Public Actors' Expenditures and Pollution in the Waste Management Sector

Rinelle Tekeu

Ph.D. Candidate, École Nationale d'Administration Publique

&

Colin Ndonfack

Ph.D. in Economics, Université de Montréal

Abstract

This paper examines the extent to which the activity of public and private waste-management actors influences waste diversion intensity and non-CO_2 greenhouse-gas (GHG) emissions from biomass in Canada. We estimate (i) a Cobb–Douglas production function to predict the value of public-sector output; (ii) event-study models explaining total GHG emissions from biomass; and (iii) a pollution model explaining the intensity of waste diversion and the resulting GHG emissions. The analysis uses a provincial panel covering 2002–2018. The key variables capture capital expenditures, operating expenditures, and operating revenues of municipalities and firms, as well as flows and stocks of landfilled waste. Results from the event-study models (ii) show that municipal capital expenditures in waste management are associated with a significant reduction in GHG emissions at a +3-year horizon (a delayed effect), whereas firms' capital is not significant. Firms' economic activity (revenues) is linked to a reduction in GHG emissions in the following year according to the event-study estimates; however, the pollution model (iii) indicates that a 1% increase in firms' output raises waste diversion intensity by 0.22%, while a 1% increase in predicted municipal output reduces it by 0.151%. GHG emissions respond strongly to new waste inflows and, more modestly, to accumulated stocks, confirming the importance of addressing both inflows and stocks simultaneously. Provincial heterogeneity suggests differentiated policies. Overall, the findings argue for greater public investment (composting, recycling, landfill-gas capture) in waste management.

Keywords: waste management; GHGs; pollution intensity; public investment.

1. INTRODUCTION

Over the period 2002–2022, the total amount of solid waste diverted increased from 212 to 254 kilograms (kg) per person, a rise of 20% (Environment and Climate Change Canada, 2024). These are wastes diverted from landfill or incineration—that is, wastes that are recycled, composted, or reused. Over the same period, the amount of solid waste disposed of in landfills fell by 11%, from 768 to 684 kg per capita (Environment and Climate Change Canada, 2024). These are wastes that are landfilled or incinerated. Under Target 12.5 of the Sustainable Development Goals (SDGs), the UN aims to substantially reduce waste generation by 2030 through prevention, reduction, recycling, and reuse (UN, 2021). In its 2022–2026 Federal Sustainable Development Strategy, the federal government seeks to contribute to this target by aiming to reduce "the amount of waste that Canadians send to disposal from a baseline of 699 kilograms per person in 2014 to 490 kilograms per person by 2030 (a reduction of 30%) and to 350 kilograms per person by 2040 (a reduction of 50%)" (Environment and Climate Change Canada, 2022). Thus, according to these two government reports, the amount of solid waste disposed of in landfills went from 699 kg per person in 2014 to 684 kg in 2022, a decrease of about 2%. A substantial effort is therefore still required to reach the 30% reduction target by 2030.

To achieve this objective, the actions to be undertaken are set out in (Environment and Climate Change Canada, 2022, p. 137), in the following order of preference: (1) waste prevention; (2) reuse; (3) refurbishment; (4) recycling; (5) energy recovery; (6) landfill. Waste prevention, the top priority, can occur at the level of consumption—especially household consumption—through strict avoidance or source reduction (Cox et al., 2010). Pricing incentives can be used for this purpose. In some Canadian cities (notably in the West), there are policies under which households pay according to the amount of waste they produce (Kelleher Environmental Robins Environmental, 2009). However, influencing household behavior remains difficult (Barr, 2007). By contrast, public actors have more levers over the intensity with which consumption-generated waste is directed to landfills, by promoting and investing in recycling (including composting) and energy recovery. Indeed, according to (Circular Inovation Council, 2017), diverting waste from landfill and incineration can be influenced "by regulations from all three levels of government (federal, provincial, and municipal)." We can define the waste emission intensity as the amount of waste deposited in landfills per dollar of goods consumed, since consumption is the economic activity that gives rise to waste. According to integrated assessment models, some of which are presented by (Nordhaus, 2013), emissions are proportional to the activities that generate them, with the proportionality coefficient representing the intensity of pollution.

Moreover, reducing disposed waste would help decrease greenhouse gas (GHG) emissions from biomass. Cutting the amount of organic waste sent to landfill—such as food scraps and yard trimmings—plays a key role in mitigating climate change, a result also highlighted by

(Castro et al., 2021), who show that waste management strategies can significantly reduce GHG emissions, including fluorinated gases. When this waste decomposes underground without oxygen, it produces methane (Environment and Changement Climatique Canada, 2023), a very potent greenhouse gas—much stronger than carbon dioxide (Environmental Protection Agency, 2024). Today, landfills are one of the main sources of methane in Canada, accounting for about 23% of national methane emissions (Environment and Changement Climatique Canada, 2023). It is therefore possible to divert this waste from landfill by valorizing it in other ways, for example through composting (Environmental Protection Agency, 2025) or biogas recovery (Environmental Protection Agency, 2024). These solutions not only reduce non-CO2 GHG emissions but also produce renewable energy or compost useful for agriculture.

As (Bogner et al., 2011) point out, methane generation in landfills is a long-term anaerobic degradation process. Emissions thus come from both recently deposited waste and waste accumulated over many years. This dynamic is captured by the LandGEM (Landfill Gas Emissions Model), developed by the EPA and presented by (Krause & Thorneloe, 2024). This model, based on a first-order decay equation, makes it possible to estimate methane production and emissions while accounting for both historical and current inputs. LandGEM is now widely used by operators and authorities to forecast air pollutant emissions from landfills.

Understanding the factors that determine the intensity of waste emissions in landfills could help better identify the levers available to public actors. According to integrated assessment models of the economics of climate change, pollution is the product of economic activities, as shown by the models presented by (Nordhaus, 2013). In these models, the amount of pollution emitted is proportional to the economic activity that generates it. Applied to waste management, this implies that consumption is a primary driver of emissions. However, the production activity of actors in the biomass management sector—that is, their waste treatment capacity—could influence the intensity of these emissions. The activity of these actors is a combination of their equipment and investments, their operating resources (labor, inputs, etc.), and their technological innovation.

Furthermore, understanding the relationship between waste disposed of in landfills and the GHGs it emits could help assess the impact on global warming of government efforts to reduce waste-related emissions. Accordingly, in this study we examine the impact of local government activities—measured by their output in the waste treatment sector—on the intensity of emissions in landfills. We also examine the relationship between waste emissions and the GHG emissions they generate. The remainder of this document presents a brief literature review on environmental degradation in relation to economic activity and on the determinants of industrial pollution and environmental innovation (Section 2), an econometric model to estimate the effects of interest (Section 3), the data and variables used (Section 4), and the preliminary results (Section 5).

2. LITERATURE REVIEW

2.1. Economic activity and environmental degradation

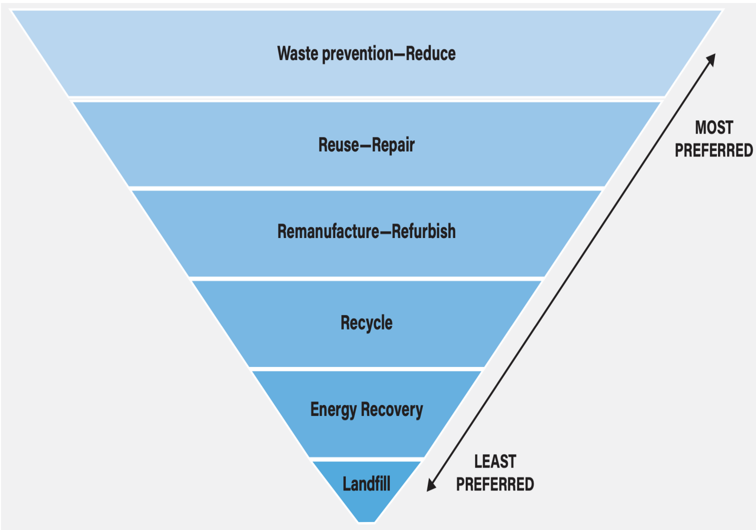
Existing studies recognize the link between economic activity and environmental degradation. According to the Environmental Kuznets Curve (EKC), first introduced by (Grossman & Krueger, 1991), there is an inverted-U relationship between economic growth and environmental degradation. The curve is named in reference to the work of (Kuznets, 1955, 1963), who proposed an inverted-U relationship between income inequality and the level of income. This relationship suggests that in the early stages of economic development, growth in a country's per-capita income is associated with an increase in per-capita pollution, which peaks when the country reaches a middle-income level. Thereafter, as the country becomes developed and technologically advanced, it increasingly adopts green technologies to combat environmental degradation. As a result, income growth is accompanied by a decrease in environmental degradation in these developed countries. Thus, under the EKC hypothesis, economic growth is a cause of environmental degradation in the early stages of development but becomes part of the solution at later stages, as developed countries have sufficient resources and technologies to tackle the problem. (Stern, 2018; Stern et al., 1996) offer a critical analysis of the EKC. (Stern et al., 1996) point out that some assumptions underlying the EKC are violated—most notably, the absence of feedback from environmental quality to economic growth itself, and the assumption that international trade has a neutral effect on environmental degradation. They also note econometric problems in EKC studies. A study by (Stern, 2018) suggests that "the true form of the relationship between emissions and income is probably monotonic, but the curve shifts downward over time."

While some studies examine the overall relationship between economic activity and environmental degradation (Grossman & Krueger, 1991; Lee et al., 2016; Stern, 2018; Stern et al., 1996), others proceed from the assumption that pollution is generated by production rather than consumption (Lopez, 2017; Nordhaus, 2013; Selden & Song, 1995), or develop models—generally overlapping-generations models—in which pollution is generated by consumption activities (John & Pecchenino, 1994; John et al., 1995). On the production side, a large literature explores the determinants of industrial pollution. These factors include the presence of environmental regulations such as property rights (Coase, 1960, 1990) or environmental taxes (Pigou, 1933); openness to international markets (Jiang et al., 2014); as well as firm-level characteristics such as the education level of personnel (Jiang et al., 2014; Weersink & Raymond, 2007) and firm size (Fang et al., 2020; Jiang et al., 2014).

2.2. Determinants of landfilled waste and the GHGs emitted by this biomass

The actions that determine the level of solid waste sent to landfills are discussed and ranked by order of desirability in (Environment and Climate Change Canada, 2022). An action is more desirable the fewer additional costs it entails. Thus, the most preferred action is to prevent and reduce waste—for example, by consuming fewer goods that generate waste. Next come the reuse of worn but still functional goods and the repair of damaged goods for reuse. Although more costly than reuse and repair, refurbishment also helps reduce the amount of worn goods that end up as solid waste. Other actions over which actors in the waste-management sector have greater control include recycling residual materials (including composting) and recovering energy (e.g., biogas extracted from organic waste).

Figure 1: Waste management hierarchy



Source: Environment and Climate Change Canada, 2022, p. 137

Thus, waste is generated by the consumption of goods (household final consumption, intermediate consumption, and consumption of producers' physical capital), but the capacity to recycle, compost, and extract energy from biomass on the part of waste-treatment actors gives them the power to influence the share of residual materials generated by consumption that ends up in landfills. Since this waste generates GHGs—mainly non-CO_2 gases such as methane (Environement et Changement Climatique Canada, 2023; Environmental Protection Agency, 2024)—reducing the intensity of landfilled waste by recovering value through recycling, composting, or biogas extraction will limit the intensity of those GHG emissions (Environmental Protection Agency, 2024, 2025). (Pardo et al., 2015) also argue that waste-management strategies significantly affect the GHGs emitted by this waste.

Although households (in their final consumption) or firms (in their intermediate or fixed-capital consumption) are the ones to prevent or reduce waste, public authorities can create incentive measures such as pricing policies. The literature distinguishes between direct and indirect pricing. Direct pricing means charging waste generators directly for treatment fees. These fees can be a flat amount or an amount proportional to the quantity of waste generated, known as Pay As You Throw (PAYT). Indirect pricing consists of levying an amount on the local government's tax base to manage waste. According to (Kelleher Environmental Robins Environmental, 2009), in cities in Western Canada, the direct pricing system is widely used by municipalities. In cities in Eastern Canada, by contrast, the indirect system predominates. Most municipalities therefore fund waste management through their tax base.

2.3. Contribution

Our work is very close to (Lee et al., 2016), who estimate Granger causality between economic growth and environmental degradation—that is, the Environmental Kuznets Curve (EKC) relationship. They assess the effect of GDP per capita on the amount of municipal solid waste (MSW) per capita; the effect of total MSW volume on greenhouse gas (GHG) emissions; and the effects of diverted waste on GHG emissions. Following (Stern, 2018), we consider that a measure of environmental degradation—given by the amount of landfilled waste—is monotonically increasing with economic activity, which we capture via GDP. Following the models described by (Nordhaus, 2013), we assume this relationship is proportional and heterogeneous. In other words, the level of pollution is proportional to the economic activity that generates it, with a heterogeneous proportionality coefficient. Accordingly, we consider that the level of landfilled waste in a province is proportional to that province's GDP. The proportionality coefficient is heterogeneous and varies over time and across provinces. Unlike (Lee et al., 2016), we therefore consider a monotonic and proportional relationship between landfilled waste and GDP. For a given province, this proportionality coefficient is given by the ratio of the amount of landfilled waste to that province's GDP. It is interpreted as a pollution-emission intensity, following (Nordhaus, 2013). One contribution of this work is to estimate the relationship between this emission intensity and the level of activity of actors in the waste-management sector. Particular attention will be paid to public actors, namely local governments. In addition, following (Lee et al., 2016), we aim to estimate the relationship between the level of landfilled waste and the level of non-CO_2 GHG emissions it generates.

3. MODEL

3.1. Production function

We aim to study the impact of the activity or production capacities of public and private actors in the waste-management sector on the intensity of waste emissions and on non-CO_2 GHG emissions from biomass. Production activities are represented by operating revenues as monetary indicators of output values. The operating revenue of a representative private firm in province i at time t is given by a Cobb–Douglas production function:

$$\mathrm{Log}(R_{it}^f) = \bar{\alpha} + \alpha_C \,\mathrm{Log}(K_{it}^f) + \alpha_O \,\mathrm{Log}(O_{it}^f) + \alpha_Y \,\mathrm{Log}(Y_{it}) + \mathrm{Log}(A_{it}) \tag{1}$$

Assuming that local governments have the same production function as private firms, the counterfactual gross revenue that a representative local government in province i at time t

would have if it sold its output on the market is:

$$\text{Log}(R^g_{it}) = \bar{\alpha} + \alpha_C \text{Log}(K^g_{it}) + \alpha_O \text{Log}(O^g_{it}) + \alpha_Y \text{Log}(Y_{it}) + \text{Log}(A_{it}) \tag{2}$$

where $K^s_{it} = K^s_{i,t-1} + C^s_{it}$ is the cumulative amount of capital expenditures by the actor in group $s \in \{f, g\}$, representing the physical capital stock. C^s_{it} is the amount of capital expenditure in period t; O^s_{it} is the amount of operating (i.e., current) expenditure; Y_{it} is GDP per capita in province i, representing the stock of waste generated by the province's overall economic activity. This generated waste constitutes an input for actors in the waste-treatment sector. Using GDP per capita rather than total GDP controls for size effects. A_{it} is an index composed of the level of technology and market prices for output.

3.2. Event Studies

As part of this study on the relationship between the activity of local governments (municipalities) in the waste-treatment sector and environmental degradation, we begin by estimating an event-study model. The goal is to examine the relationship between investment expenditures, the level of activity (given by the value of output) of actors in the waste-management sector, and the level of GHGs emitted by landfilled waste. We estimate this model separately for public and private actors. The event-study model (ES) is an econometric framework for estimating treatment effects when the treatment variable is continuous and varies across the observed units (provinces) and over time. The ES model we use here is inspired by (Freyaldenhoven et al., 2021) and is a generalization of the Differences-in-Differences (DiD) method. It is a linear model with dynamic treatment effects. Under this model, the pollution generated by landfilled waste in region i during year t is given by:

$$\text{Log}(GHG_{it}) = \alpha_i + \gamma_t + X'_{it}\lambda + \sum_{-G}^{M} \beta_m z_{i,t-m} + C_{it} + \epsilon_{it}$$

Where $\text{Log}(GHG_{it})$ represents the logarithm of a pollution variable, namely the quantity of GHGs (excluding CO_2) emitted by biomass—that is, by the amount of waste landfilled. α_i is a region fixed effect and γ_t is a time fixed effect. C_{it} is an unobservable variable potentially correlated with the treatment (policy) variable z_{it}. If they are correlated, then z_{it} is endogenous. X_{it} denotes a set of control variables, which differs depending on the policy variables.

- When $z_{i,t}$ denotes the logarithm of local governments' capital expenditures, X_{it} includes the logarithms of local governments' operating expenditures and firms' operating revenues.

- When $z_{i,t}$ denotes the logarithm of firms' capital expenditures, X_{it} includes the logarithms of firms' operating expenditures and local governments' operating revenues.

- When $z_{i,t}$ denotes the logarithm of local governments' operating revenues, X_{it} includes the logarithm of firms' operating revenues.

- When $z_{i,t}$ denotes the logarithm of firms' operating revenues, X_{it} includes the logarithm of local governments' operating revenues.

In each of the above cases, X_{it} also includes, in logarithms, the stock of past landfilled waste and GDP. GDP is a proxy for the amount of new waste generated by the economic activity of province i during period t. Dynamic treatment effects are captured by the term $\sum_{-G}^{M} \beta_m z_{i,t-m}$. Thus, pollution in region i at year t is affected only by values of the policy variable taken at most G years before t or at most M years after t, with $G \geq 0$, $M \geq 0$. Hence, values realized in past years have lagged effects, whereas values realized in future years have anticipation effects.

To estimate and directly visualize the cumulative effects (denoted δ_k), we can rewrite the model equation as:

$$\text{Log}(GHG_{it}) = \alpha_i + \gamma_t + X_{it}'\lambda + \sum_{k=-G}^{M-1} \delta_k \, \Delta z_{i,t-k} + \delta_M \, z_{i,t-M} + \delta_{-G-1}(1 - z_{i,t+G}) + C_{it} + \epsilon_{it} \quad (3)$$

k represents the delay between the year when the treatment variable changes and the year when the effect on pollution is observed. If k is negative, it is an anticipation (or announcement) effect. If k is positive, it is a lagged effect. β_k gives an isolated effect, whereas δ_k represents a cumulative effect:

$$\delta_k = \begin{cases} 0 & \text{if } k < -G \\ \sum_{m=-G}^{k} \beta_m & \text{if } -G \leq k \leq M \\ \sum_{m=-G}^{M} \beta_m & \text{if } k > M \end{cases} \quad (4)$$

Let $G = 5$ and $M = 1$. In other words, we allow for a lagged effect of up to five years and an anticipation effect of up to one year. The estimates of these δ_k are presented in Figure 3 and Table 3.

3.3. Biomass pollution model

Moreover, the amount of landfilled waste generates a quantity of non-CO_2 GHGs. The stock of past waste and new waste have different effects but interact, because newly deposited waste warms existing waste and accelerates the chemical processes that generate GHGs such as methane. To account for this interaction, we choose a Cobb–Douglas function:

$$\text{Log}(e_{it}) = \bar{\gamma} + \gamma_W \text{Log}(W_{i,t-1}) + \gamma_w \text{Log}(w_{it}) + \bar{\gamma}_i + \bar{\gamma}_t + \epsilon_{it} \tag{5}$$

where e_{it} is the amount of non-CO_2 GHGs per capita emitted in province i during period t; w_{it} is the amount of waste per capita landfilled during period t; $W_{i,t-1}$ is the total amount of waste per capita landfilled in the past up to period $t-1$; and $\bar{\gamma}_i$ and $\bar{\gamma}_t$ represent province and time fixed effects.

The amount of new waste landfilled in a province is proportional to the amount of waste generated by the province's overall economic activity. Thus, we consider it proportional to the province's GDP. This proportion is a geometric combination (i.e., a Cobb–Douglas function) of the waste-treatment capacities of firms and local governments. These waste-treatment capacities are given by the market value of the output of the relevant actors in the waste-management sector. The relationship that determines the intensity of landfilled waste is therefore:

$$\text{Log}\big(w_{it}/Y_{it}\big) = \bar{\beta} + \beta_f \text{Log}\big(N^f_{it} R^f_{it}\big) + \beta_g \text{Log}\big(N^g_{it} R^g_{it}\big) + \bar{\beta}_i + \bar{\beta}_t + \epsilon_{it} \tag{6}$$

where w_{it}/Y_{it} is the amount of landfilled waste per dollar of GDP in province i during period t. w_{it}/Y_{it} thus represents the landfilling intensity of waste generated by the province's overall economic activity. R^f_{it} is the market value of output for the representative firm, and N^f_{it} is the number of firms. R^g_{it} is the market value of output for the representative local government, and N^g_{it} is the number of local governments (i.e., the number of municipalities). $\bar{\beta}_i$ and $\bar{\beta}_t$ represent province and time fixed effects. Note that equation 6 is inspired by the notion of emissions intensity in integrated assessment models such as the RICE/DICE models described by (Nordhaus, 2013). In those models, pollution is proportional to the level of the activity that generates it, with the proportionality coefficient depending on pollution intensity and the abatement rate. The difference from the RICE/DICE models lies in the origin of pollution and in how pollution intensity is determined. In our case, waste emissions come from household consumption activities and overall industrial production, not solely from industrial production. Moreover, while effective pollution intensity is heterogeneous in our analysis as in the RICE/DICE models, in those models this heterogeneity is determined by firms' choices of abatement rates. In our analysis, it is determined exogenously by the activity of the actors who manage and treat waste, rather than by the choices of all the actors who generate this pollution.

4. DATA

4.1. Data Sources and Presentation of Variables

To study the impact of activities by public and private actors in Canada's waste management industry, we use the following datasets available through the Government of Canada's open data portal: (1) characteristics of firms in the waste management industry; (2) characteristics of local governments in the waste management industry; (3) disposed waste, by source; (4) population; (5) provincial and territorial GHG emissions by Canadian economic sector.

These data vary across Canadian provinces and over time. After merging them and selecting the information specific to the waste management industry, we obtain 17 annual periods covering 2002 to 2018.

For a region i and a year t, we can obtain the following information for the waste management industry:

- The size of the region's population (P);
- The quantity of disposed waste (w);
- The quantity of GHGs emitted by biomass (e);
- Average investment per firm (C^f), given by the ratio of firms' total capital expenditures to the number of firms;
- Average investment per local government (C^g), given by the ratio of local governments' total capital expenditures to the number of municipalities;
- Average operating expenditures per firm (O^f), given by the ratio of firms' total operating expenditures to the number of firms;
- Average operating expenditures per local government (O^g), given by the ratio of local governments' total operating expenditures to the number of municipalities;
- The number of firms (N^f);
- The number of municipalities (N^g).

Four provinces, namely New Brunswick, Nunavut, Yukon, and the Northwest Territories are excluded because they lack sufficient data on the variables of interest. Originally, the data collected on firm characteristics and on local government characteristics in the waste management industry were biennial, covering the years 2000, 2002, 2004, 2006, . . . , 2018, 2020, 2022. Information for the odd years was obtained by taking the average of the two adjacent even years. After this initial processing, some variables of interest still have missing values, mainly due to:

- non-disclosure of certain information that did not meet anonymity and confidentiality criteria;
- and the absence of certain observations in some provinces.

Where possible, these missing values were filled, for each variable in each province, using the observed values from the closest periods. Provinces where this was not possible—for example, due to a complete lack of observations—were excluded.

4.2. Data Description

Table 1 describes the variables used. In the sample, the per-capita quantity of disposed waste averages 732 kg and ranges from 378 kg per capita to 839 kg per capita. The per-capita quantity of greenhouse gases averages 825 kg CO_2-eq and ranges from 466 to 1390 kg CO_2-eq per capita. Moreover, investment by a firm in the waste management sector averages 210K CAD, which is not far from the average investment by a local government (a municipality), at 199K CAD. By contrast, the dispersion of these capital expenditures across regions and years is much larger for public actors (standard deviation = 182K CAD) compared with firms (standard deviation = 102K CAD). As for operating expenditures, they average 2.955M CAD per firm and 1.266M CAD per municipality. The resources acquired through these expenditures generated operating revenue of 3.608M CAD per firm. This average value of a firm's output ranges from 1.028M to 7.832M CAD depending on the province and period. Because the goods and services provided by local governments are generally non-market, the market value of their output is unobservable. Instead, we observe revenues collected by these public actors, which reflect only a portion of the revenue they would receive if they offered market goods. This partially observed revenue ranges from 890K to 3.224M CAD per municipality depending on the province and the year observed.

Table 1: Descriptive Statistics

Variable	n	mean	sd	min	25%	median	75%	max
P	119	4636558.105	4197869.496	934763.250	1115495.250	3724157.000	7601463.250	14297687.000
N^f	119	213.987	163.598	26.000	49.750	246.000	282.750	561.000
N^g	119	437.571	365.478	50.000	137.000	354.000	782.000	1134.000
e	119	824.633	287.063	465.516	546.138	699.112	1062.823	1389.928
w	119	732.537	188.540	378.420	657.507	759.112	838.689	1157.608
R^f	119	3608.185	1403.044	1028.368	2521.262	3509.086	4545.709	7832.413
R^g_{part}	119	960.324	889.908	11.879	306.476	640.560	1404.340	3224.346
O^f	119	2955.146	1116.389	920.218	2112.239	2789.500	3676.431	5991.925
O^g	119	1265.756	984.940	22.215	435.418	1175.556	2118.475	3112.056
C^f	119	209.720	102.493	71.447	127.430	180.157	276.627	571.442
C^g	119	198.622	182.305	3.669	41.863	143.905	330.135	785.241

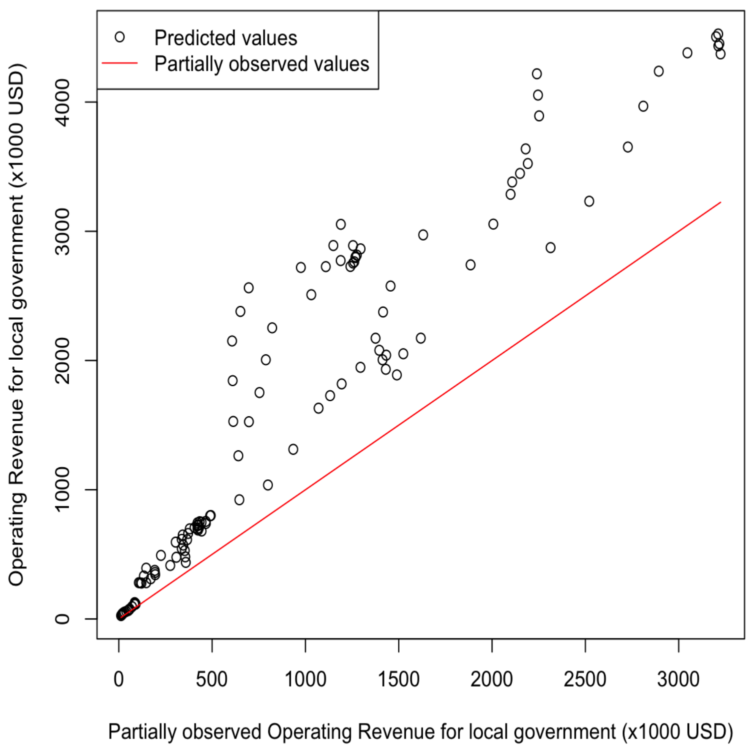
Notes P: province population; N^f: number of firms in the province operating in the waste management sector; N^f: number of municipalities in the province; e: quantity of non-CO_2 GHGs per capita emitted by waste (in kg CO_2 equivalents); w: quantity of waste per capita deposited in landfills (in kg); R^f: operating revenue per firm (thousands of USD); R^f_{part}: observed share of operating revenue per municipality (thousands of USD); O^g: operating expenditures per firm (thousands of dollars); O^f: operating expenditures per municipality (thousands of dollars); C^f: capital expenditures per firm (thousands of dollars); C^g: capital expenditures per municipality (thousands of dollars).

5. RESULTS

5.1. Production Function and Prediction of Local Government Output

The estimation of the production function is given in Table 2. The estimated parameter values of the production function are $\alpha_O = 0.894$, $\alpha_C = 0.160$, $\alpha_Y = 0.213$. Thus, a 1% increase in a firm's capital stock, a 1% increase in the firm's operating expenditures, and a 1% increase in the province's GDP per capita raise that firm's output by 0.894%, 0.16%, and 0.213%, respectively. The other coefficients shown in the table are year fixed effects (with 2002 as the reference) and province fixed effects (with AB = "Alberta" as the reference). In addition, Figure 2 shows the output value of an average local government predicted from its capital expenditures and operating expenditures, using the firms' production function and innovations (i.e., estimated residuals). The figure also shows the value of the portion of these revenues that is observed in the data. We can see that the predicted revenues are higher than the partially observed revenues.

Figure 2: Predicted local government revenue vs. partially observed revenue (in thousands of USD)



Notes On the x-axis: the value of partially observed revenues per local government. On the y-axis: the value of the partial revenues for the red line; the predicted value of the total potential revenue per local government for the scatter points.

5.2. Event Studies

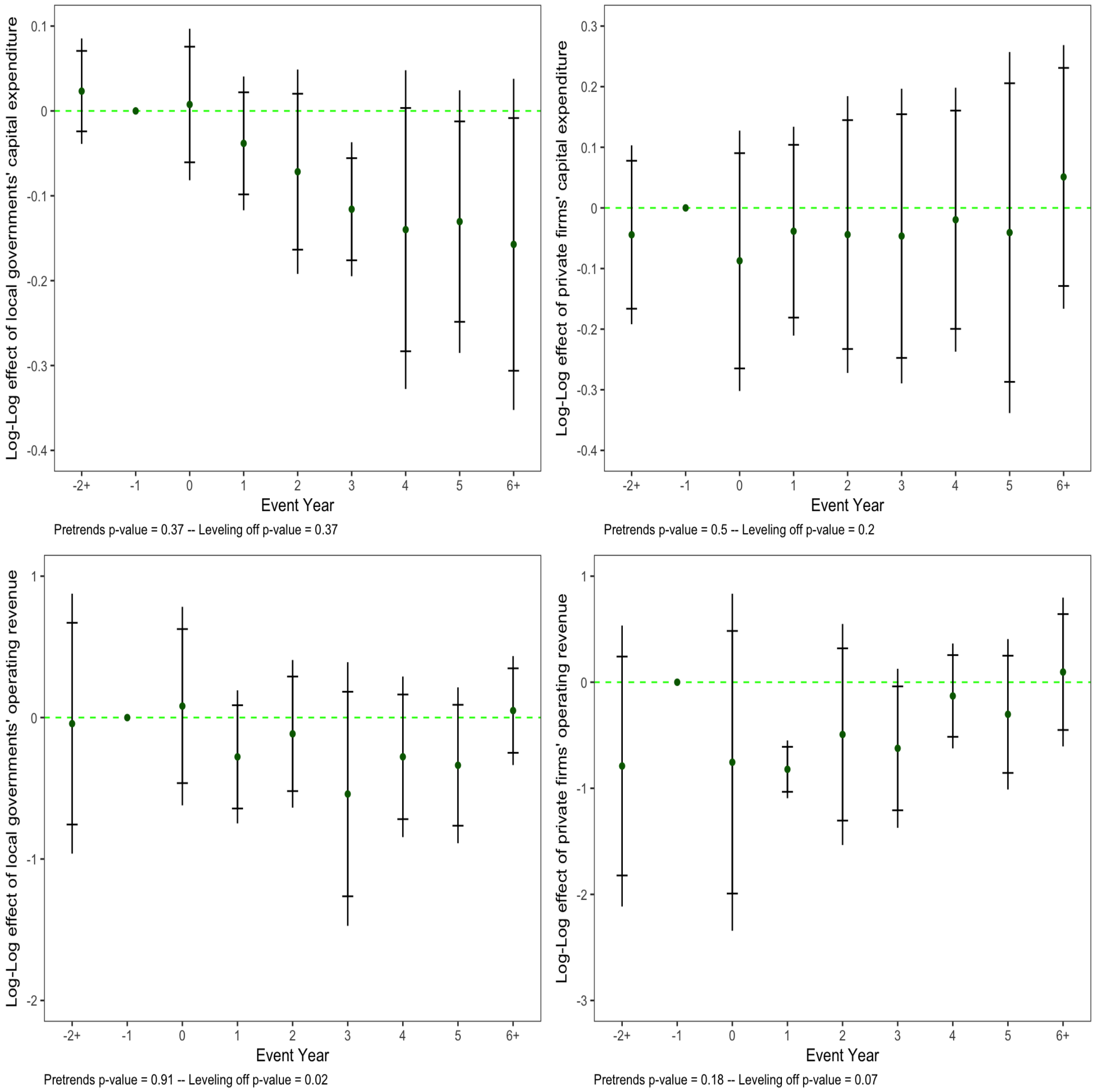
The estimation results for the event-study equations are given in Table 3 and Figure 3. According to the top-left panel of Figure 3, local governments' total capital expenditures

Table 2: OLS estimates of production function

Variable	Estimates	p-value
Constante	0.157	0.548
$Log(O^f)$	0.894	0.000
$Log(K^f)$	0.160	0.000
$Log(Y)$	0.213	0.047
Effets fixes des provinces (Reference=AB)		
BC	0.162	0.001
MB	0.161	0.004
NS	0.050	0.499
ON	-0.009	0.860
QC	0.092	0.131
SK	0.004	0.881
Effets fixes des annees (Reference=2002)		
2003	-0.122	0.000
2004	-0.200	0.000
2005	-0.237	0.000
2006	-0.263	0.000
2007	-0.282	0.000
2008	-0.317	0.000
2009	-0.313	0.000
2010	-0.322	0.000
2011	-0.335	0.000
2012	-0.342	0.000
2013	-0.352	0.000
2014	-0.357	0.000
2015	-0.367	0.000
2016	-0.380	0.000
2017	-0.380	0.000
2018	-0.378	0.000

Notes The dependent variable is the logarithm of a firm's operating revenue. $Log(O^f)$, $Log(K^f)$, and $Log(Y)$ denote, respectively, the logarithm of: the firm's operating expenditures, the firm's capital stock (i.e., current and past capital expenditures), and the GDP of the firm's province (GDP is treated as a proxy for the amount of waste generated by consumption, which is used as an input by waste-treatment actors).

Figure 3: Cumulative effects δ_k of the treatment variables on the quantity of GHGs, as a function of lags k



Notes On the x-axis, *Event Year* represents the lag k. On the y-axis are the cumulative effects δ_k. Confidence intervals are shown in the panels. The top-left panel shows the estimates from Event Study 1. The top-right panel shows the estimates from Event Study 2. The bottom-left panel shows the estimates from Event Study 3. The bottom-right panel shows the estimates from Event Study 4.

in year t (corresponding to $Event\,Year = 0$) in the waste management industry appear to be associated with a decrease in non-CO_2 GHG emissions in future years, at least from the third year onward. Thus, 1% more spending by local governments in year t reduces non-CO_2 GHG emissions from biomass by 0.116% in year $t+3$, i.e., in the third year after the increase in expenditures. By contrast, firms' total capital expenditures generally have negative but statistically insignificant effects. Moreover, local governments' revenues (predicted using the firms' production function) have negative but statistically insignificant effects, while firms' observed total revenues have statistically significant future effects, at least for year $t+1$, i.e., the year following the increase in revenues. Thus, 1% more in the value of firms' output in year t is associated with a 0.821% decrease in emissions in the following year $t+1$. In other words, a 1% increase in firms' level of activity or productive capacity in year t is associated with a 0.821% decrease in emissions in year $t+1$.

Thus, depending on the variables used to represent the scale of activities of local governments or firms—or their waste-management capacities—we find possible links with future reductions in non-CO_2 GHGs from landfilled biomass. As an implication of these links, public authorities would be more effective in the long term when they invest in capital (infrastructure, equipment), whereas firms influence emissions more through their economic performance. This may reflect differences in objectives (public service vs. profit). To better understand the impact of these different actors' activities, we will use a model that specifies both the intensity of biomass landfilling and the air pollution arising from that biomass.

5.3. Pollution

The estimates of equations 5 and 6 are presented in Table 4. Based on the estimation results, there is clear evidence of an interaction between the stock of waste accumulated in the past and the amount of new waste in their effects on the quantity of non-CO_2 greenhouse gases emitted by landfilled waste, because the coefficients of the two variables $(P_t * w_t)$ and $(P_{t-1} * W_{t-1})$ are statistically significant at the 5% level. This statistical significance constitutes evidence of a significant linear relationship between (e_t) and $(P_t * w_t)$, $(P_{t-1} * W_{t-1})$, and thus of a significant log–log (Cobb–Douglas) relationship between e_t and $P_t * w_t$, $P_{t-1} * W_{t-1}$. A 1% increase in past stocks of landfilled waste leads to a 0.069% increase in current non-CO_2 GHG emissions from landfills. In addition, a 1% increase in the current amount of newly landfilled waste leads to a 1.083% increase in current non-CO_2 GHG emissions from landfills. These results imply that reduction policies should target not only lowering incoming waste flows but also managing or remediating legacy stocks. This justifies investments in biogas solutions, methane capture, or source reduction.

Estimating province fixed effects (with $AB =$ "Alberta" as the reference) allows a comparison across provinces of the Cobb–Douglas relationship between non-CO_2 GHG emissions and landfilled waste. Provinces NS ("Nova Scotia"), SK ("Saskatchewan"), and MB ("Manitoba")

Table 3: Regression coefficients (δ_k's) of equation 3 for several event studies

	Study 1		Study 2		Study 3		Study 4	
Variable	Coef	p-value	Coef	p-value	Coef	p-value	Coef	p-value
$\Delta(NC^g_t)$	0.008	0.835						
$\Delta(NC^g_{t-1})$	-0.038	0.259						
$\Delta(NC^g_{t-2})$	-0.072	0.177						
$\Delta(NC^g_{t-3})$	-0.116	0.009						
$\Delta(NC^g_{t-4})$	-0.14	0.104						
$\Delta(NC^g_{t-5})$	-0.13	0.074						
(NC^g_{t-6})	-0.157	0.084						
(NC^g_{t+1})	0.023	0.373						
$\Delta(NC^f_t)$			-0.087	0.373				
$\Delta(NC^f_{t-1})$			-0.038	0.616				
$\Delta(NC^f_{t-2})$			-0.044	0.664				
$\Delta(NC^f_{t-3})$			-0.046	0.667				
$\Delta(NC^f_{t-4})$			-0.019	0.839				
$\Delta(NC^f_{t-5})$			-0.041	0.757				
(NC^f_{t-6})			0.051	0.598				
(NC^f_{t+1})			-0.044	0.504				
$\Delta(NR^g_t)$					0.081	0.78		
$\Delta(NR^g_{t-1})$					-0.278	0.186		
$\Delta(NR^g_{t-2})$					-0.115	0.598		
$\Delta(NR^g_{t-3})$					-0.54	0.193		
$\Delta(NR^g_{t-4})$					-0.277	0.263		
$\Delta(NR^g_{t-5})$					-0.337	0.173		
(NR^g_{t-6})					0.05	0.756		
(NR^g_{t+1})					-0.043	0.91		
$\Delta(NR^f_t)$							-0.754	0.277
$\Delta(NR^f_{t-1})$							-0.821	0
$\Delta(NR^f_{t-2})$							-0.493	0.279
$\Delta(NR^f_{t-3})$							-0.623	0.081
$\Delta(NR^f_{t-4})$							-0.13	0.534
$\Delta(NR^f_{t-5})$							-0.302	0.325
(NR^f_{t-6})							0.096	0.742
(NR^f_{t+1})							-0.79	0.184
(NO^f_t)			-0.139	0.769				
(NO^g_t)	0.084	0.581						
(NR^f_t)	-0.783	0.031			0.008	0.981		
(NR^g_t)			-0.275	0.029			-0.151	0.325
(PW_{t-1})	1.193	0.276	1.075	0.488	1.85	0.001	-0.735	0.537
(PY_t)	-0.159	0.668	-0.417	0.471	0.012	0.985	-0.436	0.372

Notes Province and year fixed effects were included but are omitted from the table.
Study 1 represents the effect of the logarithm of local governments' capital expenditures ((C^g_t)) on the logarithm of GHG emissions ((e_t)). Study 2 represents the effect of the logarithm of firms' capital expenditures ((C^f_t)). Study 3 represents the effect of the logarithm of the monetary value of local governments' output ((C^g_t)). Study 4 represents the effect of the logarithm of the monetary value of firms' output ((C^f_t)).

NX^s denotes the total value of X across all N^s members of group $s = \{f, g\}$. For example, C^f_t denotes the amount of capital expenditures per firm in the province and $NC^f_t \equiv N^f_t \times C^f_t$ denotes the total amount of these expenditures for the N^f_t firms in the province. Likewise, C^g_t denotes the amount of capital expenditures per local government (municipality) in the province and $NC^g_t \equiv N^g_t \times C^g_t$ denotes the total amount of these expenditures for the N^g_t local governments in the province. $PW_{t-1} \equiv P_{t-1} \times W_{t-1}$ denotes the total accumulated quantity of waste landfilled during prior periods, where W_{t-1} is the cumulative per-capita amount and P_{t-1} is the population. $PY_t \equiv P_t \times Y_t$ denotes the province's total GDP, where P_t is the population and Y_t is GDP per capita.

$\Delta(X_{t-r}) \equiv (X_{t-r}) - (X_{t-r-1})$ is the difference in (X_t) between its value in period $t - r$ and its value in period $t - r - 1$.

Table 4: SUR Estimates for Emission and Waste Equations [(a)]

	Log(GHG) (5)		$\text{Log}(\frac{Waste}{GDP})$ (6)	
Variable	Coef	p-value	Coef	p-value
Constante	-1.794	0.497	5.789	0.000
$Log(N_t^f * R_t^f)$			0.22	0.002
$Log(N_t^g * R_t^g)$			-0.151	0.003
$Log(P_t * w_t)$	1.083	0		
$log(P_{t-1} * W_{t-1}$	0.069	0.018		
Provinces' fixed effects (Reference=AB)				
BC	0.064	0.188	-0.012	0.55
MB	0.558	0.001	0.349	0.000
NS	0.757	0.008	-0.057	0.569
ON	-0.364	0.002	-0.016	0.791
QC	-0.257	0	0.224	0.000
SK	0.683	0	0.052	0.609
Years' fixed effects (Reference=2002)				
2003	-1.492	0.017	-0.012	0.667
2004	-1.565	0.015	-0.04	0.168
2005	-1.624	0.013	-0.07	0.023
2006	-1.651	0.013	-0.09	0.006
2007	-1.709	0.011	0	0.999
2008	-1.718	0.011	0.021	0.571
2009	-1.757	0.01	0.075	0.061
2010	-1.764	0.01	0.036	0.399
2011	-1.771	0.01	-0.019	0.657
2012	-1.772	0.011	-0.045	0.328
2013	-1.772	0.011	-0.085	0.074
2014	-1.772	0.011	-0.12	0.017
2015	-1.777	0.011	-0.126	0.013
2016	-1.755	0.013	-0.141	0.006
2017	-1.771	0.012	-0.178	0.001
2018	-1.783	0.012	-0.202	0.000

<u>**Notes**</u> (a): SUR means Seemingly Unrelated Regressions

show a stronger impact of landfilled waste than AB ("Alberta") and BC ("British Columbia"). By contrast, ON ("Ontario") and QC ("Quebec") show a weaker impact than AB and BC. National policies should therefore be adapted to regional realities, taking into account local specificities in treatment technology, climate, or the regulatory framework. Provinces with higher sensitivity could be targeted for focused efforts. Moreover, the estimated time fixed effects show a lower impact of landfilled waste on non-CO_2 GHGs in all years relative to 2002; this gap becomes smaller over time.

Furthermore, the results also show evidence of a log–log (Cobb–Douglas) relationship between the output of public and private actors in the waste-treatment sector and the amount of landfilled waste per Canadian dollar of GDP. However, we observe an increasing relationship with firms' output value (given by their total operating revenues) and a decreasing relationship with the predicted output value of local government. Specifically, a 1% increase in firms' output leads to a 0.22% increase in the intensity of landfilling, while a 1% increase in municipalities' predicted output leads to a 0.151% decrease in landfilling intensity. Thus, the private model appears to generate more landfilled waste per dollar of output, possibly due to less stringent practices or a business model less focused on waste reduction. This suggests that the public model may be more sustainable in terms of waste management, at least in its direct environmental effects. "'

6. CONCLUSION

In this study, we combined econometric methods to analyze the differing impacts of public and private actors in the waste management sector on non-CO_2 GHG emissions from landfilled waste. We used two complementary approaches: an event study to capture the dynamic effects of investments and revenues on pollution, and a semi-structural model inspired by the Cobb–Douglas production framework to model the interactions among production (by actors in the waste management sector), landfilling of waste, and emissions. The results highlight several important stylized facts. First, local governments' capital expenditures have a delayed but significant effect in reducing emissions, whereas private firms' capital expenditures have no statistically significant effect. Second, private firms' economic activity is associated with a reduction in GHG emissions the following year, while municipalities' activity has no significant direct effect—even though their investments improve conditions over the medium term. Our findings also show that the quantity of GHGs emitted is strongly influenced by both new waste and accumulated stocks, confirming the importance of accounting for dynamic interactions in emission-reduction policies. In addition, landfilling intensity varies with the type of actor: it increases with the output of private firms but decreases with the output of local governments, suggesting that the latter may pursue a more sustainable approach to waste management. Finally, the regional disparities observed in the effects of landfilled waste on emissions point to the need for province-specific environmental policies that take local technical capacities and socio-economic contexts into account. Overall, our analyses suggest that the role of local governments in waste treatment is not limited to serving as an alternative to the private sector; it is potentially a crucial lever for reducing the sector's carbon intensity. This argues for greater recognition of their role in environmental governance and for targeted support to strengthen their investment capacity.

References

Barr, S. (2007). Factors influencing environmental attitudes and behaviors: a uk case study of household waste management. *Environment and behavior*, *39*(4), 435–473.

Bogner, J. E., Spokas, K. A., & Chanton, J. P. (2011). Seasonal greenhouse gas emissions (methane, carbon dioxide, nitrous oxide) from engineered landfills: daily, intermediate, and final california cover soils. *Journal of environmental quality*, *40*(3), 1010–1020.

Castro, P. J., Aráujo, J. M., Martinho, G., & Pereiro, A. B. (2021). Waste management strategies to mitigate the effects of fluorinated greenhouse gases on climate change. *Applied Sciences*, *11*(10), 4367.

Circular Inovation Council. (2017). *How waste is regulated* [Consulted on July 4, 2025]. Retrieved July 4, 2025, from https://circularinnovation.ca/how-waste-is-regulated/?utm_source=chatgpt.com

Coase, R. (1960). The problem of social cost. *Journal of Law and Economics*, 1–44.

Coase, R. (1990). *The firm, the market, and the law* (tech. rep.). University of Chicago Press.

Cox, J., Giorgi, S., Sharp, V., Strange, K., Wilson, D. C., & Blakey, N. (2010). Household waste prevention—a review of evidence. *Waste management & research*, *28*(3), 193–219.

Environement et Changement Climatique Canada. (2023). *Federal offset protocol: landfill methane recovery and destruction* [Consulté le 4 Juillet 2025]. Governement du Canada.

Environment and Changement Climatique Canada. (2023). *Federal offset protocol: landfill methane recovery and destruction* [Consulted on July 4, 2025]. Government of Canada.

Environment and Climate Change Canada. (2022). *Federal sustainable development strategy 2022 to 2026* [Consulted on July 4, 2025]. Government of Canada. Retrieved July 4, 2025, from https://www.canada.ca/content/dam/eccc/documents/pdf/federal-sustainable-development-strategy/2022%20to%202026%20Federal%20Sustainable%20Development%20Strategy-2.pdf

Environment and Climate Change Canada. (2024). *Canadian environmental sustainability indicators: solid waste diversion and disposal* [Consulted on July 4, 2025]. Government of Canada. Retrieved July 4, 2025, from https://www.canada.ca/en/environment-climate-change/services/environmental-indicators/solid-waste-diversion-disposal.html

Environmental Protection Agency. (2024). *Basic information about landfill gas* [Consulted on July 4, 2025]. Government of United States. Retrieved July 4, 2025, from https://www.epa.gov/lmop/basic-information-about-landfill-gas

Environmental Protection Agency. (2025). *Environmental benefits of anaerobic digestion (ad)* [Consulted on July 4, 2025]. Government of United States. Retrieved July 4, 2025, from https://www.epa.gov/anaerobic-digestion/environmental-benefits-anaerobic-digestion-ad

Fang, J., Gao, C., & Lai, M. (2020). Environmental regulation and firm innovation: evidence from national specially monitored firms program in china. *Journal of Cleaner Production*, *271*, 122599.

Freyaldenhoven, S., Hansen, C., Pérez, J. P., & Shapiro, J. M. (2021). *Visualization, identification, and estimation in the linear panel event-study design* (tech. rep.). National Bureau of Economic Research.

Grossman, G. M., & Krueger, A. B. (1991). Environmental impacts of a north american free trade agreement.

Jiang, L., Lin, C., & Lin, P. (2014). The determinants of pollution levels: firm-level evidence from chinese manufacturing. *Journal of Comparative Economics*, *42*(1), 118–142.

John, A., & Pecchenino, R. (1994). An overlapping generations model of growth and the environment. *The Economic Journal*, *104*(427), 1393–1410.

John, A., Pecchenino, R., Schimmelpfennig, D., & Schreft, S. (1995). Short-lived agents and the long-lived environment. *Journal of public economics*, *58*(1), 127–141.

Kelleher Environmental Robins Environmental. (2009). *Implementation of a sustainable financing structure for solid waste management in ontario. discussion paper 4: household fees and payt rates* [Consulted on July 4, 2025]. Retrieved July 4, 2025, from https://stewardshipontario.ca/wp-content/uploads/2013/03/Household-Fees-and-PAYT-Rates.pdf?utm_source=chatgpt.com

Krause, M., & Thorneloe, S. (2024). *Landfill gas emissions model (landgem) version 3.1 user manual and tool*. US Environmental Protection Agency, Office of Research; Development.

Kuznets, S. (1955). Economic growth and income inequality. *The American Economic Review*, *45*(1), 1–28.

Kuznets, S. (1963). Quantitative aspects of the economic growth of nations: viii. distribution of income by size. *Economic development and cultural change*, *11*(2, Part 2), 1–80.

Lee, S., Kim, J., & Chong, W. K. (2016). The causes of the municipal solid waste and the greenhouse gas emissions from the waste sector in the united states. *Waste management*, *56*, 593–599.

Lopez, R. (2017). The environment as a factor of production: the effects of economic growth and trade liberalization 1. In *International trade and the environment* (pp. 239–260). Routledge.

Nordhaus, W. (2013). Integrated economic and climate modeling. In *Handbook of computable general equilibrium modeling* (pp. 1069–1131, Vol. 1). Elsevier.

Pardo, G., Moral, R., Aguilera, E., & Del Prado, A. (2015). Gaseous emissions from management of solid waste: a systematic review. *Global change biology*, *21*(3), 1313–1327.

Pigou, A. (1933). The economics of welfare. *The Economic Journal*, *43*(170), 329.

Selden, T. M., & Song, D. (1995). Neoclassical growth, the j curve for abatement, and the inverted u curve for pollution. *Journal of Environmental Economics and management*, *29*(2), 162–168.

Stern, D. I. (2018). The environmental kuznets curve. In *Companion to environmental studies* (pp. 49–54). Routledge.

Stern, D. I., Common, M. S., & Barbier, E. B. (1996). Economic growth and environmental degradation: the environmental kuznets curve and sustainable development. *World development*, *24*(7), 1151–1160.

UN. (2021). *The sustainable development goals report 2021* [Consulted on July 4, 2025]. United Nations. Retrieved July 4, 2025, from https://unstats.un.org/sdgs/report/2021/The-Sustainable-Development-Goals-Report-2021.pdf

Weersink, A., & Raymond, M. (2007). Environmental regulations impact on agricultural spills and citizen complaints. *Ecological economics*, *60*(3), 654–660.