Geography and the Technique Effect: Evidence from Canada*

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Abstract

The technique effect – the reduction in aggregate pollution emissions due to reductions in the pollution intensity of individual industries – is often interpreted as evidence that countries are getting cleaner because of improvements in how goods and services are produced. We extend the standard decomposition used in previous research to show the technique effect may also capture within-country changes in where production occurs; that is, changes in the geography of economic activity. An empirical application to Canada suggests such geographic changes are economically important. While the technique effect decreased aggregate Canadian pollution intensity by 24% between 2009-2022, if the pollution intensity of production had remained fixed, within-industry shifts in production across Canadian provinces would have increased aggregate pollution intensity by 14.2%. The technique effect decreased Canadian pollution intensity because these within-industry shifts were accompanied by reductions in pollution intensity that were greatest in provinces that received the largest within-industry reallocation of economic activity.

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1 Introduction

Over the past three-plus decades, many countries have experienced a "cleanup" of production: the quantity of pollution emitted during the production of goods and services has been declining despite increased output. This reduction in the aggregate pollution intensity of production – that is, the level of pollution emitted per unit of output – appears to be due to reductions in the pollution intensity of individual industries (the technique effect) rather than in shifts of economic activity toward industries that are relatively clean (the composition effect).[1] The dominance of the technique effect is often interpreted as evidence countries are getting cleaner due to changes in *how* goods and services are produced. In this paper, we investigate whether the technique effect is also capturing changes in *where* economic activity occurs within a country.

Our starting point is a novel extension of the standard decomposition used in previous research that shows if there is within-industry heterogeneity in the emission intensity of production across regions within a country, the measured technique effect need not necessarily reflect changes in how goods and services are produced, but rather may reflect within-country shifts in where economic activity occurs. Specifically, we show that the technique effect can be further decomposed into four distinct regional-level components that reflect region specific changes in an industry's pollution intensity, as well as changes from within-industry shifts in economic activity across the set of regions in which the industry operates. If there is heterogeneity in industry pollution intensities across regions within a country, our decomposition suggests that the technique effect could be simply be capturing shifts in economic activity from regions that are relatively dirty to regions that are relatively clean.

[1] While it is not uniform in nature, the primacy of the technique effect has been documented for a number of pollutants and countries, including the United States (Levinson (2009, 2015); Shapiro and Walker (2018); Brunel and Levinson (2022)), the European Union (Brunel (2017)), China (Cole and Zhang (2019); Rodrigue et al. (2022)), Canada (Bruneau and Renzetti (2009), Najjar and Cherniwchan (2021)), Germany (Rottner and von Graevenitz (2024)), India (Barrows and Ollivier (2018)) and others (Grether et al. (2009); Copeland et al. (2022)).

We examine this possibility by employing our extended decomposition to study changes in the pollution intensity of Canadian production over the period 2009 to 2022. Canada is an ideal context for our study for three main reasons. The first is practical: Canada has detailed industry-by-region (here, industry-by-province) data on greenhouse gas emissions and output that is needed to apply our extended decomposition empirically. To the best of our knowledge, similarly detailed data is unavailable in other settings. Second, as we show below, there is substantial cross-sectional heterogeneity in industry pollution intensity across Canadian provinces, allowing us to provide a meaningful test of whether within-industry shifts in economic activity across regions are an economically significant determinant of the technique effect. Third, Canada has experienced a reduction in aggregate greenhouse gas intensity that is primarily driven by the technique effect, mirroring reductions that have been documented elsewhere, both for greenhouse gas emissions and other pollutants (e.g. Brunel and Levinson (2022), Copeland et al. (2022)). This suggests our results may be useful for understanding the forces driving aggregate emissions changes in other countries.

The pollution intensity of Canadian production as a whole fell by 27.6% during our period of study. Applying the standard industry-level decomposition that has been used elsewhere in the literature suggests that this decline is primarily due to the technique effect, mirroring findings from prior research. Our estimates indicate that the technique effect accounts for 87% of the reduction in Canadian pollution intensity; it reduced aggregate pollution intensity by 24%, whereas the composition effect decreased aggregate pollution intensity by only 3.8%.[2]

These results would typically be interpreted as evidence that aggregate pollution intensity in Canada primarily declined because of changes in how goods and services

[2] It is worth noting that the co-movement between changes in the composition of production and changes in the pollution intensity of individual industries – the interaction effect – accounts for the remaining change in aggregate pollution intensity (an increase of of approximately 0.2%). This interaction effect is not typically reported in the existing literature due to the fact that previous studies employ decompositions derived under the assumption that changes in emission intensity are small. See Section 2 for further discussion.

are produced. However, our extended decomposition suggests that the technique effect may also capture the effects of changes in where economic activity occurs– i.e., its geography– when industry pollution intensities differ across regions within a country, as is the case in Canada. Applying our extended decomposition empirically, we find that if each industry's pollution intensity in each province where the industry is located (hereafter, its industry×province pollution intensity) had been held fixed at 2009 levels, then changes in the spatial distribution of economic activity across provinces would have increased aggregate greenhouse gas intensity by 14.2%, a phenomenon we term the *regional reallocation effect*. Why, then, did the technique effect cause Canadian pollution intensity to fall to the extent that it did? The answer appears to lie in what we term the *regional technique* and *regional interaction effects*. Our estimate of the regional technique effect indicates that if the spatial distribution of Canadian production had been held fixed as of 2009, aggregate emission intensity would have declined by just over 24.4% by 2022 due to within-industry×province reductions in pollution intensity. Our estimate of the regional interaction effect indicates that these reductions were unevenly distributed across Canada; this estimate indicates that the co-movement of within-industry shifts in economic activity and within-industry×province reductions in emission intensity led to an additional 13.6% reduction in aggregate pollution intensity.[3] Together these findings suggest that within-country reallocations of economic activity across space are important for understanding changes in aggregate pollution levels around the world.

One potential concern with these results is that energy production – a key driver of greenhouse gas emissions – has played a large role in shaping the Canadian economy (e.g. Loertscher and Pujolas (2024)), meaning our findings may simply reflect shifts in the geography of this sector. To address this issue, we again employ both the standard industry-level decomposition and our extended decomposition, but decompose the greenhouse gas intensity of the energy sector separately from the rest of the Canadian

[3] The last element of our extended decomposition, the *regional selection effect*, suggests that the entry and exit of industries from Canadian provinces had no meaningful effect on aggregate pollution intensity.

economy. Doing so suggests that our main findings are not driven by the energy sector. While the technique effect is the primary driver of reductions in pollution intensity in both cases, the regional reallocation and regional interaction effects for the energy sector are roughly one-third the magnitude of their counterparts for the rest of the economy.

As the final step in our analysis, we investigate whether there is any further heterogeneity in the importance of changes in the spatial distribution of economic activity within industries in explaining the technique effect across the non-energy sectors of the Canadian economy. Here, we divide non-energy production into two broad sectors: goods and services. Again, we first decompose aggregate pollution intensity using the standard industry-level decomposition used in previous work to assess the relative magnitudes of the composition, technique and interaction effects, and then further decompose the technique effect using our extended decomposition.

The results from this exercise suggest that changes in the spatial distribution of economic activity play drastically different roles in explaining the technique effect across the two sectors. In the non-energy goods sector, changes in the spatial distribution of economic activity appear to be economically important: the regional reallocation effect increased the emission intensity of the goods sector by 31.7%, which was offset by a 9.4% reduction due to the regional technique effect, and a 31.6% reduction due to the regional interaction effect. In contrast, in the non-energy services sector, changes in the spatial distribution of economic activity appear to not matter at all: the regional technique effect reduced the emission intensity of services by 27.9% while the regional reallocation effect increased it by just over 1.6% and the regional interaction effect decreased it by close to 2.2%.[4] While a full examination of the causes of these stark differences in the importance of changes in the spatial distribution of economic activity is beyond the scope of this paper, one potential explanation for the disparity is differences in the importance of inter-provincial trade costs across sectors; internal trade costs in Canada are much higher

[4] It is worth noting that in both sectors, regional selection effects reduced aggregate pollution intensity by less than 0.1%.

for services than for goods production (Albrecht and Tombe, 2016) making changes in the spatial distribution of economic activity in services more difficult.

Altogether, this paper makes three main contributions to the literature. The first is to the body of research that builds on the approach taken by Levinson (2009, 2015) and employs the standard industry decomposition first articulated by Grossman and Krueger (1993) and formalized by Copeland and Taylor (1994, 1995) to study the sources of changes in aggregate pollution emissions. As noted at the outset, this approach has been used extensively in previous research and the literature typically finds that the technique effect is the primary determinant of aggregate pollution emissions around the world. By extending the standard industry decomposition to further decompose the technique effect, our work bears close similarity to that of Cherniwchan et al. (2017) who decompose the technique effects to allow for within-industry changes in pollution intensity due to shifts in economic activity across firms. Our work proceeds in a similar vein but instead extends the canonical industry decomposition to examine within-industry changes due to shifts in the spatial distribution of economic activity across locations. We conduct our analysis at the industry-province level because it is the most granular geographic data available that includes information on both pollution emissions and output for the entire economy. However, as we show in the appendix, our decomposition can be easily extended to the firm level along the lines of Cherniwchan et al. (2017).[5]

Our findings also contribute to a broader literature trying to understand the technique effect.[6] Researchers have attributed the technique effect to the effects of environmental regulations (e.g. Shapiro and Walker (2018), Najjar and Cherniwchan (2021)) and international trade (e.g. Cherniwchan (2017), Akerman et al. (2024), Leisner et al.

[5]Given that decompositions are accounting identities defined over the universe of firms in an economy, implementing the firm-level extension of our decomposition requires emissions data for the all firms in an economy. To the best of our knowledge, no such data exists; previous studies (e.g. Barrows and Ollivier (2018), Holladay and LaPlue III (2021), Rodrigue et al. (2022)) have relied on sub-samples of the potential universe of firms in their analyses. For further discussion, see Cherniwchan and Najjar (2022).

[6]See Cherniwchan and Taylor (2022) for a recent overview of this literature.

(2023)).[7] However, existing studies have primarily focused on understanding the extent to which these two mechanisms explain the pattern of emission intensities across industries. Our work highlights two new empirical facts that may be useful for understanding the relative contributions of environmental regulation and international trade to the clean-up of production: (i) changes in an industry's pollution intensity can vary widely across regions within a county, and (ii) within-industry shifts in economic activity across regions within a country can play an important role in determining aggregate pollution intensity.

Finally, our findings contribute to the literature examining the sources of changes in aggregate pollution emissions in Canada. Much of this literature has focused on examining the effects of environmental policy (e.g. Najjar and Cherniwchan (2021), Ahmadi et al. (2022), or Pretis (2022)), or relied on input-output tables to study changes in emissions (e.g Dolter and Victor (2016) or Fellows and Dobson (2017)). By employing a decomposition, our work is most closely related to that of Bruneau and Renzetti (2009) who decompose aggregate Canadian greenhouse gas intensity into composition and technique effects over the period 1990-2002. We build on their work by further decomposing the technique effect to allow for the effects of geography and studying a more recent period (2009-2022).

The remainder of this paper proceeds as follows. Section 2 develops our extension of the standard decomposition, while Section 3 discusses our data and Section 4 presents our results. Section 5 concludes.

[7] The technique effect has also been attributed to the effects of technological change (Grossman and Krueger, 1993), but as Cherniwchan and Taylor (2022) note, currently empirical evidence highlighting the role of technology is quite limited.

2 Extending the Standard Industry Decomposition

Following Levinson (2009, 2015), decompositions have become the standard approach for investigating the sources of changes in a country's aggregate emissions or aggregate emission intensity. This method starts from a simple accounting identity that adds up pollution from all N industries observed in an economy:

$$Z_t = \sum_{i \in N} Z_{it} = \sum_{i \in N} X_{it} E_{it} = X_t \sum_{i \in N} \Phi_{it} E_{it} \tag{1}$$

where Z_{it} denotes emissions from industry i at time t, X_{it} is the value of industry output, $\Phi_{it} = X_{it}/X_t$ denotes industry i's share of total output at time t, and $E_{it} = Z_{it}/X_{it}$ denotes the emission intensity of industry i at time t. It follows that aggregate emission intensity can then be written as an output weighted sum of the emission intensities of the industries operating in the economy:

$$E_t = \frac{Z_t}{X_t} = \sum_{i \in N} \Phi_{it} E_{it}. \tag{2}$$

With some algebra, the growth rate of aggregate emission intensity across any two periods t and $t-1$ can be written as:

$$\begin{aligned} \frac{E_t - E_{t-1}}{E_{t-1}} = \sum_{i \in N} \Theta_{it-1} \left[\frac{\Phi_{it} - \Phi_{it-1}}{\Phi_{it-1}} \right] + \sum_{i \in N} \Theta_{it-1} \left[\frac{E_{it} - E_{it-1}}{E_{it-1}} \right] \\ + \sum_{i \in N} \Theta_{it-1} \left[\frac{\Phi_{it} - \Phi_{it-1}}{\Phi_{it-1}} \right] \left[\frac{E_{it} - E_{it-1}}{E_{it-1}} \right] \end{aligned} \tag{3}$$

where $\Theta_{it} = Z_{it}/Z_t$ is industry i's share of total pollution emissions at time t. Equation (3) is a version of the now standard industry decomposition that has been employed elsewhere in the literature.[8] The first term on the right hand side of Equation (3) is the

[8] The typical formulation is derived directly from Equation (1) rather than from Equation (2) and focuses on emissions rather than emission intensity. As such, the itit also results in an estimate of the *scale effect*, that is the change in emissions resulting from changes in the total scale of economic output in the economy holding industry emission intensity and the composition of industrial production fixed. As our

composition effect that captures the change in aggregate pollution intensity created by changes in the composition of production, holding the pollution intensity of production fixed. The second term is the *technique effect* that captures changes in aggregate pollution intensity due to changes in the pollution intensity of individual industries, holding the industrial composition of the economy fixed. The last term is the *interaction effect* that captures changes in aggregate emission intensity arising from the co-movement of changes in industrial composition and industry emission intensity.[9]

Standard practice has been to take industry decompositions such as Equation (3) directly to the data to construct estimates of the composition and technique effects. The resulting estimates suggest that the technique effect has been the primary source of reductions in aggregate pollution intensity in many countries around the world and have been interpreted as evidence that aggregate emission intensities are falling primarily due to changes in how production occurs. However, what has traditionally been labeled the technique effect may be capturing the effects of within-country shifts in the spatial distribution of economic activity across regions with different emission intensities, making it difficult to determine if existing estimates of the technique effect actually reflect changes in *how* production occurs, as opposed to changes in *where* it occurs.

To see this explicitly, note that the emission intensity of any individual industry i can be written as a weighted sum of the emission intensities for the industry across all R_{it}

ultimate goal is in understanding the technique effect, and the two approaches deliver the same formulas for the composition and technique effects, for clarity we focus on Equation (3).

[9]It is worth noting that while previous studies employ discrete decompositions of the form presented inEquation (3) to conduct their empirical analyses, the last term is typically ignored. This is because it has become standard practice to derive the decomposition by totally differentiating Equation (2) which yields:

$$\frac{dE_t}{E_t} = \sum_{i=1}^{N} \Theta_{it} \left[\frac{d\Phi_{it}}{\Phi_{it}} \right] + \sum_{i=1}^{N} \Theta_{it} \left[\frac{dE_{it}}{E_{it}} \right]$$

As in Equation (3), the two terms on the right hand side of the above equation correspond to the composition and technique effects. The last term in Equation (3) arises if one considers potentially large, rather than small, changes in pollution.

regions in which it operates at time t:

$$E_{it} = \sum_{r \in R_{it}} \phi_{irt} e_{irt}. \tag{4}$$

Similar to Equation (2), here $\phi_{irt} = X_{irt}/X_{it}$ is the share of industry i's output that is produced in region r, and $e_{irt} = Z_{irt}/X_{irt}$ is the emission intensity of industry i in region r at time t. With some algebra, the change in industry emission intensity across any two periods t and $t-1$ can be written as:

$$\begin{aligned}\frac{E_{it} - E_{it-1}}{E_{it-1}} &= \sum_{r \in R_{it}^{C}} \theta_{irt-1} \left[\frac{e_{irt} - e_{irt-1}}{e_{irt-1}}\right] + \sum_{r \in R_{it}^{C}} \theta_{irt-1} \left[\frac{\phi_{irt} - \phi_{irt-1}}{\phi_{irt-1}}\right] \\ &+ \sum_{r \in R_{it}^{C}} \theta_{irt-1} \left[\frac{e_{irt} - e_{irt-1}}{e_{irt-1}}\right] \left[\frac{\phi_{irt} - \phi_{irt-1}}{\phi_{irt-1}}\right] + \sum_{r \in R_{it}^{E}} \theta_{irt} \left[\frac{E_{it}}{E_{it-1}}\right] - \sum_{r \in R_{it}^{X}} \theta_{irt-1} \end{aligned} \tag{5}$$

where $\theta_{irt} = z_{irt}/Z_{it}$ is region r's share of industry i's pollution at time t, R_{it}^{C} denotes the set of regions in which industry i operates in at both time t and $t-1$, R_{it}^{E} denotes the set of regions in which industry i operates in at time t, but not at time $t-1$, and R_{it}^{X} denotes the set of regions in which industry i operates in at time $t-1$, but not at time t.

It is worth emphasizing that Equation (5) bears resemblance to the work of Cherniwchan et al. (2017), who similarly decompose industry pollution intensity into changes within and across units. However, Cherniwchan et al. do not account for geography and decompose industry pollution intensity to the firm level. Here we abstract from firms due to data limitations. Implementing a Cherniwchan et al.-type decomposition requires information on the pollution emissions and output for the universe of firms in an economy; to the best of our knowledge, no such data exists. While firms are not the focus of our analysis due to these data limitations, in Section A we show how Equation (5) can be further extended to incorporate firms along the lines of Cherniwchan et al. (2017) if suitable firm-level data were to become available.

Substituting Equation (5) into the technique effect in Equation (3) yields our extended decomposition:[10]

$$\begin{aligned}\frac{E_t - E_{t-1}}{E_{t-1}} &= \sum_{i\in N} \Theta_{it-1}\left[\frac{\Phi_{it}-\Phi_{it-1}}{\Phi_{it-1}}\right] + \sum_{i\in N} \Theta_{it-1}\left[\frac{\Phi_{it}-\Phi_{it-1}}{\Phi_{it-1}}\right]\left[\frac{E_{it}-E_{it-1}}{E_{it-1}}\right] \\ &+ \sum_{i\in N} \Theta_{it-1}\left[\sum_{r\in R_{it}^C} \theta_{irt-1}\left[\frac{e_{irt}-e_{irt-1}}{e_{irt-1}}\right]\right] + \sum_{i\in N} \Theta_{it-1}\left[\sum_{r\in R_{it}^C} \theta_{irt-1}\left[\frac{\phi_{irt}-\phi_{irt-1}}{\phi_{irt-1}}\right]\right] \\ &+ \sum_{i\in N} \Theta_{it-1}\left[\sum_{r\in R_{it}^C} \theta_{irt-1}\left[\frac{e_{irt}-e_{irt-1}}{e_{irt-1}}\right]\left[\frac{\phi_{irt}-\phi_{irt-1}}{\phi_{irt-1}}\right]\right] \\ &+ \sum_{i\in N} \Theta_{it-1}\left[\sum_{r\in R_{it}^E} \theta_{irt}\left[\frac{E_{it}}{E_{it-1}}\right] - \sum_{r\in R_{it}^X} \theta_{irt-1}\right] \qquad (6)\end{aligned}$$

As in the standard decomposition given in Equation (3), the first two terms on the right-hand side of Equation (6) capture the composition and interaction effects, respectively. The next four terms arise from decomposing the technique effect. We refer to the third term on the right-hand side of Equation (6) as the *regional technique effect* that reflects the change aggregate pollution intensity due to within industry×region changes in emission intensity holding the regional composition of industrial activity constant, while we refer to the fourth term as the *regional reallocation effect* that captures the change in aggregate pollution intensity due to within-industry shifts in economic activity across regions holding industry×region pollution intensity constant. The fifth term, which we refer to as the *regional interaction effect*, is similar to the interaction effect reported in Equation (3), and captures the change in aggregate emission intensity from the co-movement of within-industry changes in the spatial distribution of economic activity across regions, and changes in industry×region pollution intensity. We refer to the final term as the *regional selection effect* that captures the change in aggregate emission intensity due to the entry and exit of industries from different regions.[11]

[10] In principle, Equation (5) could similarily be substituted into the interaction effect in Equation (3), but we refrain from doing so because, as we show below, the interaction effect is economically insignificant in our setting.

[11] In principle, the regional selection effect could be separated into a *regional entry effect* and a *regional*

As Equation (6) shows, the technique effect need not reflect changes in how production occurs (as captured by the regional technique effect), but rather could result from inter-regional shifts in the distribution of economic activity within the industry (as captured by the regional reallocation, interaction and selection effects). If the technique effect is primarily due to changes in how production occurs, then the last three terms of Equation (6) should contribute little to observed changes aggregate pollution intensity. In what follows, we investigate this explicitly by taking Equation (6) directly to the data.

3 Data

Employing Equation (3) and Equation (6) to study the sources of changes in aggregate pollution intensity requires data on pollution emissions and output by both industry and region. We obtain these data for Canada over the period 2009-2022 from two data sets constructed by Statistics Canada.

Our pollution emissions data comes from Statistics Canada (2024b), which reports detailed province-level data on the emissions of greenhouse gases by industry.[12] These data are constructed using data from the Physical Flow Accounts for Energy Use and from Canada's Greenhouse Gas Emissions Inventory, and contain information on emissions of three greenhouse gases: carbon dioxide, methane, and nitrous oxide.

Our output data comes from Statistics Canada (2024a), which contains province-level data on real value added by industry, measured in 2017 dollars. We use these data to construct measures of total value added, industry shares of total value added, and provincial shares of industry value added. We combine these data with our emissions data to calculate emission intensity, both by industry and industry-province for 57 in-

exit effect that capture the effects of industries entering and leaving different regions, respectively. We focus on the combined selection effect here for expositional simplicity.

[12]An earlier version of this dataset was used by Bruneau and Renzetti (2009) to study the greenhouse gas intensity of Canadian production over the period 1990-2002. However, these earlier data are not available at the industry×province level, making them unsuitable for our purposes.

dustries and 12 provinces (and territories).

One issue that arises from using these two datasets is that they are reported using different industry classifications. Statistics Canada (2024b) employs the classification system used in Canada's System of National Accounts, while Statistics Canada (2024a) is reported using the North American Industry Classification System (NAICS). We match the two datasets using a concordance from Statistics Canada. It is worth noting that the 57 industries in our data roughly correspond to three-digit NAICS sub-sectors.

A second potential issue created by our data is the possibility that our estimates could understate the role of the composition effects in driving aggregate changes in emission intensity. While the data that we use contain the most detailed industry definitions available while also reporting geographic information, each "industry" that we observe in our data is potentially comprised of many more narrowly defined industries (akin to six-digit NAICS industries), meaning any within-"industry" change in emission intensity could reflect shifts in economic activity across these narrowly defined industries. As a result, our estimates of both the technique effect and its sub-components could reflect unmeasured changes in industry composition.[13]

Before we turn to our results, here we highlight four key facts from our data. The first is that Canada has undergone a reduction in greenhouse gas intensity similar to those in many other countries studied elsewhere in the literature. This can be seen from Figure 1, which displays the percentage change in pollution intensity relative to the 2009 baseline year for the period 2009-2022. As the figure shows, aggregate pollution intensity decreased by 27.6%, indicating that Canadian output has become less greenhouse gas intensive over time.

The second fact we highlight is the significant heterogeneity in pollution intensity within industries across provinces, that is, the heterogeneity in pollution intensity across industry$\times$provinces. This variation can be seen in Table 1, which reports both the mean

[13] See Levinson (2015) for further discussion of the issue of industry aggregation in the context of the United States.

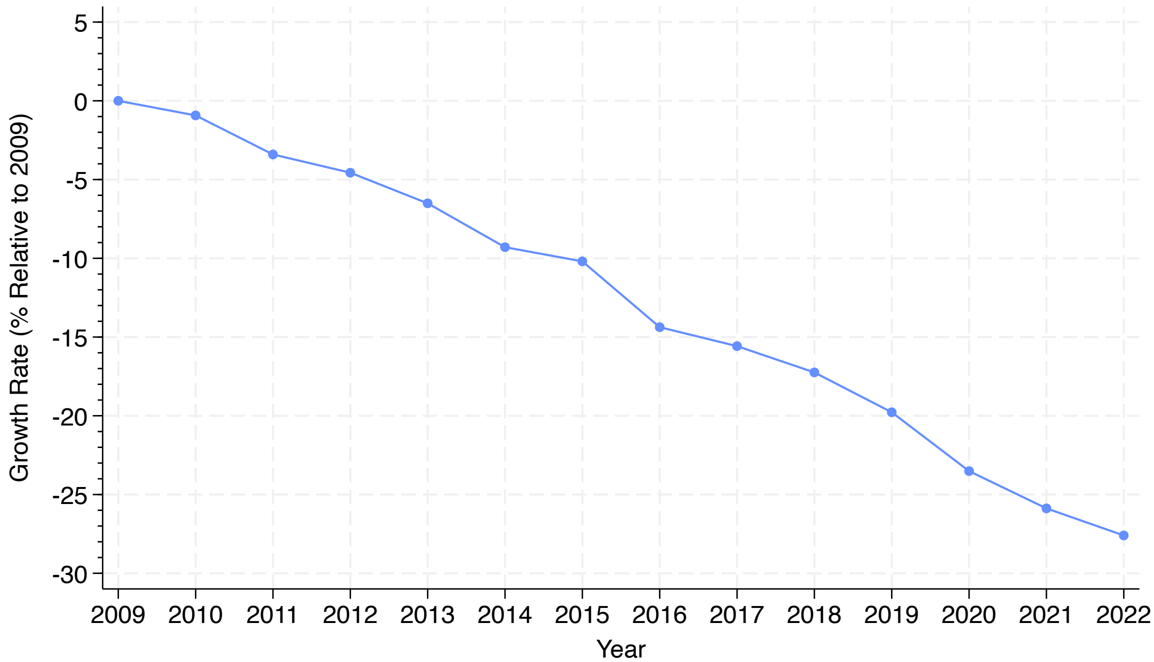


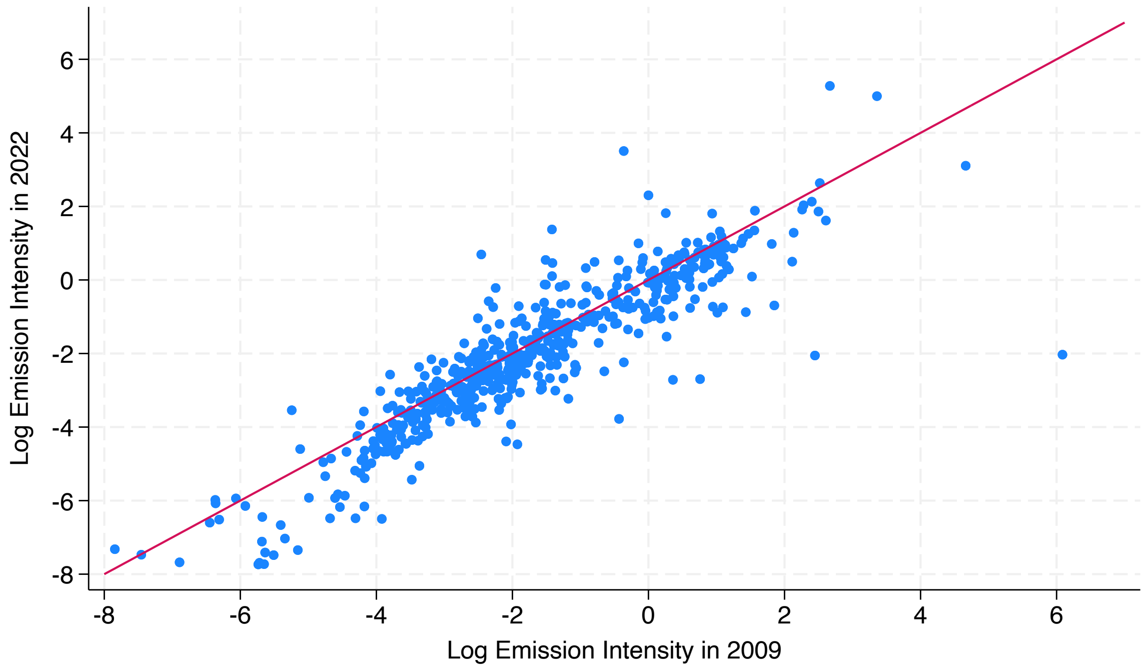
Figure 1: Changes in Aggregate Pollution Intensity in Canada: 2009-2022

and standard deviation of emissions, output and emission intensity across provinces within broad two-digit sectors in our data for 2009.[14] As this Table shows, there is substantial variation in emission intensity within sectors across provinces. Such variation is necessary for testing the role of geographic reallocations of economic activity within industries as a driver of the technique effect.

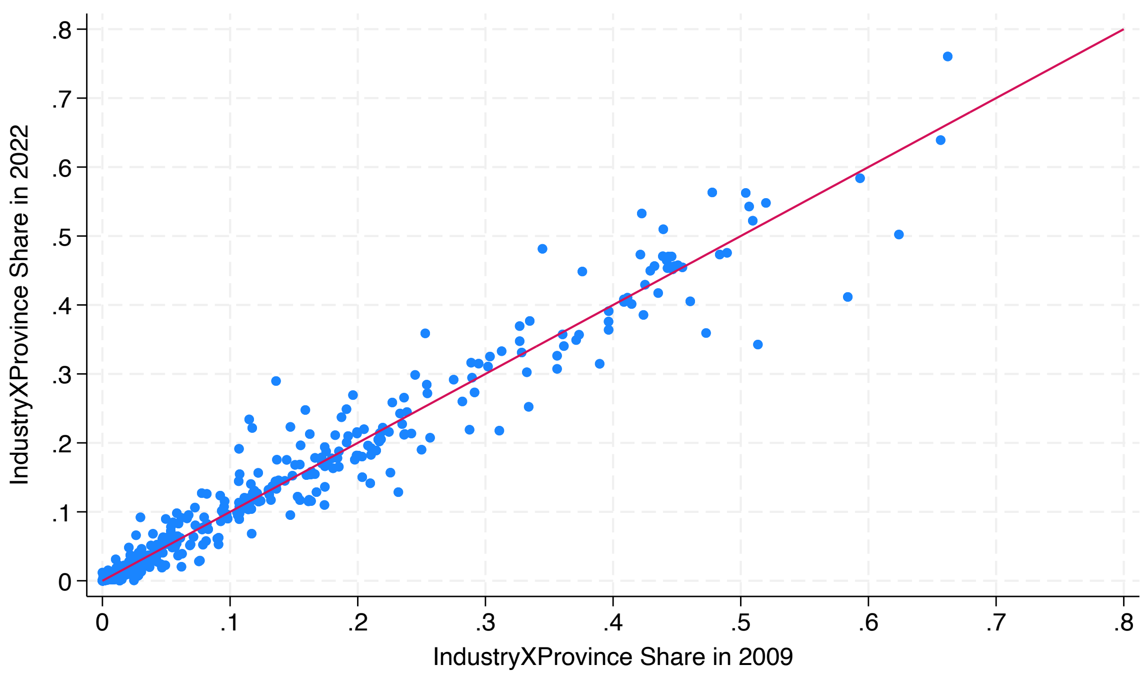
Table 1 also shows that there is also significant variation in emission intensity across broad two-digit sectors. Sectors that include energy-related industries, such as mining, quarrying, and oil and gas extraction (sector 21), utilities (sector 22), manufacturing (sector 32) and transport (sector 48) have substantially higher pollution intensities and emission levels than other sectors in the Canadian economy. Given that emissions shares are the primary weights in Equation (6), this suggests that energy related industries may drive our decomposition results. We return to investigate this further in Section 4.2.

The third fact from our data that we highlight is the significant heterogeneity in

[14]While we conduct our analysis below at the three-digit industry level, here we report these summary statistics at the two-digit level for expositional convenience.



(a) Pollution Intensity



(b) Output Shares

Figure 2: Changes in Industry×Province Pollution Intensity and Output Shares

Table 1: Emissions, Output and Emission Intensity by 2-Digit Sector in 2009

	Emissions		Value Added		Pollution Intensity	
Sector	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
11	5.45	6.59	2.47	2.38	1.55	1.15
21	13.98	33.89	5.85	10.50	1.32	1.05
22	8.30	14.43	3.07	4.53	3.97	5.02
23	0.51	0.66	9.33	12.97	0.06	0.02
31	0.43	0.60	2.57	4.14	0.21	0.15
32	8.18	10.60	5.17	8.04	1.73	1.33
33	2.05	4.44	6.08	11.72	0.21	0.14
41	0.77	1.19	6.41	10.67	0.14	0.09
48	4.42	5.41	4.49	5.98	1.19	0.39
49	0.17	0.25	1.00	1.66	0.19	0.09
51	0.12	0.19	6.73	11.13	0.02	0.01
52	0.11	0.18	8.81	16.27	0.03	0.05
53	0.82	1.15	16.36	24.72	0.06	0.04
54	0.16	0.25	7.53	12.69	0.03	0.04
56	0.45	0.72	3.82	6.35	0.19	0.17
61	0.02	0.03	7.54	11.62	0.00	0.00
71	0.02	0.04	1.07	1.69	0.02	0.02
72	0.12	0.15	2.90	3.98	0.07	0.05
81	0.25	0.36	2.80	4.16	0.09	0.03

Notes: Table reports variation in greenhouse gas emissions, value added and pollution intensity across provinces by 2-digit sector in 2009. For expositional convenience, greenhouse gasses are measured in megatonnes, and value added in billions of 2017 dollars, meaning pollution intensity is measured in tonnes per $1,000.

changes in pollution intensity across industry×provinces during our period of study. This variation is shown in Panel (a) of Figure 2, which plots industry×province pollution intensity in 2009 against industry×province pollution intensity in 2022. For expositional convenience, the figure depicts the natural log of industry×provinces pollution intensity in each year to account for the significant skewness in the distribution of pollution intensities. From the figure it is clear that pollution intensity fell over this period in most industry×provinces. If industry×province pollution intensities had not changed, all points would lie on the 45° line. However, the majority of points on the graph lie below the 45° line, indicating that pollution intensity in 2022 was lower than in 2009 for these industry×provinces. However, as the figure shows, there is substantial heterogeneity in these decreases and emission intensity *increased* for a number industry×provinces.

This heterogeneity highlights a potential role for the regional technique effect to explain aggregate changes in pollution intensity.

The fourth, and final, fact from our data that we highlight is the significant heterogeneity in changes in the spatial distribution of economic activity across industry×provinces between 2009-2022. These changes can be seen from Panel (b) of Figure 2, which plots the industry output shares of each industry×province in 2009 and 2022. Similar to Panel (a), if the industry output shares of each industry×province had not changed, all points would lie on the 45° line. However, as Panel (b) shows, most points lie off the 45° line, meaning there were numerous across-province shifts in economic activity within industries. These shifts in the spatial distribution of economic activity within industries suggests there is also scope for the regional reallocation effects to potentially explain the technique effect.

4 Results

4.1 Decomposing Aggregate Emission Intensity

We begin our analysis by using our discrete version of the standard decomposition (Equation (3)) to decompose the changes in aggregate emission intensity depicted in Figure 1 into the composition, technique and interaction effects. The results from this exercise are reported in Figure 3.

As Figure 3 shows, the reduction in aggregate greenhouse gas emission intensity of Canadian production has primarily been driven by the technique effect. Our estimate of the technique effect (given by the long-dashed line marked with diamonds) indicates that if the composition of Canadian industries had been held fixed as of 2009, aggregate pollution intensity would have declined by 24% by 2022. In contrast, our estimate of the composition effect (given by the dashed line marked with triangles) suggests that, if the emission intensity of Canadian output had been held fixed at the start of our period of

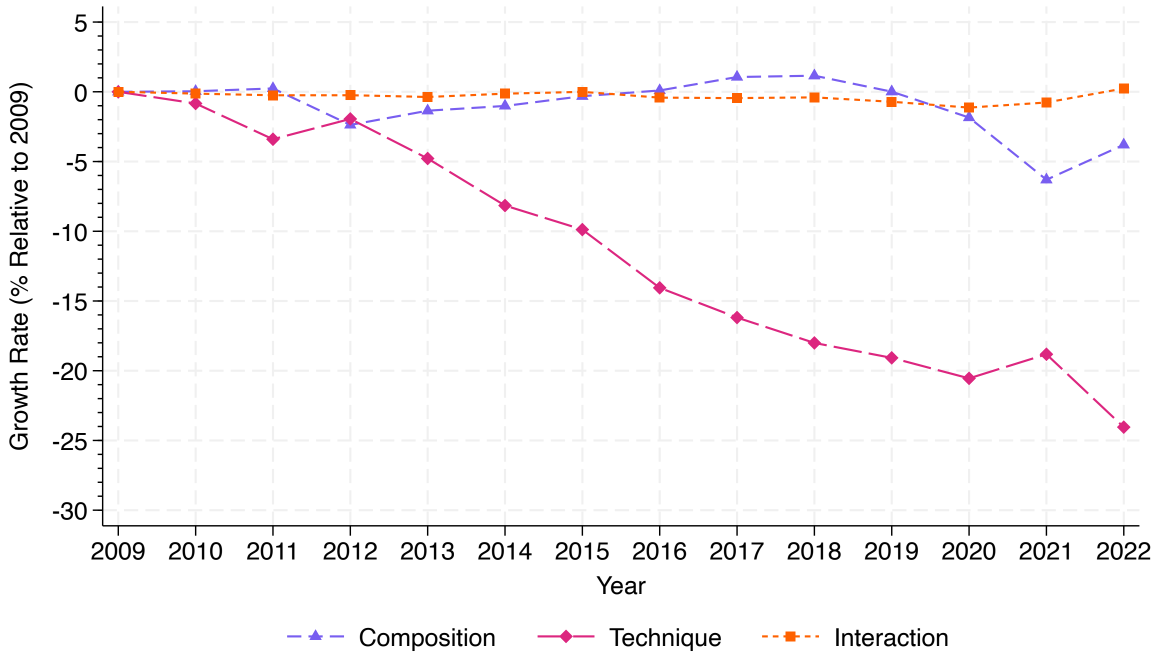


Figure 3: Decomposing Aggregate Emission Intensity

study, aggregate emission intensity would have declined by 3.8% over the same period. Our estimates also suggest that the interaction effect (depicted by the short-dashed line marked with squares) arising from reductions in emission intensity in industries that have grown in economic importance over our sample period is small; we find that this interaction caused aggregate emission intensity to increase by 0.2% by 2022.

Our finding that the technique effect is the primary determinant of the reduction in the aggregate greenhouse gas emission intensity of Canadian production mirrors findings for other time periods and pollutants both in Canada (e.g. Najjar and Cherniwchan (2021)), and for many countries elsewhere in the world (e.g. Levinson (2009, 2015), Brunel (2017), Cole and Zhang (2019), Copeland et al. (2022)). Next, we apply our extended decomposition given by Equation (6) to examine the extent to which the technique effect is capturing the effects of changes in the geographic distribution of economic activity across Canada. The results of this exercise are displayed in Figure 4. For the sake of expositional clarity, this figure again displays the technique effect pre-

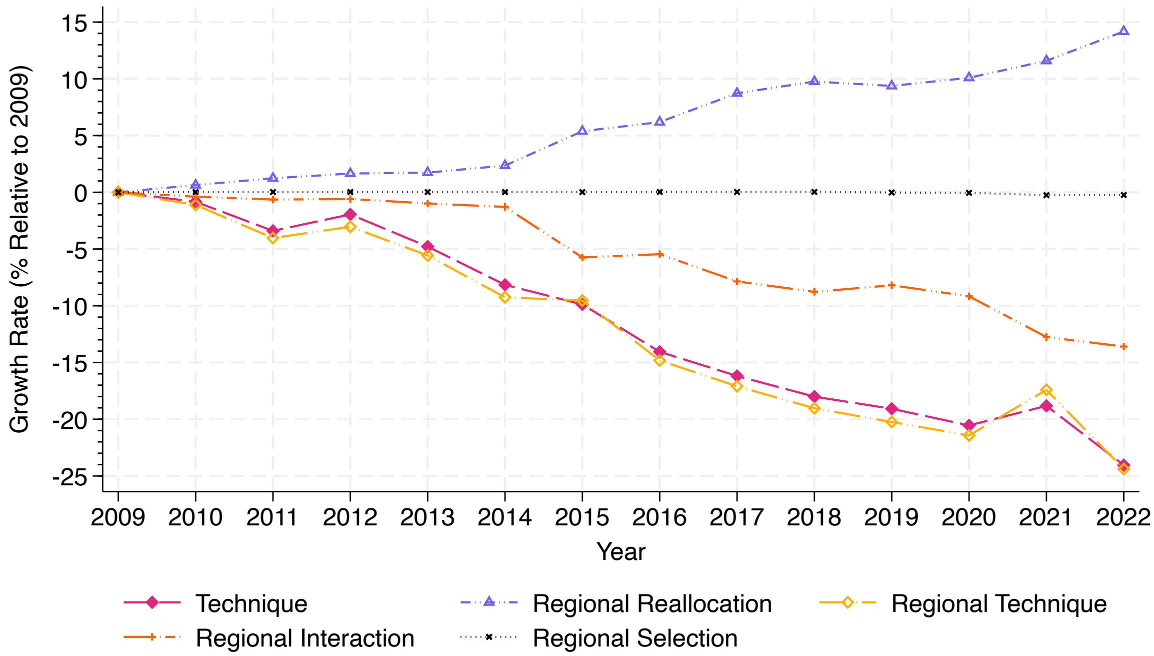


Figure 4: Decomposing The Technique Effect

viously reported in Figure 3, as well as the regional technique, reallocation, interaction and selection effects given by the last four terms in Equation (6).

As Figure 4 shows, changes in the geographic distribution of economic activity within industries increased aggregate pollution intensity in Canada. Our estimate of the regional reallocation effect (depicted by the short-dashed dotted line marked with hollow triangles) suggests that there were substantial within-industry shifts in the spatial distribution of economic activity towards relatively emission intensive provinces during our period of study. This estimate suggests that if the regional emission intensity of industry had been held fixed at 2009 levels, then the technique effect would have *increased* aggregate emission intensity by 14.2% by 2022. Strikingly, this within-industry compositional change is substantially larger in magnitude (in absolute value) than the traditional across-industry composition effect reported in Figure 3.

Why then, did the technique effect reduce aggregate emission intensity to the extent that it did? The answer appears to be the combination of regional technique and regional interaction effects. Our estimate of the regional technique effect (given by the long-dash dotted line marked by hollow diamonds) indicates that if the industry and geographic composition of Canadian output had been held fixed as of 2009, aggregate emission intensity would have declined by 24.4% by the end of our sample period. Moreover, our estimate of the regional interaction effect (depicted by the dash dotted line marked by crosses) shows, as economic activity shifted within-industry towards relatively emission intensive provinces, the emission intensity of these industries in these provinces began to fall. This co-movement of within-industry shifts in economic activity and within-industry×province reductions in emission intensity led to a 13.6% reduction in aggregate emission intensity that, when combined with the regional technique effect, more than offset the increase from the regional reallocation effect.

It is also worth noting that the entry and exit of industries from provinces played little role in explaining aggregate emission intensity in Canada between 2009 and 2022. We find that the regional selection effect (depicted in Figure 4 by the dotted lined marked with x's) decreased aggregate emission intensity by 0.2% during this period.

4.2 The Energy Sector

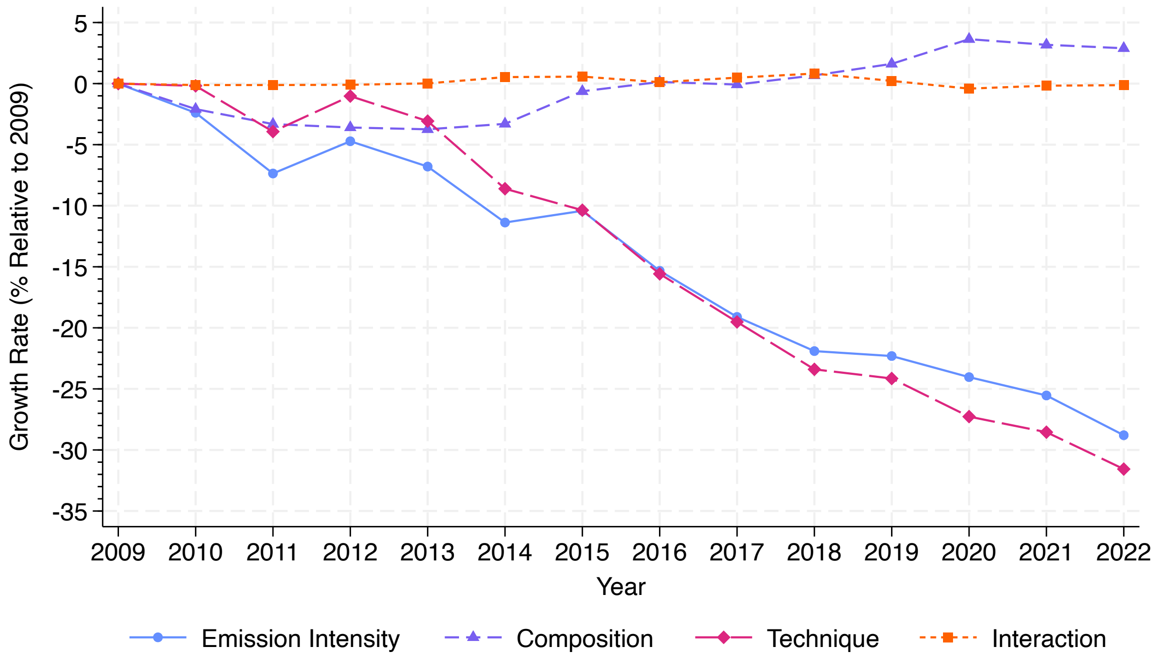
Altogether, the estimates presented in Figures 3 and 4 suggest that within-industry shifts in the spatial distribution of economic activity across provinces are an important determinant of aggregate greenhouse gas intensity in Canada. However, as we noted in the introduction, one potential concern with this finding is that is driven by industries in the energy sector, as this sector is an important driver of the Canadian economy (Loertscher and Pujolas, 2024). Indeed, as we showed in Section 3, energy related sectors are substantially more pollution intensive and emit more pollution than other sectors of the Canadian economy. Given that each of the terms on the right-hand in Equation (6) is a weighted sum of industry emission shares, our main results may be driven by industries in the energy sector.

To investigate whether this is the case, we again employ Equations (3) and (6) to decompose aggregate emission intensity and the technique effect, but we now perform these decompositions separately for the energy sector and the rest of the Canadian economy. Here we follow the approach taken by Statistics Canada (2024a) and define the energy sector as being comprised of NAICS sub-sectors in mining, quarrying, and oil and gas extraction (sub-sectors 211, 212, and 213), utilities (sub-sector 221), petroleum and coal product manufacturing (sub-sector 324) and pipeline transportation (sub-sector 486). The results from this exercise are presented in Figures 5 and 6. For convenience, the effects presented in Figures 5 and 6 are labeled similarly to Figures 3 and 4, but the two panels of Figure 5 now also include changes in aggregate pollution intensity (as depicted in the solid blue lines marked with circles).

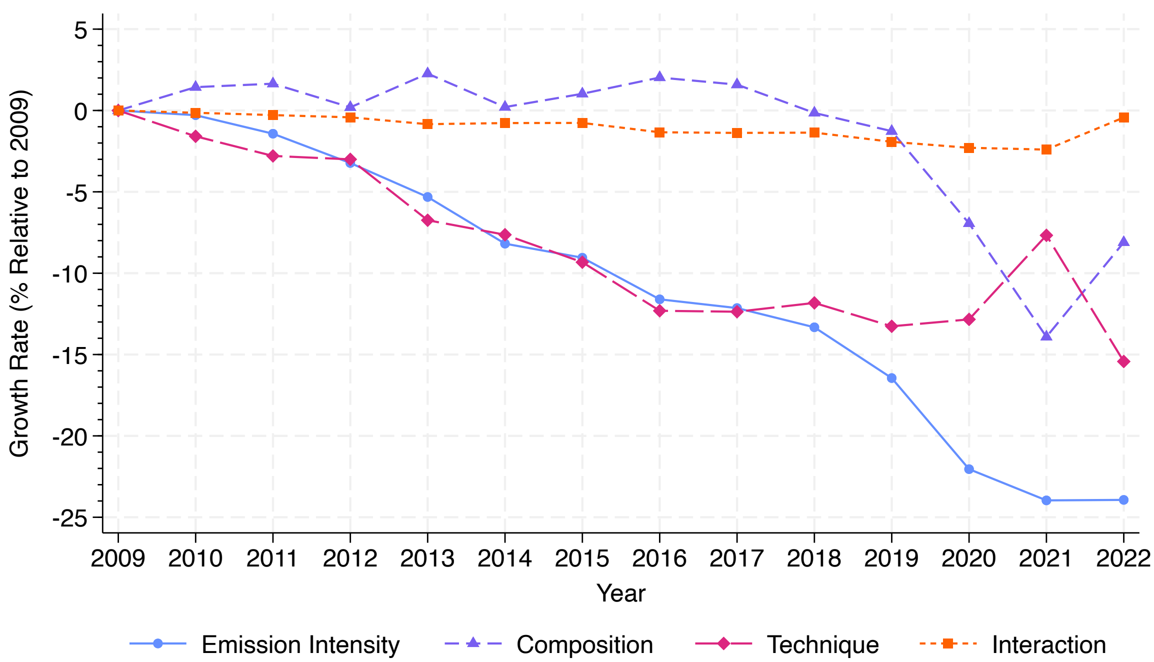
As the results presented in the two panels of Figure 5 show, the pollution intensity of production has been falling in both the energy sector and the rest of the Canadian economy primarily as a result of the technique effect. As Panel (a) of the figure shows, the pollution intensity of the energy sector has fallen by 28.8%, while Panel (b) of the figure shows that the pollution intensity of the rest of the Canadian economy has fallen by 23.9%. Our estimate of the technique effect for the energy sector reported in Panel (a) suggests that if the industrial composition of the sector was held fixed at 2009 levels, the greenhouse gas intensity of the energy sector would have fallen by 31.5%; this effect was offset by a positive composition effect of 2.9%. For the rest of the Canadian economy, the technique effect decreased aggregate pollution intensity by 15.4%, while the composition effect decreased aggregate emission intensity by 8.1%, as shown in Panel (b).[15]

The estimates reported in Figure 6 indicate that our primary finding – that changes in the spatial distribution of economic activity across provinces are an important determi-

[15] It is worth noting that while the technique effect is the primary driver of aggregate emission intensity in the rest of the Canadian economy at the end of our study, the relative importance of the composition and technique effects appears to have changed briefly in 2021. While explaining this change is beyond the scope of the current paper, it appears to coincide with the effects of the COVID-19 pandemic. For further discussion of the effects of the COVID-19 on Canada, see Slade (2022) or Cotton et al. (2022).

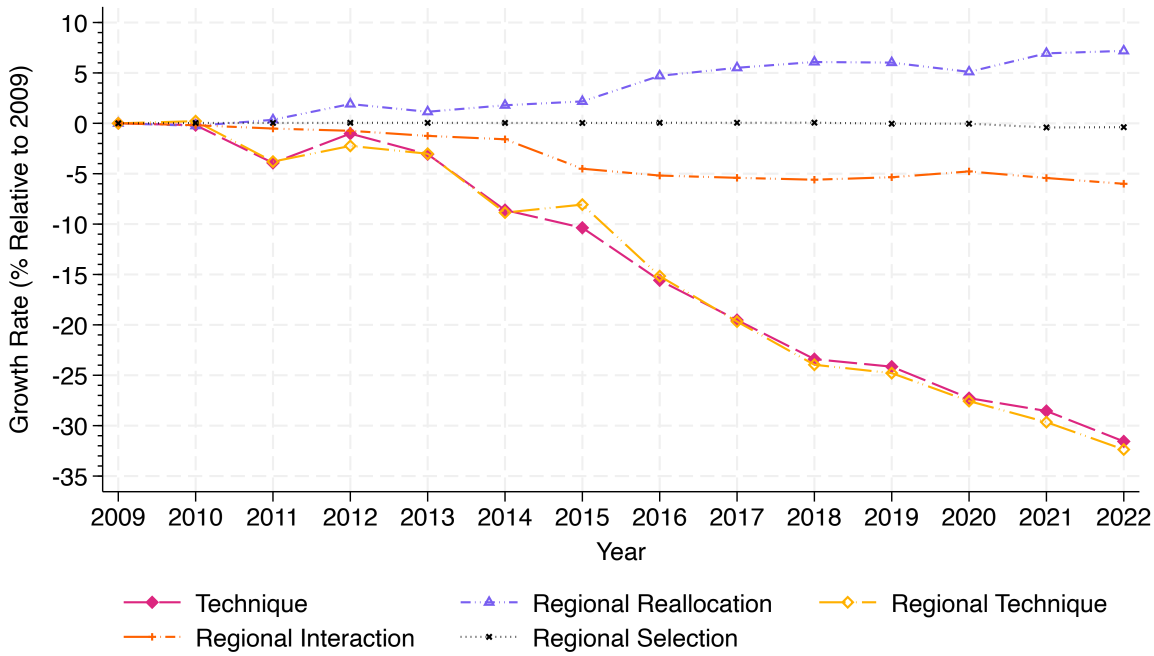


(a) The Energy Sector

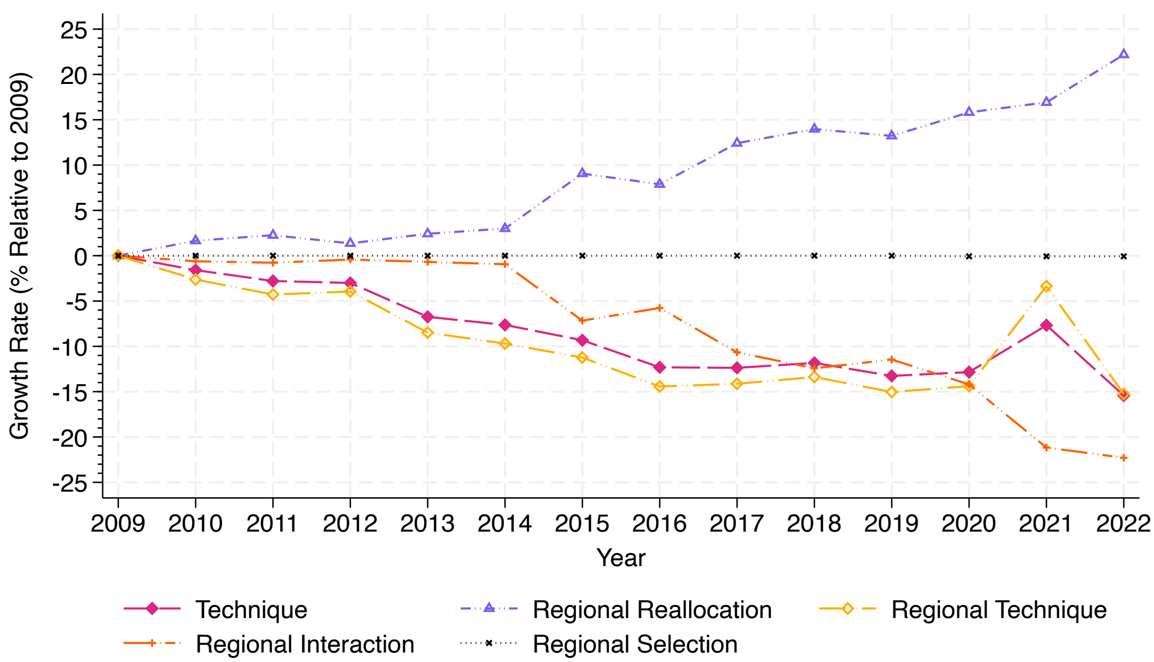


(b) The Rest Of The Economy

Figure 5: The Energy Sector vs. Other Economic Activity



(a) The Energy Sector



(b) The Rest Of The Economy

Figure 6: The Technique Effect: Energy vs. Other Sectors

nant of aggregate greenhouse gas intensity in Canada – is not being driven by the energy sector, despite its outsized role in determining aggregate greenhouse gas emissions. Instead, changes in the energy sector appear to be masking larger changes in the spatial distribution of economic activity across provinces elsewhere in the economy. As Panel (a) of the figure shows, the regional reallocation effect increased the pollution intensity of energy sector by 7.2%; the pollution intensity of the energy sector fell because this increase was offset by a regional interaction effect of -6.0% and a regional technique effect of -32.4%. Panel (b) shows that the regional reallocation and regional interaction effects were much larger for the rest of the Canadian economy during our period of study. As the panel shows, the regional reallocation effect increased the pollution intensity for the rest of the Canadian economy by 22.2%, which was offset by a 22.3% reduction from the regional interaction effect and a 15.2% reduction from the regional technique effect.[16]

4.3 Goods vs. Services

Our analysis thus far suggests that changes in the spatial distribution of economic activity across provinces are particularly important for determining the aggregate emission intensity of non-energy related production for the Canadian economy. As the last step in our analysis, we ask if there is any further heterogeneity in the importance of geography in driving the technique effect. To do so, we divide non-energy production in Canada into two broad sectors: goods and services.[17]

We again first decompose changes in the aggregate emission intensity of each sector

[16] It is worth emphasizing that the entry and exit of industries from provinces again has little role in explaining aggregate emission intensity; it decreased the pollution intensity of the energy sector by 0.4% and the pollution intensity of rest of the Canadian economy by 0.6%.

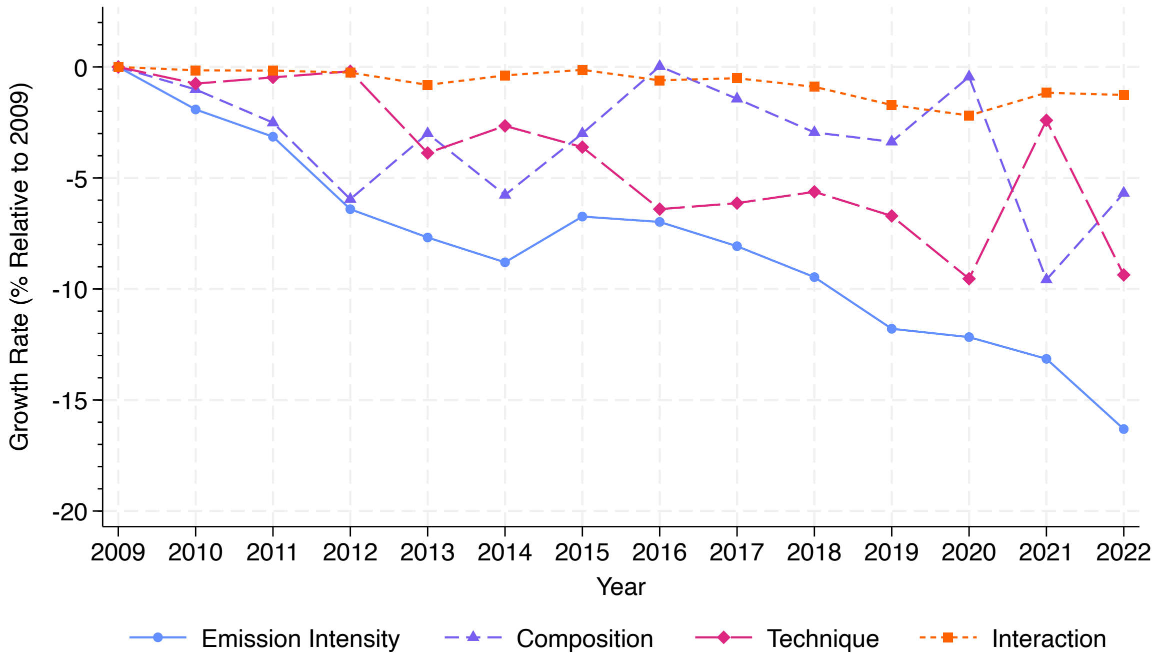
[17] Here, we again follow Statistics Canada (2024a) in grouping non-energy related sub-sectors into goods and services. What we term the goods producing sector roughly corresponds to the set of three digit NAICS sub-sectors contained in NAICS codes 11 (agriculture), 23 (construction), and 31-33 (manufacturing, excluding sub-sector 324), and what we term the services sector roughly corresponds to the set of three digit NAICS sub-sectors contained in NAICS codes 41 (wholesale trade), 44-45 (retail trade), 48-49 (transportation and warehousing, excluding subsector 486), 51 (information), 52 (finance and insurance), 53 (real estate), 54 (professional services), 56 (administrative services), 61 (education services), 71 (arts and entertainment), 72 (accommodation and food services), and 81 (other services).

into the composition, technique and intensity effects using Equation (3), and then further decompose the technique effect using equation Equation (6). The results of this exercise are presented in the two panels of Figures 7 and 8, respectively. Panel (a) in each figure displays the results of the relevant decomposition for the non-energy goods sector, while Panel (b) in each figure reports the results for the non-energy services sector. For convenience, the effects presented in Figures 7 and 8 are again labeled as before.

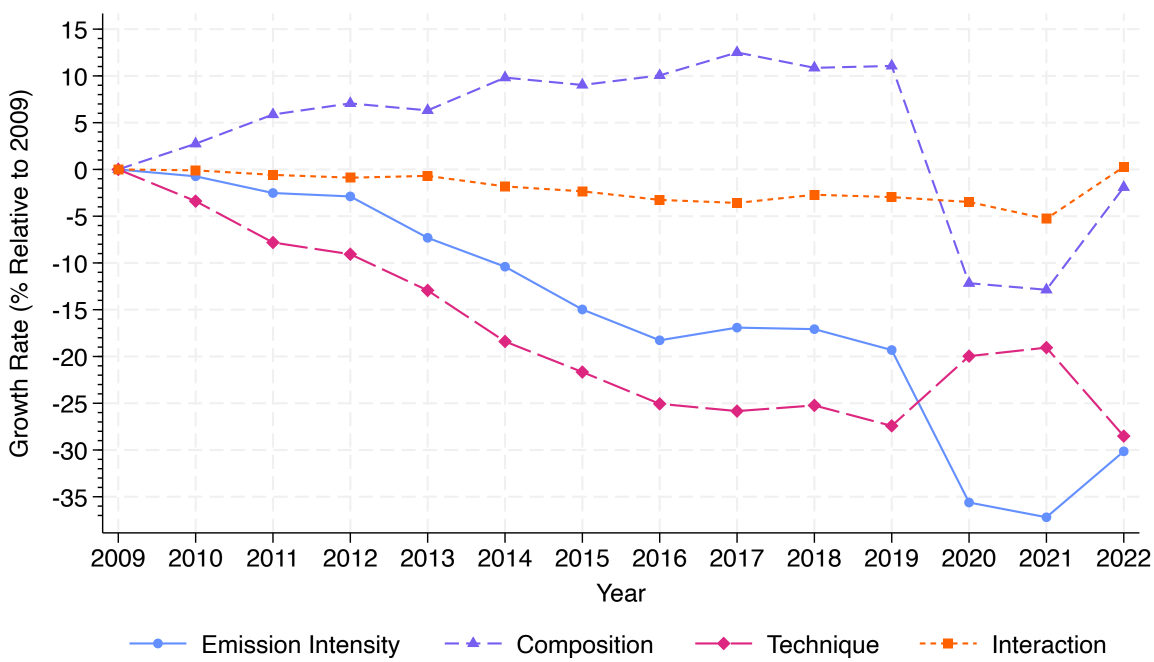
As Figure 7 shows, the emission intensities of both the goods sector and services sector declined during our period of study. The greenhouse gas intensity of goods production fell by 16.3%, whereas the greenhouse gas intensity of services fell by 30.1% between 2009 and 2022. These declines are both primarily due to the technique effect. As shown Panel (a), the technique effect accounts the majority of the decline in the emission intensity of the goods sector; if the composition of this sector had remained unchanged, the sector's emission intensity would have have fallen by 9.4% due to the technique effect. Similarly, the technique effect accounts for a similarly large share of the decline in the emission intensity of the Canadian services sector. The estimates reported in Panel (b) indicate that if its composition had remained fixed as of 2009, the service sector's emission intensity would have have fallen by 28.5% due to the technique effect, which accounts for most of the overall reduction in the sector's emission intensity. In the goods sector, the composition effect decreased aggregate emission intensity by 5.7%, while the interaction effect caused emission intensity to decline by 1.3%, whereas in the services sector, the composition effect decreased the sector's emission intensity by 1.9% and the interaction effect increased it by 0.3%.[18]

While the technique effect is the primary driver of reductions in the emission intensity of both sectors, the role of spatial shifts in economic activity differ starkly across goods and services. This can be seen clearly from the two panels of Figure 8. As Panel

[18]It is again worth noting that the COVID-19 pandemic appears to have coincided with stark changes in the relative importance of the composition and technique effects in explaining changes in the aggregate greenhouse gas intensity of both the goods and services sector. We again leave further investigation of this to future work.

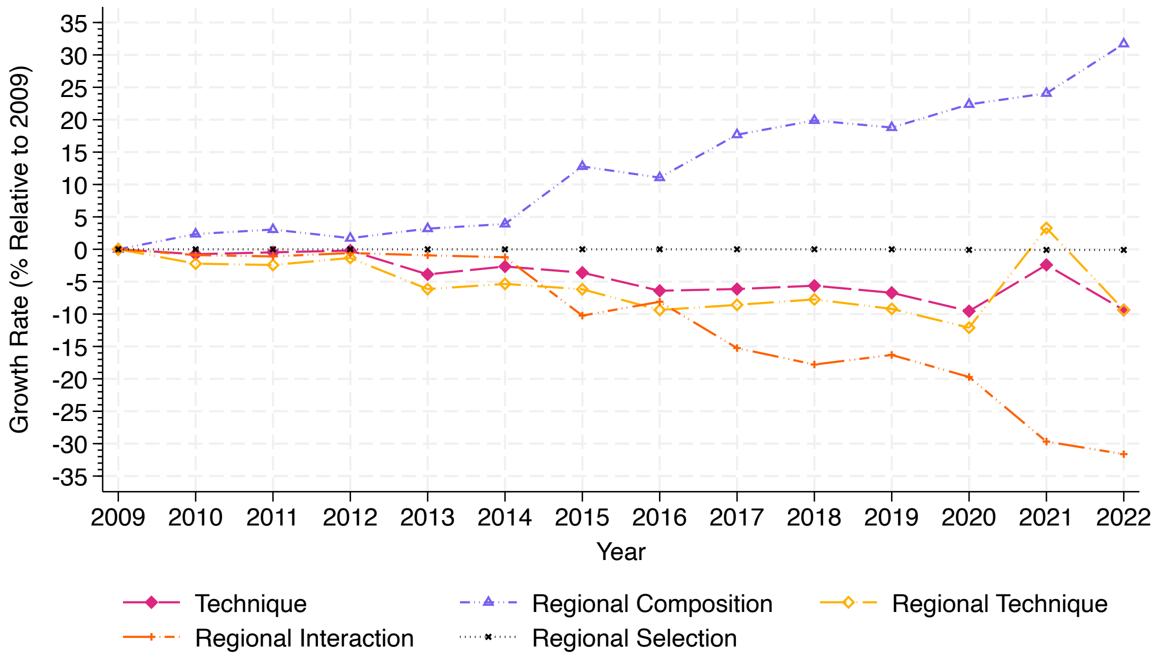


(a) Goods

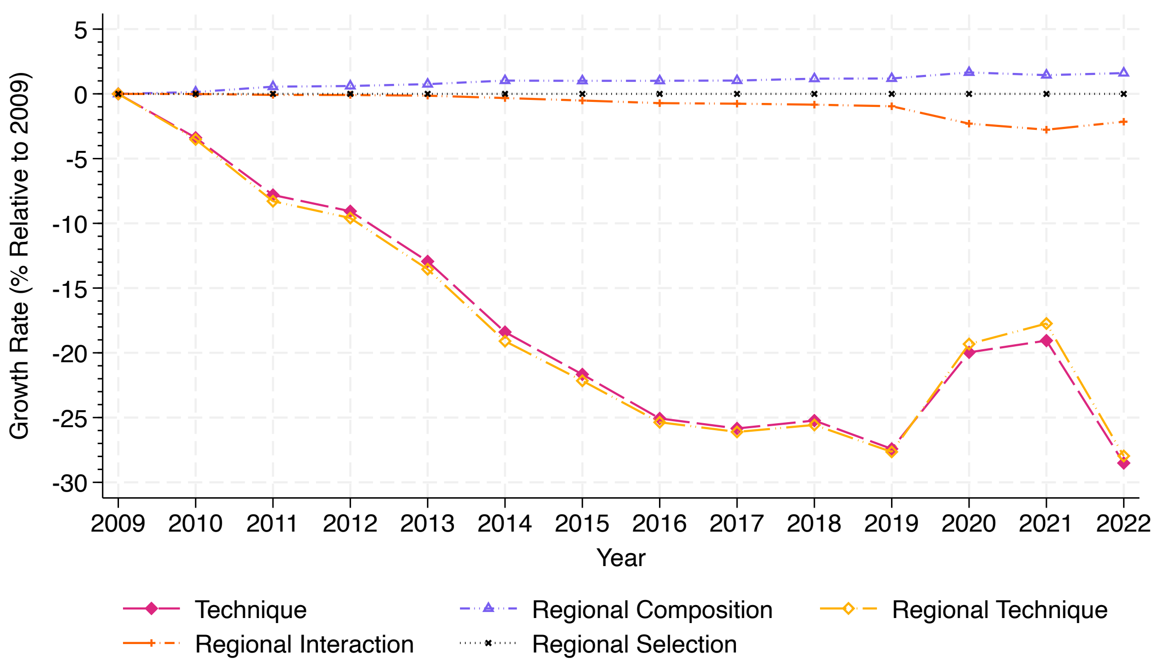


(b) Services

Figure 7: Decomposing Aggregate Pollution Intensity By Sector



(a) Goods



(b) Services

Figure 8: Decomposing the Technique Effect By Sector

(a) of the figure shows, in the goods sector within-industry shifts in the spatial distribution of economic activity are significant; the regional technique effect is accompanied by large regional reallocation and regional interaction effects. The regional technique and regional interaction effects reduced the emission intensity of the goods sector by 9.4% and 31.6%, respectively, offsetting an 31.7% increase arising from the regional reallocation effect.[19] In contrast, in the services sector within-industry shifts in the spatial distribution of economic activity play almost no role in driving sectoral pollution intensity as the technique effect is almost completely explained by the regional technique effect. As shown in Panel (b), the regional technique effect reduced emission intensity of services by 27.9%, while the regional reallocation effect increased it by 1.6% and the regional interaction effect decreased it by 2.2%.[20]

While a full examination of the causes of these stark differences in the importance of changes in the spatial distribution of economic activity across these two sectors is beyond the scope of this paper, one potential explanation for the disparity is differences in the importance of inter-provincial trade costs. In Canada, internal trade costs are much lower for goods than for services (Albrecht and Tombe, 2016). As such, the observed difference in the magnitude of regional reallocation and regional interaction effects could reflect sectoral differences in the ease of shifting economic activity across provinces.

5 Concluding Remarks

This paper examines how changes in the geographic distribution of economic activity have contributed to the technique effect. We extend the standard industry-level decomposition that has been used in the existing literature to formally show the technique effect may reflect within-country shifts in the geography of economic activity and use this extended decomposition to study changes in the pollution intensity of Canadian

[19] The regional selection effect reduced the emission intensity of the goods sector by 0.1%.

[20] The regional selection effect reduced services sector emission intensity by less than 0.01%.

production over the period 2009 to 2022.

Our analysis suggests that the technique effect may be driven, in part, by changes in the geographic distribution of economic activity within industries across regions within countries. Our estimates indicate that if industry×region emission intensity had been held fixed at 2009 levels, within-industry shifts in economic activity towards relatively dirty provinces would have increased the aggregate greenhouse gas intensity of Canadian production by 14.2% by 2022. We find that the technique effect caused Canadian pollution intensity to decline by 24% in aggregate because industry×region emission intensity decreased, and these decreases were largest in those industry×regions that also increased in economic importance due to within-industry shifts in economic activity.

Our analysis also finds that the relative importance of changes in the geographic distribution of economic activity within industries differ substantially across major sectors of the economy. Our results suggest that reallocations of economic activity have the largest impact on aggregate emissions in non-energy goods production, and have substantially smaller effects in the energy sector and in non-energy services. While trade costs offer one explanation for this finding, unpacking the causes of these differences would be a worthwhile topic for future study.

Although our results provide some initial support for the possibility that the technique effect captures, in part, changes in where production occurs, there are at least two caveats to our analysis worth mentioning. The first is aggregation. As we noted above, while we are using the most disaggregated data available for Canada that also report geographic information, our estimates of both the technique effect and its sub-components may reflect unmeasured compositional changes. Second, we measure pollution using data on greenhouse gas emissions. As such, our conclusions may not extend to other pollutants. We also leave further investigation of these possibilities to future work.

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Appendix A An Extension to the Firm Level

As we noted in the main text, while we focus on the industry×region level due to data limitations, our decomposition can be easily extended to the firm level along the lines of Cherniwchan et al. (2017). To see this, first suppose that in each region r, there is a set of firms operating in industry i at time t. Denote this set Ω_{irt}. Furthermore, let ι_{firt} and ν_{firt} denote output and emissions from firm f, respectively. Then the pollution intensity of industry i in region r at time t can be written as a weighted sum of firm pollution intensities:

$$e_{irt} = \sum_{f \in \Omega_{irt}} s_{firt} \epsilon_{firt} \tag{7}$$

where $s_{firt} = \iota_{firt}/x_{irt}$ is firm f's share of industry i's output in region r, and $\epsilon_{firt} = \nu_{firt}/\iota_{firt}$ is firm f's pollution intensity. It is possible to show that the change in the pollution intensity of industry i in region r across two periods t and $t-1$ can be written:

$$\begin{aligned} \frac{e_{irt} - e_{irt-1}}{e_{irt}} = & \sum_{f \in \Omega^C_{irt}} \vartheta_{firt-1} \left[\frac{\epsilon_{firt} - \epsilon_{firt-1}}{\epsilon_{firt}} \right] + \sum_{f \in \Omega^C_{irt}} \vartheta_{firt-1} \left[\frac{s_{firt} - s_{firt-1}}{s_{firt}} \right] \\ & + \sum_{f \in \Omega^C_{irt}} \vartheta_{firt-1} \left[\frac{\epsilon_{firt} - \epsilon_{firt-1}}{\epsilon_{firt}} \right] \left[\frac{s_{firt} - s_{firt-1}}{s_{firt}} \right] \\ & + \sum_{f \in \Omega^E_{irt}} \vartheta_{firt} \left[\frac{\epsilon_{firt}}{\epsilon_{firt-1}} \right] - \sum_{f \in \Omega^X} \vartheta_{firt-1} \end{aligned} \tag{8}$$

where $\vartheta_{firt} = \nu_{firt}/z_{irt}$ is firm f's share of total emissions from industry i in region r. The first term on the right-hand side is akin to what Holladay and LaPlue III (2021) and Najjar and Cherniwchan (2021) term the *firm-level process effect*; it reflects the change in industry×region pollution intensity due to reductions in the pollution intensity of individual firms. The second term on the right hand side is akin to the *firm-level reallocation effect*; it reflects the change in industry×region pollution intensity due to reallocations of economic activity across firms. The third term is a *firm-level interaction effect* that captures changes in industry×region pollution intensity due to the co-movement between firm pollution intensity and firm output shares. The last two terms are akin to the *firm entry and firm exit effects* that capture changes in industry×region pollution intensity due to changes in the set of firms operating in an industry×region. Combined, these last two terms are akin to what Holladay and LaPlue III (2021) and Najjar and Cherniwchan (2021) term the *selection effect*.

Substituting equation (8) into the technique effect in equation (6) yields the full firm level decomposition:

$$
\begin{aligned}
\frac{E_t - E_{t-1}}{E_{t-1}} = & \sum_{i \in N} \Theta_{it-1} \left[\frac{\Phi_{it} - \Phi_{it-1}}{\Phi_{it-1}} \right] + \sum_{i \in N} \Theta_{it-1} \left[\frac{\Phi_{it} - \Phi_{it-1}}{\Phi_{it-1}} \right] \left[\frac{E_{it} - E_{it-1}}{E_{it-1}} \right] \\
& + \sum_{i \in N} \Theta_{it-1} \left[\sum_{r \in R_{it}^C} \theta_{irt-1} \left[\frac{\phi_{irt} - \phi_{irt-1}}{\phi_{irt-1}} \right] \right] \\
& + \sum_{i \in N} \Theta_{it-1} \left[\sum_{r \in R_{it}^C} \theta_{irt-1} \left[\frac{e_{irt} - e_{irt-1}}{e_{irt-1}} \right] \left[\frac{\phi_{irt} - \phi_{irt-1}}{\phi_{irt-1}} \right] \right] \\
& + \sum_{i \in N} \Theta_{it-1} \left[\sum_{r \in R_{it}^E} \theta_{irt} \left[\frac{E_{it}}{E_{it-1}} \right] - \sum_{r \in R_{it}^X} \theta_{irt-1} \right] \\
& + \sum_{i \in N} \Theta_{it-1} \left[\sum_{r \in R_{it}^C} \theta_{irt-1} \left[\sum_{f \in \Omega_{irt}^C} \vartheta_{firt-1} \left[\frac{\epsilon_{firt} - \epsilon_{firt-1}}{\epsilon_{firt}} \right] \right] \right] \\
& + \sum_{i \in N} \Theta_{it-1} \left[\sum_{r \in R_{it}^C} \theta_{irt-1} \left[\sum_{f \in \Omega_{irt}^C} \vartheta_{firt-1} \left[\frac{s_{firt} - s_{firt-1}}{s_{firt}} \right] \right] \right] \\
& + \sum_{i \in N} \Theta_{it-1} \left[\sum_{r \in R_{it}^C} \theta_{irt-1} \left[\sum_{f \in \Omega_{irt}^C} \vartheta_{firt-1} \left[\frac{\epsilon_{firt} - \epsilon_{firt-1}}{\epsilon_{firt}} \right] \left[\frac{s_{firt} - s_{firt-1}}{s_{firt}} \right] \right] \right] \\
& + \sum_{i \in N} \Theta_{it-1} \left[\sum_{r \in R_{it}^C} \theta_{irt-1} \left[\sum_{f \in \Omega_{irt}^E} \vartheta_{firt} \left[\frac{\epsilon_{firt}}{\epsilon_{firt-1}} \right] - \sum_{f \in \Omega^X} \vartheta_{firt-1} \right] \right] \qquad (9)
\end{aligned}
$$

where, as before, the first term on the right hand side is the composition effect, the second is the interaction effect, the third is the regional reallocation effect, the fourth is the regional interaction effect and the fifth is the regional selection effect. Now, the regional technique effect has been further decomposed into firm level process, reallocation, interaction and selection effects.