start here for two reasons. First, it provides some indication as to the effectiveness of the CWS; if the regulations were responsible for the reduction in pollution levels documented in Section 2, then we should observe reductions in the emissions of targeted pollutants as a result of the CWS. Second, this also provides us with a means to assess the external validity of our results. As we discussed above, there is little evidence as to the effects of environmental regulation on the emission

<sup>42</sup>A related, but distinct question, is to ask what the CWS did to regional air quality. While this is beyond the scope of this paper, in the online appendix we provide descriptive evidence that air quality improved in Canada over this period (see Section B.3).

intensity of manufacturing plants. Focusing on pollution levels allows us to directly compare the effects of the CWS with the effects of other environmental policies.

Table 3 reports our estimates of the effects of the CWS on plant pollution emissions. We estimate Equation (3) for two samples of plants. The first sample (in Panel A) are plants that emit  $\text{PM}_{2.5}$ , which is the main contributor to  $\text{PM}_{2.5}$  pollution. The second sample (in Panel B) are plants that emit  $\text{NO}_x$ , which is the main contributor to  $\text{O}_3$  pollution.<sup>43</sup> The first column of each panel reports estimates from a version of Equation (3) that only includes the particulate matter standard. Similarly, the second column reports estimates from a specification that only includes the ozone standard. Finally, column (3) in each panel reports estimates from the specification given in Equation (3). The first row in each panel reports the effect of the  $\text{PM}_{2.5}$  standard ( $\beta_{\text{PM}}$  in Equation (3)); the second row shows the effect of the  $\text{O}_3$  standard ( $\beta_{\text{O}_3}$  in Equation (3)). The dependent variable in each of these regressions is the natural log of plant pollution emissions for the relevant pollutant. Each regression is weighted to correct for potential sample bias introduced by the procedure used to match plants in the NPRI with plants in the ASM.<sup>44</sup> In all cases, standard errors clustered at the CMA-industry level are reported in parentheses.

The estimates reported in Panel A of Table 3 indicate that the CWS particulate matter regulations led to statistically significant reductions in the emissions of both particulate matter and nitrogen oxide from affected plants. Our baseline estimates for  $\text{PM}_{2.5}$ , reported in column (3) of Panel A, indicate that the CWS particulate matter regulations are associated with a 15.1% reduction in emissions from affected plants. Our baseline estimates for  $\text{NO}_x$ , reported in column (6) of Panel B indicate that the ozone regulations are associated with 32.5% decrease in emissions from affected plants. The estimates reported in Panels

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<sup>43</sup>There are other pollutants that may also contribute to  $\text{PM}_{2.5}$  and  $\text{O}_3$  pollution, including volatile organic compounds and carbon monoxide. In the online appendix we examine the CWS' effects on the emissions of a number of other pollutants (see Section B.3).

<sup>44</sup>In brief, the potential bias happens because the probability of a successful match is positively correlated with a plant's size. If the effects of the CWS vary by plant-size, then relying on the matched data would produce biased estimates. Details on the weighting procedure used to address this can be found in Section B.1 of the online appendix.



Table 3: The Effects of the CWS on Plant Pollution Emissions

	Panel A: PM <sub>2.5</sub>			Panel B: NO <sub>x</sub>		
	(1)	(2)	(3)	(4)	(5)	(6)
PM <sub>2.5</sub> Standard	-0.149** (0.076)		-0.151** (0.076)	0.107 (0.070)		0.106 (0.069)
O <sub>3</sub> Standard		-0.105 (0.164)	-0.113 (0.164)		-0.327* (0.183)	-0.325* (0.179)
$R^2$	0.175	0.175	0.175	0.310	0.311	0.311
$N$	6501	6501	6501	3012	3012	3012

*Notes:* Table reports estimates of the effects of the CWS on plant pollution emissions. Each panel reports results for a different sample of emitters. Each column displays estimates from a different regression. In all cases, the dependent variable is the natural log of pollution emissions. The first row reports the effects of the PM<sub>2.5</sub> standard, and the second row reports the effects of the O<sub>3</sub> standard. All regressions include plant, industry-year and CMA-year fixed effects, and are weighted by the inverse of the match probability to control for potential match-induced sample bias. Standard errors are clustered by CMA-industry. Asterisks denote significance at the 1% (\*\*\*), 5% (\*\*), and 10% (\*) levels, respectively.

A and B also show no statistically significant cross-effects of either standard. That is, O<sub>3</sub> regulation did not significantly affect particulate matter emissions and PM regulation didn't significantly affect NO<sub>x</sub> emissions.

We view the results in Table 3 as an exploratory analysis of the CWS effects on plants. While the effect of O<sub>3</sub> on NO<sub>x</sub> emitters is only marginally significant, we call attention to these estimates because, as we show later in this section, the average effects of the CWS mask considerable heterogeneity across plants (see Section 5.3.3). Taken together, our evidence suggests O<sub>3</sub> regulation had a meaningful effect on manufacturing plants. Moreover, our theory suggests an average treatment effect is not very illustrative of how plants respond to a policy such as the CWS.

These results are consistent with the few existing estimates of the effects of air quality regulation on pollution emissions from manufacturing plants. For example, Fowlie et al. (2012) find California's NO<sub>x</sub> trading program reduced NO<sub>x</sub> emissions from regulated plants by between 10% and 30% over the period 1990-2005. Similarly, Gibson (2016) finds that Clean Air Act regulation reduced PM emissions from regulated plants by 38% between 1987 and 2014.<sup>45</sup> This suggests that the CWS had similar effects on pollution levels as the

<sup>45</sup>Greenstone (2003) also finds the US Clean Air Act regulation reduced the growth of particulate matter, lead, and VOC emissions from regulated plants by between 4% and 7% over the period 1987-1997.

environmental policies enacted elsewhere.

It is also worth noting that the estimates reported in Table 3 are not simply capturing pre-existing differences in trends across plants or the effects of a negative relationship between a CMA’s air quality and the production choices of the plants therein. Moreover, the estimates are robust to accounting for preemptive changes by regulated plants to avoid regulation, plants that account for a significant fraction of their CMA’s air pollution, differential trends across large and small emitters, and firm ownership. For the sake of brevity, these results are presented in Section B.2 of the online appendix.

### **5.3.2 The CWS and the Clean-up of Manufacturing**

Having determined the CWS significantly affected plant pollution levels, we now turn to estimating the process, reallocation, and selection effects caused by the CWS. To do this, we start by estimating the effect of the CWS on the emission intensity, output, and exit of affected manufacturing plants. We then use these estimates to determine the implied contribution of the CWS to the clean-up of Canadian manufacturing.

#### *Plant-Level Estimates*

In Table 4 we report our estimates of the CWS’ effect on the emission intensity of manufacturing plants. As in Table 3, panel A shows estimates of Equation (3) for the sample of plants that emit  $PM_{2.5}$  and panel B shows estimates for the  $NO_x$  emitters. In each panel, we report estimates from two separate regressions each with a different measure of emission intensity, as well as reproducing our baseline estimates of the CWS’ effects on plant pollution levels. The first column shows the CWS effect on pollution levels. In the second column, we show the CWS’ effects on emission intensity, measured as the ratio of emissions to total plant shipments (sales), given this is the measure of output used previously in the literature documenting the manufacturing clean-up. In the third column, we measure emission intensity as the ratio of emissions to value-added. Value added may provide a more accurate reflection of the level of productive activity that occurs in each plant (Cherniwchan et al., 2017). However, we focus on the estimates in the second column of each panel, as

Table 4: The Effects of the CWS on Plant Emission Intensity

	Panel A: PM <sub>2.5</sub>			Panel B: NO <sub>x</sub>		
	(1)	(2)	(3)	(4)	(5)	(6)
	PM <sub>2.5</sub>	PM <sub>2.5</sub> /Sales	PM <sub>2.5</sub> /VA	NO <sub>x</sub>	NO <sub>x</sub> /Sales	NO <sub>x</sub> /VA
PM <sub>2.5</sub> Std.	-0.151** (0.076)	-0.043 (0.096)	-0.013 (0.110)	0.106 (0.069)	0.127 (0.080)	0.333*** (0.098)
O <sub>3</sub> Std.	-0.113 (0.164)	-0.169 (0.169)	-0.224 (0.189)	-0.325* (0.179)	-0.286* (0.153)	-0.200 (0.157)
<i>R</i> <sup>2</sup>	0.175	0.161	0.156	0.311	0.281	0.260
<i>N</i>	6501	6501	6501	3012	3012	3012

*Notes:* Table reports estimates of the effects of the CWS on plant emission intensity for PM<sub>2.5</sub> (panel A) and NO<sub>x</sub> (panel B) emitting plants. For each group of emitters, the first column reports estimates from a regression of the CWS regulations on the natural log of plant emissions. The second column shows the CWS' effects on the plant emissions-sales ratio, while the third reports estimates from a regression of the regulations on the natural log of the emissions-value added ratio. In all cases, the first row reports the effects of PM<sub>2.5</sub> regulations, and the second row reports the effects of the O<sub>3</sub> regulations. All regressions include plant, industry-year, and CMA-year fixed effects, and are weighted by the inverse of the NPRI-ASM match probability to control for potential sample bias. Standard errors clustered by CMA-industry are reported in parentheses. Asterisks denote significance at the 1% (\*\*\*), 5% (\*\*), and 10% (\*) levels.

our goal is to contribute to a literature that uses shipments as its measure of output.<sup>46</sup> In both cases, the dependent variable is the natural log of emission intensity. The first row in each panel reports the effect of the PM<sub>2.5</sub> regulation ( $\beta_{PM}$  in Equation (3)) and the second row reports the effect of the O<sub>3</sub> regulation ( $\beta_{O_3}$  in Equation (3)). As before, each regression is weighted to correct for potential bias from matching the NPRI and ASM, while standard errors clustered by CMA-industry are reported in parentheses.

The estimates reported in Panel A of Table 4 indicate PM<sub>2.5</sub> regulation had little-to-no effect on the emission intensity of plants that emitted PM<sub>2.5</sub>, with an estimated coefficient in column (2) that is relatively small and statistically insignificant. In contrast, the CWS O<sub>3</sub> regulations appear to have caused a significant reduction in NO<sub>x</sub> pollution intensity. The estimate reported in column (5) of Table 4 indicate that the CWS ozone regulations are associated with a 28.6% decrease in the level of NO<sub>x</sub> emitted per unit of output.<sup>47</sup>

In addition, PM<sub>2.5</sub> regulation caused a significant increase in NO<sub>x</sub> intensity measured

<sup>46</sup>In addition, value added may be less precisely reported in our context. This occurs because Statistics Canada is able to use corporate tax filings to check annual shipment amounts reported by plants, but cannot do so for value added.

<sup>47</sup>Though there are no existing estimates to which we can directly compare, Martin et al. (2014) show a carbon tax levied in the United Kingdom led to an 18% drop in energy intensity at affected manufacturing plants.

in value added terms. These results are driven by a very small number of plants that are regulated by the  $\text{PM}_{2.5}$  standard and emit  $\text{NO}_X$ , but not  $\text{PM}_{2.5}$ . For these plants,  $\text{PM}_{2.5}$  regulation caused a large increase in  $\text{NO}_X$  emissions and decrease in value added. We do not probe these findings further, as they are driven by fewer than ten plants.<sup>48</sup>

$\text{PM}_{2.5}$  regulation caused a sizable reduction in plant  $\text{PM}_{2.5}$  emissions, but had no significant effect on plant emission intensities. On the other hand, the  $\text{O}_3$  standard caused a large reduction in  $\text{NO}_X$  emissions in both levels and pollution intensity. This implies the  $\text{PM}_{2.5}$  standard must have led to large decreases in output from affected plants, whereas the ozone standard had relatively minor effects on output. We confirm these conclusions by directly estimating Equation (3) on both sales and value added.

Estimates of the effects of the CWS on plant output are given in Table 5 for both  $\text{PM}_{2.5}$  (Panel A) and  $\text{NO}_X$  (Panel B) emitters, with each panel reporting estimates from two separate regressions. In the first, we measure output as the value of total plant shipments (sales), and in the second as value added. In both cases, the dependent variable is the natural log of output. The first row in each panel reports the effect of the  $\text{PM}_{2.5}$  regulation ( $\beta_{\text{PM}}$  in Equation (3)) and the second row reports the effect of the  $\text{O}_3$  regulation ( $\beta_{\text{O}_3}$  in Equation (3)). As before, each regression is weighted to correct for potential bias from the NPRI-ASM matching procedure, and standard errors clustered by CMA-industry are reported in parentheses.

The estimates reported in Panel A of Table 5 confirm the  $\text{PM}_{2.5}$  standard led to a large decrease in output from affected plants that emitted particulate matter. The estimate in column (1) of Panel A indicate the CWS particulate matter regulation is associated with a 10.8% decrease in sales from plants that emitted  $\text{PM}_{2.5}$ . Conversely, the estimates in panel B show the  $\text{O}_3$  standard had no statistically significant effects on output.<sup>49</sup>

Lastly, we estimate a variant of our main specification (Equation (3)) in which we compare

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<sup>48</sup>Dropping these plants yields a point estimate of the  $\text{PM}_{2.5}$  regulation's effect on  $\text{NO}_X$  emissions of 0.052 with a standard error of 0.073.

<sup>49</sup>Note that  $\text{PM}_{2.5}$  regulation also caused a significant reduction in value-added from affected  $\text{NO}_X$  emitters. As we discuss above, this is driven by a very small number of plants. Thus, we pay little attention to this result.

Table 5: The Effects of the CWS on Plant Output

	Panel A: PM <sub>2.5</sub>		Panel B: NO <sub>x</sub>	
	(1) Sales	(2) Value Added	(3) Sales	(4) Value Added
PM <sub>2.5</sub> Standard	-0.108** (0.050)	-0.138** (0.065)	-0.022 (0.059)	-0.227*** (0.083)
O <sub>3</sub> Standard	0.056 (0.060)	0.111 (0.070)	-0.039 (0.161)	-0.125 (0.188)
$R^2$	0.224	0.221	0.265	0.294
$N$	6501	6501	3012	3012

*Notes:* Table reports estimates of the effects of the CWS on plant output for PM<sub>2.5</sub> and NO<sub>x</sub> emitting plants. For each panel, each column reports the results of a different regression. In the first column, the dependent variable is the natural log of plant sales. In the second, the dependent variable is the natural log of plant value added. In each panel, the first row reports the effects of PM<sub>2.5</sub> standard, and the second row reports the effects of the O<sub>3</sub> standard. All regressions include plant, industry-year and CMA-year fixed effects and are weighted by the inverse of the NPRI-ASM match probability to control for potential sample bias. Standard errors clustered by city-industry are reported in parentheses. Asterisks denote significance at the 1% (\*\*\*), 5% (\*\*), and 10% (\*) levels.

the number of plants operating in a treated industry-CMA-year cell to the number operating in an untreated industry-CMA-year cell. That is, we estimate the following regression

$$N_{ict} = \beta_{PM} T_{ict}^{PM} + \beta_{O3} T_{ict}^{O3} + \alpha I(\text{CWS})_{ic} + \xi_{ct} + \lambda_{it} + \varepsilon_{ict}, \quad (4)$$

where  $N_{ict}$  is the number of active plants in industry  $i$  in CMA  $c$ ,  $T_{ict}^j$  is the treatment indicator for standard  $j$  (which takes a value of one for industries targeted by the CWS for years in which their CMA exceeds threshold  $j$ ),  $I(\text{CWS})_{ic}$  is an indicator for whether the industry-CMA was ever regulated by the CWS,  $\lambda_{it}$  are industry-year fixed effects,  $\xi_{ct}$  are CMA-year fixed effects, and  $\varepsilon_{ict}$  is an error term that captures idiosyncratic changes in outcomes across industry-regions. The main coefficients of interest ( $\beta_{PM}$  and  $\beta_{O3}$ ) show the number of plants that exit an industry-CMA due to the CWS.

As the dependent variable is a count variable, we estimate Equation (4) using both ordinary least squares and Poisson regression. As above, we report estimates for two groups of plants: those that emit PM<sub>2.5</sub> (Panel A) and those that emit NO<sub>x</sub> (Panel B). These results are presented in Table 6, which includes standard errors clustered by CMA in parentheses.

Table 6: The Effects of the CWS on Plant Exit

	Panel A: Emit PM		Panel B: Emit NO <sub>x</sub>	
	OLS	Poisson	OLS	Poisson
PM <sub>2.5</sub> Std.	-1.134** (0.626)	-0.347** (0.169)	-0.188 (0.293)	-0.031 (0.119)
O <sub>3</sub> Std.	0.726 (0.547)	0.142 (0.147)	-0.457 (0.489)	-0.135 (0.221)
$R^2$	0.481	0.365	0.443	0.207
$N$	2776	3023	1252	1582

*Notes:* Table reports estimates of the effects of the CWS on the number of plants operating in an industry-CMA-year. Panel A shows estimates using plants that emit particulate matter only, and Panel B shows estimates using plants that emit nitrogen oxide only. In each panel, the first column shows the results using OLS estimation and the second column shows results using Poisson estimation. In all cases, the first row reports the effects of PM<sub>2.5</sub> regulations, and the second row reports the effects of the O<sub>3</sub> regulations. All regressions include industry-year and CMA-year fixed effects. Standard errors clustered by CMA are reported in parentheses. Asterisks denote significance at the 1% (\*\*\*), 5% (\*\*), and 10% (\*) levels.

We find a significant reduction in the number of plants operating in an industry-region in response to particulate matter regulation. For example, the estimates in column (1) of Panel A show that PM<sub>2.5</sub> regulation reduced the number of operating plants in the average affected industry-CMA by 1.134 plants. In contrast, O<sub>3</sub> regulation had no significant effect on plant exit. This is consistent with the predictions of our model, as abatement carries a high fixed cost for PM<sub>2.5</sub> and a low fixed cost for NO<sub>x</sub>.

#### *Aggregate Implications*

The implication of the results presented in Table 4, Table 5, and Table 6 is that the CWS contributed to the manufacturing clean-up through different channels for different pollutants. The particulate matter standard primarily caused a reduction in output at regulated plants and plants to exit. In contrast, the ozone standard caused regulated plants to adopt cleaner processes. To quantify the total contribution of the CWS to the manufacturing clean-up we present a simple counterfactual exercise in which we ask how much of the clean-up can be attributed to the process, reallocation and selection effects induced by the CWS. We do this by using our estimates, paired with an empirical analogue of the industry decomposition given by Equation (2), to compute the implied change in manufacturing pollution intensity over our sample that occurred because of each of the CWS channels. We then compare these

estimates to the observed change in manufacturing pollution intensity.<sup>50</sup>

To develop an empirical analogue to Equation (2), we follow an approach used in much of the labor literature and consider total changes in emission intensity over time (for a relevant review, see Foster et al. (2001)). To start, add  $t$  as an index for time in the decomposition presented in Section 2.1, such that industry  $i$ 's pollution intensity at time  $t$  is  $E_{it} = \int_0^{n_{it}} e_{it}(n)\lambda_{it}(n)dn$ , where  $e_{it}(n)$  is a plant's pollution intensity,  $\lambda_{it}(n)$  is a plant's share of industry output, and  $n_{it}$  is the marginal surviving plant. Assuming, for convenience, that plants only exit the industry over time and never enter, then the change in an industry's emission intensity from  $t - 1$  to  $t$  is given by

$$E_{it} - E_{it-1} = \int_0^{n_{it}} e_{it}(n)\lambda_{it}(n)dn - \int_0^{n_{it}} e_{it-1}(n)\lambda_{it-1}(n)dn - \int_{n_{it}}^{n_{it-1}} e_{it-1}(n)\lambda_{it-1}(n)dn.$$

In the online appendix (see Section B.4), we show that the percentage change in an industry's emission intensity,  $\dot{E}_{it} = \frac{E_{it} - E_{it-1}}{E_{it-1}}$ , can then be expressed as

$$\begin{aligned} \dot{E}_{it} = & \int_0^{n_{it}} s_{zit-1}(n)\dot{e}_{it}(n)dn + \int_0^{n_{it}} s_{zit-1}(n)\dot{\lambda}_{it}(n)dn \\ & - \int_{n_{it}}^{n_{it-1}} s_{zit-1}(n)dn + \int_0^{n_{it}} s_{zit-1}(n)\dot{e}_{it}(n)\dot{\lambda}_{it}(n)dn, \end{aligned} \quad (5)$$

where  $s_{zit-1}(n)$  is plant  $n$ 's share of industry  $i$ 's pollution at time  $t - 1$ , and dot notation is used to denote percentage changes. The first three terms of Equation (5) are the process, reallocation, and selection effects that we discussed previously in Section 2.1. The final term is an interaction effect created by the interaction between the process and reallocation effects, and can be thought of as the approximation error in Equation (2) caused by focusing on small, rather than potentially large, changes.

We use our estimates presented above in Section 5.3.2 to construct the four terms on the left-hand side of Equation (5). As such, let  $\hat{\beta}_e$ ,  $\hat{\beta}_x$ , and  $\hat{\beta}_n$  denote our estimates of the

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<sup>50</sup>For simplicity, we will focus on the direct effects of each standard and ignore any cross-pollutant effects. That is, we ignore the PM standard's effect on NO<sub>x</sub> emitters and the O<sub>3</sub> standard's effect on PM emitters.

effects of the CWS on plant pollution intensity (from Table 4), plant output (from Table 5), and selection (from Table 6), respectively. Moreover, recall that, given our identification assumptions,  $\hat{\beta}_e$  captures the average change in emission intensity due to the CWS, meaning that we can write

$$\dot{e}_{it}(n) = \begin{cases} \hat{\beta}_e, & \text{if } n \text{ is treated} \\ 0, & \text{otherwise.} \end{cases} \quad (6)$$

In addition, an estimate of  $\dot{\lambda}_{it}(n)$  and  $\int_{n_{it}}^{n_{it-1}} s_{it-1}^z(n) dn$  can be constructed from  $\hat{\beta}_x$  and  $\hat{\beta}_n$ , respectively. In the online appendix (see Section B.4), we show that

$$\dot{\lambda}_{it}(n) = \begin{cases} \frac{\hat{\beta}_x(1-s_{xit-1}^{Treat})+s_{xit-1}^{Exit}}{1-s_{xit-1}^{Exit}+\hat{\beta}_x s_{xit-1}^{Treat}}, & \text{if } n \text{ is treated} \\ \frac{s_{xit-1}^{Exit}-\hat{\beta}_x s_{xit-1}^{Treat}}{1-s_{xit-1}^{Exit}+\hat{\beta}_x s_{xit-1}^{Treat}}, & \text{otherwise,} \end{cases} \quad (7)$$

where  $s_{xit-1}^{Treat}$  and  $s_{xit-1}^{Exit}$  are the fraction of output in time  $t-1$  from treated and exiting plants, respectively. Substituting Equation (6) and Equation (7) into Equation (5) gives estimates of the process, reallocation, and interaction effects. Letting  $s_{zit-1}^{Treat}$  be the share of industry  $i$ 's pollution in time  $t-1$  from treated plants, then the process effect is

$$\widehat{PE} = \hat{\beta}_e s_{zit-1}^{Treat}. \quad (8)$$

Similarly, the reallocation effect is given by

$$\widehat{RE} = \frac{s_{xit-1}^{Exit} + \hat{\beta}_x (s_{zit-1}^{Treat} - s_{xit-1}^{Treat})}{1 - s_{xit-1}^{Exit} + \hat{\beta}_x s_{xit-1}^{Treat}}, \quad (9)$$

and the interaction effect is given by

$$\widehat{IE} = \hat{\beta}_e s_{zit-1}^{Treat} \left[ \frac{\hat{\beta}_x (1 - s_{xit-1}^{Treat}) + s_{xit-1}^{Exit}}{1 - s_{xit-1}^{Exit} + \hat{\beta}_x s_{xit-1}^{Treat}} \right] \quad (10)$$



Table 7: Counterfactual Estimates

	Process Effect (1)	Reallocation Effect (2)	Selection Effect (3)	Interaction Effect (4)	Total (5)
PM <sub>2.5</sub>	0.034	0.109	0.073	-0.004	0.212
NO <sub>x</sub>	0.409	0.140	0.085	-0.025	0.610

*Notes:* Table reports the share of the total change in manufacturing pollution intensity from 2004 to 2010 attributable to each CWS channel. The first row shows estimates for PM<sub>2.5</sub> and the second row for NO<sub>x</sub>. Columns (1) through (4) show the estimates of each channel. Column (5) shows the total across all channels.

To construct an estimate of the selection effect, recall our estimate of  $\hat{\beta}_n$  tells us the number of facilities that closed in an industry-CMA cell because of the CWS. Letting  $N^{Treat}$  be the number of regulated industry-CMA cells, then the selection effect is

$$\widehat{SE} = \hat{\beta}_n N^{Treat} \bar{s}_{zit-1}^{Exit}, \quad (11)$$

where  $\bar{s}_{zit-1}^{Exit}$  is the average exiting plant's share of industry  $i$ 's pollution in time  $t - 1$ .

In Table 7 we present our estimates of each of the CWS channels relative to the observed change in manufacturing pollution intensity. The first row shows the fraction of the PM<sub>2.5</sub> clean-up due to the CWS and the second shows the fraction of the NO<sub>x</sub> clean-up due to the CWS. Our estimates of the process effect, reallocation effect, selection effect and interaction effect for each pollutant are reported in columns (1)-(4), respectively. Column (5) reports the implied change in manufacturing pollution intensity that can be explained by the CWS.

The results of this exercise show that both the PM<sub>2.5</sub> and O<sub>3</sub> standards enacted under the CWS played a considerable role in the clean-up of Canadian manufacturing. The estimates in column (5) show that, from 2004 to 2010, the O<sub>3</sub> standard is responsible for 61% of the reduction in manufacturing NO<sub>x</sub> intensity and the PM<sub>2.5</sub> standard is responsible for 21% of the reduction in manufacturing PM<sub>2.5</sub> intensity. However, the channels responsible varied considerably across pollutants. The process effect, for example, associated with NO<sub>x</sub> regulation accounts for almost 41% of the clean-up. In contrast, the process effect accounts

for just over 3% of the clean-up for PM<sub>2.5</sub>. Instead, the PM<sub>2.5</sub> regulation primarily reduced aggregate emission intensity through a combination of reallocation and selection effects.

### 5.3.3 Explaining How Industries Clean-Up

The results presented above show that the channels through which the CWS caused the manufacturing sector to clean-up varied across pollutants. Our theoretical model in Section 4 provides a potential explanation for this: differences in the fixed costs of abatement across pollutants. Indeed, as we discussed in Section 3, engineering assessments of these pollutants argue abatement of NO<sub>x</sub> can be accomplished at low-cost, while abatement of PM<sub>2.5</sub> pollution typically requires large fixed costs (Environmental Protection Agency, 1999a; Canadian Council of Ministers of the Environment, 1998; Environment Canada, 2002). We now turn to assess this mechanism further and examine other potential explanations for our findings to the extent possible with our data.

#### *Differential Effects by Plant Productivity Level*

We begin by testing our model’s prediction that there should be large differences across plants in how they respond to regulation when abatement fixed costs are high, but that the responses should be relatively uniform when fixed costs are low. As we cannot observe the fixed costs of abatement directly, this is the most direct test of our hypothesized mechanism.

To test this prediction, we use an approach similar in spirit to that of Bustos (2011) and allow the effects of the CWS to differ across plants on the basis of their initial productivity. That is, we estimate the following regression

$$Y_{pict} = \sum_{q=1}^3 \beta_{PM}^{Q_q} [T_{ict}^{PM} \times Q_q] + \sum_{q=1}^3 \beta_{O3}^{Q_q} [T_{ict}^{O3} \times Q_q] + \rho_p + \xi_{ct} + \lambda_{it} + \varepsilon_{pict}, \quad (12)$$

where  $Q_q$  is an indicator that takes the value one if plants that are in productivity tercile  $q$ ,  $T_{ict}^j$  takes a value of one for all plants in targeted industries for years in which their CMA violates standard  $j$ ,  $\beta_j^{Q_q}$  is the treatment effect of standard  $j$  on plants in productivity tercile

$q$ , and the remaining variables are as defined for Equation (3).<sup>51</sup>

We use Equation (12) to examine the CWS' effects on plant pollution levels, emission intensity, and sales. Examining pollution levels allows us to assess whether the CWS affected emissions from plants of all productivity levels, whereas examining emission intensity and sales allows us to quantify the channels by which regulation affected each plant.

These results are shown in Table 8. Panel A reports our estimates for PM<sub>2.5</sub> emitters; Panel B for NO<sub>x</sub> emitters. In each panel, we report estimates from three separate regressions. The first column in each panel shows our estimates from Equation (12) on plant emissions, the second column shows the effects on plant emissions per dollar of sales, and the third on plant sales. Natural logarithms are taken of all dependent variables. The first three rows in each panel report the effects of the PM<sub>2.5</sub> regulation (the  $\beta_{PM}^{Q_q}$  coefficients in Equation (12)). The first row shows the effect on plants in the lowest productivity tercile, the second row the effect on plants in the middle tercile, and the third row the effects on plants in the highest tercile. Similarly, the final three rows report the effects of the O<sub>3</sub> regulation ( $\beta_{O_3}^{Q_q}$  in Equation (12)). The fourth row shows the effect on plants in the lowest productivity tercile, the fifth row the effect on plants in the middle tercile, and the sixth row the effects on plants in the highest tercile. As before, each regression is weighted to correct for potential bias from the NPRI-ASM matching procedure. In all cases, standard errors clustered by CMA-industry are reported in parentheses.

The results for the PM<sub>2.5</sub> standard show stark differences across PM<sub>2.5</sub> plants of different productivity levels. PM<sub>2.5</sub> regulation caused a drop in emissions among the bottom two-thirds of the productivity distribution, with a reduction in emissions of 16.3% for low productivity plants and 27.9% for middle productivity PM<sub>2.5</sub> emitters. In contrast, PM<sub>2.5</sub>

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<sup>51</sup>We construct  $Q_q$  by sorting plants in each sample into terciles based on their initial productivity level. We proxy a plant's initial productivity using value added per worker in the first year a plant enters each sample. To account for potential differences in average productivity levels across industries and time, we regress plants' initial productivity levels on entry-year and industry fixed effects, and use the residuals from this regression as our measure of plant productivity. Finally, we divide the distribution of initial productivity residuals into thirds, and place plants into three bins according to their place in the productivity distribution. These bins are used to construct the indicators  $Q_q$ . Note that because we construct these bins separately for PM<sub>2.5</sub> and NO<sub>x</sub> emitters, the composition of plants in each tercile may vary across each pollutant sample.

Table 8: The Effects of the CWS by Plant Productivity Level

	Panel A: PM <sub>2.5</sub>			Panel B: NO <sub>x</sub>		
	(1)	(2)	(3)	(4)	(5)	(6)
	PM <sub>2.5</sub>	PM <sub>2.5</sub> / Sales	Sales	NO <sub>x</sub>	NO <sub>x</sub> / Sales	Sales
<hr/>						
PM <sub>2.5</sub> Std.						
x Q1	-0.163** (0.083)	0.038 (0.102)	-0.201*** (0.073)	0.079 (0.091)	0.084 (0.118)	-0.005 (0.084)
x Q2	-0.279** (0.134)	-0.251* (0.143)	-0.028 (0.056)	0.155 (0.120)	0.188 (0.126)	-0.032 (0.096)
x Q3	-0.023 (0.100)	-0.016 (0.101)	-0.007 (0.057)	0.079 (0.134)	0.109 (0.134)	-0.030 (0.056)
O <sub>3</sub> Std.						
x Q1	-0.281 (0.210)	-0.353 (0.222)	0.072 (0.074)	-0.457** (0.207)	-0.412** (0.207)	-0.045 (0.205)
x Q2	0.076 (0.195)	0.065 (0.227)	0.011 (0.130)	-0.340** (0.173)	-0.277* (0.160)	-0.063 (0.056)
x Q3	-0.093 (0.237)	-0.150 (0.232)	0.057 (0.071)	-0.183 (0.177)	-0.182 (0.180)	-0.001 (0.167)
<hr/>						
R <sup>2</sup>	0.176	0.162	0.226	0.312	0.282	0.266
N	6501	6501	6501	3012	3012	3012

*Notes:* Table reports estimates of the effects of the CWS where the estimated treatment effects are allowed to vary by plant initial productivity level. Panel A shows the effects on PM<sub>2.5</sub> emitters and Panel B on NO<sub>x</sub> emitters. For each panel, the first column reports estimates from a regression of the CWS regulations on the natural log of plant emissions, the second column shows estimates on the natural logarithm of the emissions-sales ratio, and the third shows estimates on the natural logarithm of plant sales. In all cases, the first row reports the effects of PM<sub>2.5</sub> regulations for plants in the bottom tercile of their industry's productivity distribution. The second row shows the effects of PM<sub>2.5</sub> regulations for plants in the middle tercile of their industry's productivity distribution. The third row shows the effects of PM<sub>2.5</sub> regulations for plants in the top tercile of their industry's productivity distribution. Rows four through six show similar estimates for the O<sub>3</sub> regulations. All regressions include plant, industry-year, and CMA-year fixed effects, and are weighted by the inverse of the NPRI-ASM match probability to control for potential sample bias. Standard errors clustered by CMA-industry are reported in parentheses. Asterisks denote significance at the 1% (\*\*\*), 5% (\*\*), and 10% (\*) levels.

regulation had no significant effect on the most productive PM<sub>2.5</sub> plants, suggesting they were unaffected by regulation.

The results in columns (2) and (3) indicate how the affected PM<sub>2.5</sub> pollutants reduced their emissions varied considerably across the productivity distribution. The drop in emissions among the middle-productivity plants was almost entirely driven by a drop in plant emission intensity, with pollution intensity falling by 25.1%. The drop in emissions from low-productivity plants was driven by a reduction in output, with no significant change in pollution intensity and a 20.1% drop in output. These findings suggest changes in plant

pollution intensity driven by regulation played a role in the particulate matter clean-up, however, only among relatively productive plants.

In contrast to the effects of  $PM_{2.5}$  regulation, the  $O_3$  standard had relatively uniform effects across  $NO_X$  emitters.  $NO_X$  emissions fell considerably across the entire productivity distribution, with estimated reductions of between 18-46%, though not significant for the most productive plants. The  $NO_X$  clean-up in response to the CWS was primarily driven by changes in plant production techniques, as plant-level changes in emission intensities explain 80-100% of the reduction in emissions.

The results in Table 8 are consistent with our theory, and the hypothesis that the channels of the CWS clean-ups varied across pollutants because of differences in abatement costs.<sup>52</sup> As the abatement of  $PM_{2.5}$  requires paying a relatively high fixed cost, only relatively productive plants should choose to do so. These highly productive plants, in turn, experience a reduction in pollution intensity with a relatively small change in output and production inputs. The less productive plants, on the other hand, experience an increase in production costs, leading to a reduction in input use, output, and productivity. In contrast, as  $NO_X$  can be abated at a relatively low cost, there are smaller differences across plants of different productivity levels. For both pollutants, the most productive plants in an industry use state of the art technology, and are thus unaffected by the CWS.

#### *Other Margins of Plant Adjustment*

Lastly, we examine the effects of the CWS on several additional margins of plant adjustment, including changes in primary inputs, intermediate inputs, and productivity. Doing so allows us to examine a number of alternative explanations as to why the  $PM_{2.5}$  and  $O_3$  standards caused the manufacturing sector to clean-up through different channels.

Thus far, the hypothesis we have focused on is that  $PM_{2.5}$  and  $NO_X$  have different abatement costs, which affects a plant's willingness to adopt cleaner production processes. An

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<sup>52</sup>This conclusion holds even if we consider alternative specifications in which we split the productivity distribution into quartiles or quintiles, or use a quadratic interaction of plant productivity with the treatment indicators.

alternative hypothesis is that the opportunities for input substitution may vary across pollutants. For example, there could be readily available alternatives to the inputs that create  $\text{NO}_x$  pollution, but not for the inputs that create  $\text{PM}_{2.5}$  pollution. If this were the case, then regulation would reduce  $\text{NO}_x$  intensity but not  $\text{PM}_{2.5}$  intensity.

Examining the effect of the CWS on input use allows us to assess the above hypothesis. If this hypothesis were true, then the CWS should have caused an increase in spending on inputs for  $\text{NO}_x$  emitters.<sup>53</sup> In addition, examining the effect of the CWS on input use for plants of different productivity levels allows us to indirectly test our main hypothesis. While our model does not contain intermediate inputs, their use should be positively correlated with output. As our model predicts a reduction in output only for the least productive  $\text{PM}_{2.5}$  emitters, this should also be accompanied by a reduction in spending on intermediate inputs for these less-productive plants.

The literature on the Porter Hypothesis provides an additional alternative hypothesis. This literature posits environmental regulation could cause an increase in innovative activities and productivity among regulated firms.<sup>54</sup> If the average plant became less productive in response to  $\text{PM}_{2.5}$  regulation, but more productive in response to  $\text{NO}_x$  regulation, then this could generate the findings reported in Section 5.3.2. Examining the effect of the CWS on plant productivity allows us to test this hypothesis.

We examine these alternative hypotheses using data on the total number of plant employees<sup>55</sup>, spending on both production materials and fuel and energy, value added per worker, and the probability a plant is involved in research and development.

Estimates of the effects of the CWS on productivity and input use for the average manufacturing plant are shown in Table 9. Panel A shows estimates of Equation (3) for  $\text{PM}_{2.5}$  emitters and Panel B shows estimates for  $\text{NO}_x$  emitters. In each panel, we report estimates

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<sup>53</sup>Here we have assumed plants would use the cheapest input in the absence of regulation.

<sup>54</sup>For a recent review of this literature, see Ambec et al. (2013)

<sup>55</sup>Although we do not observe plant capital stock information, given our relatively short period of study we expect capital adjustment to play a minor role in this context. While capital adjustment could play an important role over larger time horizons, the existing literature seems to find limited evidence of capital stock adjustments in response to environmental regulation. See, e.g., Greenstone (2002) and Levinson (1996).

from five separate regressions corresponding to the different mechanisms of interest. Natural logarithms are taken of the dependent variables in columns one to four. The first column shows the CWS' effects on employment, the second spending on materials, the third spending on energy, and the fourth labour productivity. The final column estimates the CWS effect on an indicator for whether the plant is involved in research and development using a linear probability model. In each specification, the first row reports the effect of the PM<sub>2.5</sub> regulation and the second row reports the effect of the O<sub>3</sub> regulation. As before, each regression is weighted to correct for potential bias from the NPRI-ASM matching procedure. In all cases, standard errors clustered by CMA-industry are reported in parentheses.

We also examine if the effects of the CWS on productivity and input use differ across the initial plant productivity distribution. These estimates are reported in Table 10.<sup>56</sup> Panel A shows the results for PM<sub>2.5</sub> emitters and Panel B for NO<sub>x</sub> emitters. Each column in each panel corresponds to a different dependent variable, each measured in natural logarithms. Each regression is weighted to correct for potential bias from the NPRI-ASM matching procedure. In all cases, standard errors clustered by CMA-industry are reported in parentheses.

As the estimates reported in Table 9 and Table 10 show, the main channels by which the average PM<sub>2.5</sub> emitting plant responded to PM<sub>2.5</sub> regulation appears to be through changes in intermediate input use and labor productivity. PM<sub>2.5</sub> regulation decreased spending on production materials by 11.9%, caused a drop in energy spending (although not significant at conventional levels), and reduced labor productivity (also not significant at conventional levels). PM<sub>2.5</sub> regulation also caused a significant reduction in labor productivity among NO<sub>x</sub> emitters. There is no evidence of a change in employment or R&D propensity in response to the PM<sub>2.5</sub> standard.

The estimates of the effects of the PM<sub>2.5</sub> standard by productivity level are also consistent with our main hypothesis. These results show that the reductions in materials, energy inputs, and labor productivity in response to the PM<sub>2.5</sub> standard were driven by the least productive

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<sup>56</sup>The effects on R&D are omitted, but are available upon request.

Table 9: Other Margins of Plant Adjustment

	Panel A: PM <sub>2.5</sub>				
	<u>Prim. Inputs</u>	<u>Inter. Inputs</u>		<u>Productivity</u>	
	(1) Employment	(2) Materials	(3) Energy	(4) VA/Worker	(5) Pr(R&D)
PM 2.5 Standard	-0.040 (0.064)	-0.119* (0.064)	-0.086 (0.056)	-0.098 (0.073)	0.033 (0.040)
O3 Standard	0.071 (0.068)	-0.008 (0.071)	0.224** (0.108)	0.039 (0.060)	-0.086 (0.060)
$R^2$	0.188	0.218	0.151	0.185	0.155
$N$	6501	6499	6478	6501	6501

	Panel B: NO <sub>x</sub>				
	<u>Prim. Inputs</u>	<u>Inter. Inputs</u>		<u>Productivity</u>	
	(1) Employment	(2) Materials	(3) Energy	(4) VA/Worker	(5) Pr(R&D)
PM 2.5 Standard	0.003 (0.069)	0.039 (0.077)	-0.094 (0.093)	-0.231*** (0.085)	0.061 (0.060)
O3 Standard	-0.064 (0.157)	-0.069 (0.154)	0.085 (0.264)	-0.062 (0.117)	-0.143 (0.119)
$R^2$	0.285	0.276	0.218	0.242	0.248
$N$	3012	3012	3009	3012	3012

*Notes:* Table reports estimates of the effects of the CWS on additional margins of adjustment for plants that emit either PM<sub>2.5</sub> or NO<sub>x</sub>. For each group of emitters, each column shows the results of a different regression. The first column reports estimates from a regression of the CWS regulations on the natural log of the number of workers employed at the plant. The second and third columns report estimates of the CWS' effects on the natural log of spending on production materials and fuel and energy, respectively. The fourth column reports estimates of the CWS' effects on the natural log of value added per worker. The final column reports estimates of the CWS' effects on an indicator for whether the plant spends money on research and development, using a linear probability model. In all cases, the first row reports the effects of PM<sub>2.5</sub> regulations, and the second row reports the effects of the O<sub>3</sub> regulations. All regressions include plant, industry-year, and CMA-year fixed effects, and are weighted by the inverse of the NPRI-ASM match probability to control for potential sample bias. Standard errors clustered by CMA-industry are reported in parentheses. Asterisks denote significance at the 1% (\*\*\*), 5% (\*\*), and 10% (\*) levels.

plants. In response to PM<sub>2.5</sub> regulation, the least productive plants reduced spending on material inputs by 19.4% and energy inputs by 12.5%, and value added per worker fell by 24.7%. PM<sub>2.5</sub> regulation had no significant effect on these mechanisms at relatively more productive plants. Interestingly, PM<sub>2.5</sub> regulation had no significant effect on employment for the least productive plants, but reduced employment among the middle-productivity plants. Though output did not fall for the middle-productivity plants, regulation appears to have



Table 10: CWS Mechanisms by Plant Productivity Level

	Panel A: PM <sub>2.5</sub>				Panel B: NO <sub>x</sub>			
	(1) Emp.	(2) Materials	(3) Energy	(4) VA/ Worker	(5) Emp.	(6) Materials	(7) Energy	(8) VA/ Worker
PM <sub>2.5</sub> Std.								
x Q1	0.003 (0.113)	-0.194** (0.094)	-0.125* (0.074)	-0.247** (0.119)	0.141 (0.097)	0.165* (0.099)	-0.080 (0.122)	-0.418*** (0.124)
x Q2	-0.093* (0.055)	-0.044 (0.070)	-0.051 (0.073)	0.058 (0.061)	-0.031 (0.079)	-0.007 (0.094)	-0.189 (0.146)	-0.188** (0.092)
x Q3	-0.065 (0.072)	-0.049 (0.095)	-0.041 (0.098)	0.027 (0.089)	-0.116 (0.100)	-0.049 (0.122)	-0.044 (0.102)	-0.076 (0.111)
O <sub>3</sub> Std.								
x Q1	0.131 (0.086)	0.004 (0.092)	0.311** (0.128)	-0.058 (0.078)	-0.079 (0.200)	-0.004 (0.194)	-0.181 (0.304)	-0.177 (0.156)
x Q2	0.024 (0.128)	-0.031 (0.149)	0.252 (0.243)	0.014 (0.099)	-0.057 (0.163)	-0.108 (0.166)	0.190 (0.257)	0.011 (0.157)
x Q3	0.047 (0.076)	-0.016 (0.082)	0.109 (0.142)	0.136 (0.092)	-0.010 (0.170)	-0.053 (0.159)	0.237 (0.279)	-0.085 (0.120)
$R^2$	0.189	0.219	0.152	0.188	0.288	0.277	0.220	0.245
$N$	6501	6499	6478	6501	3012	3012	3009	3012

*Notes:* Table reports estimates of the effects of the CWS where the estimated treatment effects are allowed to vary by plant initial productivity level. Panel A shows the effects on PM<sub>2.5</sub> emitters and Panel B on NO<sub>x</sub> emitters. For each group of emitters, each column shows the results of a different regression. The first column reports estimates from a regression of the CWS regulations on the natural log of the number of workers employed at the plant. The second and third columns report estimates of the CWS' effects on the natural log of spending on production materials and energy, respectively. The final column reports estimates of the CWS' effects on the natural logarithm of value added per worker. In all cases, the first row reports the effects of PM<sub>2.5</sub> regulations for plants in the bottom tercile of their industry's productivity distribution. The second row shows the effects of PM<sub>2.5</sub> regulations for plants in the middle tercile of their industry's productivity distribution. The third row shows the effects of PM<sub>2.5</sub> regulations for plants in the top tercile of their industry's productivity distribution. Rows four through six show similar estimates for the O<sub>3</sub> regulations. All regressions include plant, industry-year, and CMA-year fixed effects, and are weighted by the inverse of the NPRI-ASM match probability to control for potential sample bias. Standard errors clustered by CMA-industry are reported in parentheses. Asterisks denote significance at the 1% (\*\*\*), 5% (\*\*), and 10% (\*) levels.

made them less labor-intensive, in addition to causing them to adopt cleaner production processes. A potential explanation for this is that the  $\text{PM}_{2.5}$  process changes may have required new capital investments, thereby changing the plants' capital-labor ratio. Finally, the drop in productivity among  $\text{NO}_x$  emitters in response to the  $\text{PM}_{2.5}$  standard appears to be driven by relatively less-productive plants.

The estimates reported in Table 9 and Table 10 also suggest  $\text{O}_3$  regulation did not have a significant effect on input use, employment, labor productivity, or R&D propensity at the average affected plant. The exception to this is an increase in energy spending among  $\text{PM}_{2.5}$  emitters. Allowing the effects of the CWS to vary across plant productivity levels, we still find no significant effect on  $\text{NO}_x$  emitter employment, input spending, or labor productivity. These results are inconsistent with the two additional hypotheses described above, as neither productivity nor input spending rise in response to regulation, which further suggests our results are driven by the fixed costs of abatement.

## 6 Conclusion

In this paper, we examine the channels through which environmental regulations have contributed to the “clean-up” of the Canadian manufacturing sector. We start by showing the Canadian manufacturing sector has cleaned-up considerably in recent decades, both in terms of aggregate pollution emissions, and pollution emissions per dollar of output (emission intensity). This clean-up was primarily driven by reductions in industry emission intensity, similar to the clean-ups observed in the U.S. and Europe. We then present a simple model to show how environmental regulation can cause a reduction in an industry's emission intensity through three channels: the reallocation in output across plants, plant entry and exit, or the adoption of cleaner production processes at surviving plants. Finally, we examine how Canadian manufacturing plants responded to a major revision to environmental policy, the Canada-Wide Standards for Particulate Matter and Ozone, and use the resulting empirical estimates to quantify the channels through which environmental regulations have contributed

to the manufacturing clean-up. Given the similarity between the clean-ups and regulatory structures in Canada, the US, and Europe, we believe our results provide insights relevant for all three regions.

Our estimates imply that this policy explains approximately 60% of the drop in nitrogen oxide emission intensity of the Canadian manufacturing sector, and approximately 20% of the drop in particulate matter emission intensity. However, how this policy caused manufacturing to clean up varied considerably across pollutants. Over two-thirds of the nitrogen oxide clean-up caused by this policy was due to the adoption of cleaner production processes by surviving plants. In contrast, over 80% of the particulate matter clean-up caused by this policy was due to plant exit and the reallocation of output from regulated to unregulated plants.

These results suggests that transitioning to a less-pollution intensive economy may require large changes in an industry's composition. However, the degree to which an industry's composition will need to change likely depends on the costs of adopting cleaner production processes. When these costs are low, as we argue is the case for nitrogen oxide process improvements, process improvements may yield considerable reductions in industry pollution intensity, even in the absence of plant exit or reallocation across plants.

This work also highlights the importance of linked pollution and production data in assessing the effects of environmental regulation. The mechanisms by which plants respond to regulation appears to vary considerably across emitters of different pollutants, and across plants that emit a common pollutant. Accounting for this heterogeneity is likely important in both the design and assessment of environmental policy, and doing so requires rich information on firm economic and environmental performance.

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## Online Appendices

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