From Waste to Energy: Assessing the Efficacy of the Landfill Methane Outreach Program

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Preliminary draft

Abstract

We examine the efficacy of the Landfill Methane Outreach Program (LMOP) in mitigating methane emissions from municipal solid waste (MSW) landfills in the United States. LMOP is a voluntary program initiated by the United States' Environmental Protection Agency to incentivize landfill owners to undertake landfill gas-to-energy (LFGE) projects for the generation of new energy sources. Using a staggered difference-in-differences approach to account for the heterogeneity in the timing of LMOP participation, our empirical results show that the program increases the likelihood of LFGE project development by 40.3%. Despite this positive impact on LFGE project development, no significant reduction in fugitive methane emissions is observed, possibly due to the independent installation of landfill gas collection and control systems. However, LFGE project development is found to decrease net greenhouse gas emissions–which account for avoided carbon emissions due to energy generation from captured methane gas–by 31.4%. The findings underscore the important contribution of LMOP in promoting LFGE project development and reducing greenhouse gas emissions in the absence of legal mandates.

Keywords: landfill methane outreach program, landfill gas-to-energy project, landfill gas collection system, difference in differences.

JEL Codes: Q53, Q54, Q58

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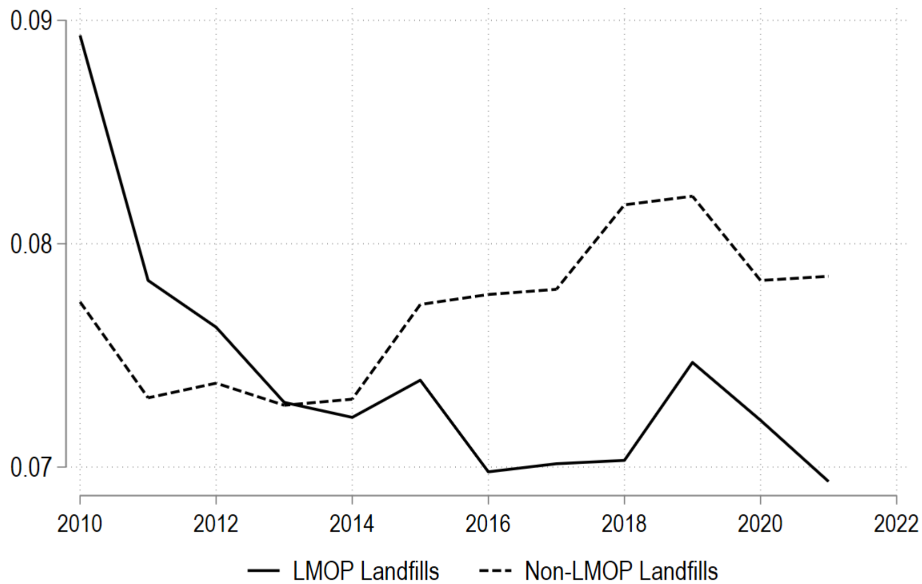
1 Introduction

Methane is short-lived but has 28 times the global warming potential of carbon dioxide over 100 years (IPCC, 2014). The United States Environmental Protection Agency (EPA) has strived to mitigate anthropogenic methane emissions—mostly coming from enteric fermentation, natural gas systems, and municipal solid waste (MSW)—through several regulations and voluntary programs, including the Landfill Methane Outreach Program (LMOP), AgSTAR, and Natural Gas STAR Partnership (EPA, 2023a; Melvin et al., 2016). In particular, overall methane emissions from MSW landfills have declined by 44.1% even though the amount of MSW deposited has increased by 5.4% between 1990 and 2021 (EPA, 2023a). In this paper, we focus on the effects of LMOP on methane emissions from MSW landfills in the United States.

LMOP was launched by the EPA in 1994 with the goal of curbing methane emissions generated as a byproduct of the decomposition of organic waste in MSW landfills. The program encourages landfill owners to develop a landfill gas-to-energy (LFGE) project that recovers landfill gas for the purpose of new energy generation, including electricity and heat (EPA, 2021a). As a voluntary environmental program (VEP), LMOP is open to any entity that wishes to engage in LFGE project development. Partners include landfill owners, LFGE project developers, energy buyers, state agencies, and local communities (EPA, 2022). LMOP provides participants with technical assistance and public recognition for their environmental commitment (EPA, 2021a) to overcome the reluctance by landfill owners to engage in LFGE project development due to technical unfamiliarity and uncertainty of profitability (Trisolini, 2012; Hogan, 1996).

Figure 1 displays the time trend of average fugitive methane emissions from MSW landfills by LMOP participation from 2010 to 2021. While the solid line reveals a declining trend in methane releases over time among LMOP landfills, overall emissions for non-LMOP landfills have been increasing (the dotted line). This stark distinction may imply salutary effects of LMOP in reducing methane emissions although it is merely suggestive. Since the decision to participate is LMOP voluntary, a simple comparison of methane emission levels between LMOP and non-LMOP landfills would likely result in biased estimates of the effects of LMOP on methane releases. For instance, the environmental preferences of landfill owners might influence both their involvement in LMOP and their decision to launch LFGE projects and reduce methane emissions.

Figure 1: Average methane emissions by LMOP participation.



Notes: This figure illustrates the average methane emissions by LMOP participation between 2010 and 2021. The unit is a million metric tons of carbon dioxide equivalents. LMOP landfills represent landfills that are owned by LMOP participants; non-LMOP landfills represent landfills that are owned by non-LMOP participants.

To mitigate the endogeneity concern, we adopt a staggered difference-in-differences approach suggested by Callaway and Sant'Anna (2021). Their approach is well-suited to our research context as the timing of LMOP participation varies over time, and participants remain in the program once they join it. For the ensuing analysis, we use landfill-level methane emission data obtained from the Greenhouse Gas Reporting Program (GHGRP) and information about LMOP participation and LFGE projects from the LMOP database. We control for landfill, county, and state characteristics, including landfill openness, population, and weather, while unobserved factors that are time-invariant or time-varying but the same across landfills are accounted for by landfill and year fixed effects, respectively. We are particularly interested in shedding light on the following two interlinked research questions: 1) Does LMOP participation promote LFGE project development? and 2) Does LFGE project development reduce methane emissions?

We find that LMOP participation increases the probability of LFGE project development by 5.6 percentage points one year after landfills join the program, and the effects persist over time. This amounts to a 40.3% increase in the probability of LFGE project development compared to nonparticipants. The effects are largely driven by landfills that do not have previous gas recovery experience (64% increase in the probability of participation) and public landfills (163.8%). These types of landfills are more likely to face higher obstacles to developing LFGE projects, hence more likely to benefit from the program's incentives. On the other hand, we do not find significant effects of LFGE project development on fugitive methane emissions. One plausible explanation for this lack of impact is that LFGE projects rely on landfill gas captured by a landfill gas collection and control system (GCCS) which can be installed independently of LFGE project development. Since a GCCS reduces fugitive releases of methane by capturing landfill gas even without LFGE project development, installing additional extraction wells and improving the efficiency of an existing GCCS would be the only remaining channels through which an LFGE project can affect methane emissions; there is no significant evidence supporting these pathways. However, LFGE projects contribute to mitigating global warming with the generation of alternative energy sources which can substitute for fossil fuel use. We find that LFGE project development significantly reduces net greenhouse gas emissions, which account for avoided carbon emissions, by 31.4%.

We contribute to the literature that examines climate change mitigation strategies within the waste management sector by empirically evaluating the effectiveness of a government-sponsored initiative targeting MSW landfills. The numerous engineering studies that have explored the effects of various landfill gas management practices-ranging from open dumping and flaring to gas recovery– on methane emissions from MSW landfills (Yang et al., 2013; Manfredi et al., 2009; Yao et al., 2019; Purmessur and Surroop, 2019; Pour et al., 2018; Jaramillo and Matthews, 2005) predominantly rely on life cycle assessment methodologies rather than empirical evidence with a causal effects framework. Besides, the determinants of LFGE project development and its impact on methane emissions have been understudied (Li et al., 2015). Using a random effects logit model, Li et al. (2015) find that renewable energy policies, including investment tax credits and renewable portfolio standards, promote LFGE project development and contribute to methane reductions. Melvin et al. (2016) investigate the effects of climate change initiatives, including LMOP using descriptive statistics; our study delves into the specific effects of LMOP on LFGE project implementation and methane emissions reduction through a causal inference framework. Our findings provide a more comprehensive understanding of the environmental program and its effects on methane emissions from MSW landfills. Our study also contributes to the literature exploring the effects of VEPs on environmental outcomes, including toxic pollutant releases (Zhou et al., 2020; Hoang et al., 2018; Prakash and Potoski, 2012), greenhouse gas emissions (Welch et al., 2000; Videras and Alberini, 2000; Moon and Ko, 2013; Scott et al., 2023), and environmental innovation (Carrión-Flores et al., 2013; Chang and Sam, 2015; Brouhle et al., 2023). Even though LMOP is the only VEP that addresses methane emissions from landfills in the United States, no studies to our knowledge have been conducted to empirically evaluate the effectiveness of the program. Our results show that LMOP, as a VEP, plays an important role in mitigating climate change by promoting the development of LFGE projects which, in turn, reduce methane emissions in the waste management sector.

The remainder of the paper is as follows. Section 2 provides a background on LFGE project and LMOP. Section 3 discusses the hypotheses being tested. Section 4 discusses the data used in the analysis. Section 5 addresses the identification strategy. Section 6 presents the estimation results. Section 7 concludes the paper.

2 Background

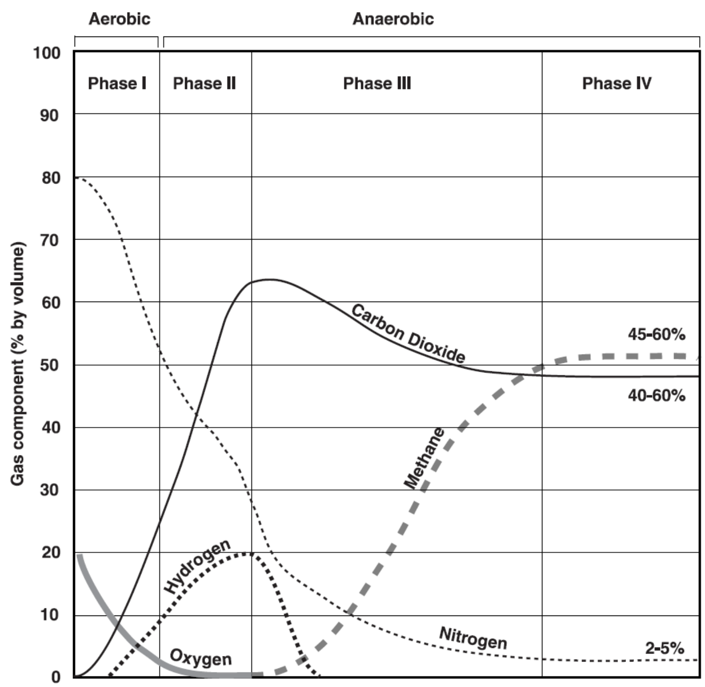
2.1 LFGE project development

Figure 2 illustrates how the composition of landfill gas changes upon waste burial over time (EPA, 2021a; Bove and Lunghi, 2006). Once organic waste is deposited in a landfill, aerobic bacteria begin to consume oxygen, generating carbon dioxide and nitrogen (Phase I). As oxygen becomes depleted, anaerobic decomposition takes place, creating a more suitable environment for methanogenic bacteria to grow and produce methane (Phase II-III). When landfill gas eventually becomes stabilized (Phase IV), it consists of methane (45-60%), carbon dioxide (40-60%), nitrogen (2-5%), and non-methane organic compounds (NMOC) (less than 1%) (Purmessur and Surroop, 2019; Nanda and Berruti, 2021; Farquhar and Rovers, 1973; Tchobanoglous et al., 1993; Themelis and Ulloa, 2007).[1] While the time for each phase varies with organic waste composition in a landfill, Phases I through

[1] In addition to bacterial decomposition, which is the primary driver of landfill gas generation, volatilization of organic compounds and chemical reactions involving certain compounds, such as bleach and ammonia, also contribute to the formation of landfill gas (ATSDR, 2001).

III take around 4 months to 3 years, and Phase IV takes 5-50 years (Andriani and Atmaja, 2019). If left uncontrolled, landfill gas escapes into the atmosphere, leading to fugitive methane emissions and contributing to global warming.

Figure 2: Landfill gas composition.



Notes: This figure illustrates changes in landfill gas composition as the decomposition of waste proceeds in a landfill. The horizontal axis represents the time since the waste is buried. Phase I spans the first 7-30 days, and Phase II lasts 1-6 months. Phase III and IV take 3-30 months and 5-50 years, respectively (Andriani and Atmaja, 2019). Sources: ATSDR (2001)

Not only is landfill gas a contributor to global warming, but it is also hazardous due to its flammability and toxicity. Methane has a high potential for explosions (ATSDR, 2001), and NMOCs include toxic air pollutants such as benzene and vinyl chloride that are know to induce adverse health effects, including carcinogenic and respiratory diseases (ATSDR, 2001; Pan et al., 2023; Purmessur and Surroop, 2019). Landfill gas also creates odors, causing environmental nuisance to nearby residents (Palmiotto et al., 2014; Aatamila et al., 2011; Nanda and Berruti, 2021). To address this potential environmental damage, the New Source Performance Standards (NSPS) and Emission Guidelines (EG) for MSW landfills were put in place to limit gas releases from landfills. The NSPS and EG, under the Clean Air Act, require landfills with a design capacity of over 2.5

million megagrams or 2.5 million m^3 of volume and emit NMOCs greater than or equal to 34 megagrams per year, to collect and control landfill gas through GCCS (EPA, 2021b).[2] While the NSPS and EG do not explicitly address methane, when GCCS captures landfill gas, the release of methane into the air is reduced. The landfill gas collected by GCCS can either be flared or recovered through LFGE projects (Bennett, 2011; Anshassi et al., 2022).

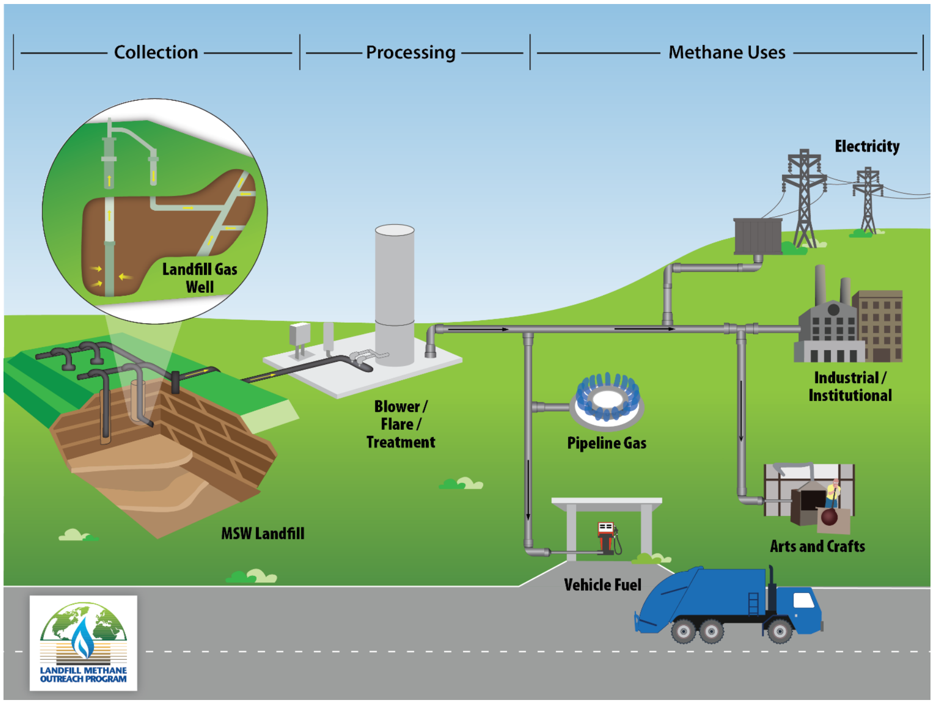
Figure 3 illustrates LFGE project process that utilizes landfill gas to generate new energy sources. After going through a purification process in the treatment systems, including dehumidification, filtration, and compression if needed (Pour et al., 2018; EPA, 2021a; Yechiel and Shevah, 2016), the landfill gas collected is used to generate new energy sources, including electricity, renewable natural gas for vehicle fuel, and the landfill gas for direct-use by nearby boilers, kilns, and cement production facilities (EPA, 2011). As of March 2021, 550 projects were operated, with 70% of the projects generating electricity, and direct-use of landfill gas and renewable natural gas accounting for 17% and 13%, respectively (EPA, 2021a).

The financial viability of Landfill Gas to Energy (LFGE) projects often hinges on supplementary fiscal mechanisms beyond the direct revenue generated from energy sales. Investment Tax Credits, Renewable Energy Certificates, and state-level grants serve as critical financial incentives that can render LFGE projects economically feasible (EPA, 2021a; Li et al., 2015). An analysis provided by the Environmental Protection Agency EPA (2021a) illustrates this dynamic; in the absence of such fiscal incentives, an LFGE project equipped with a 3-megawatt engine could face a negative net present value (NPV) of approximately \$2.7 million (2020 dollars). Conversely, the integration of these tax and environmental credits can transform the financial outlook of the same project to a positive NPV of \$2.1 million.[3] This underscores the essential role of policy-driven incentives in offsetting initial investment and operational costs, ensuring the sustainability and expansion of LFGE initiatives within the broader context of renewable energy development and environmental stewardship.

[2] In our dataset, as of 2021, 79.4% of the landfills have the design capacity above 2.5 million megagrams, implying that most of the landfills are regulated to install GCCS.

[3] The revenue and costs of LFGE projects vary depending on landfill characteristics and the project type. For instance, an LFGE project that generates electricity with a 3-megawatt engine costs about \$6 million dollars for initial development and around \$0.7 million for annual operation and maintenance (O&M). Initial development includes design, permits, and installation of utilities, and O&M includes materials, labor, and taxes. The estimated costs do not include GCCS and flaring system costs, which are approximately \$1.3 million for initial development and \$0.2 million for annual O&M.(EPA, 2021a).

Figure 3: LFGE project process.



Notes: This figure outlines the process of LFGE projects, from the collection of landfill gas to the generation of new energy sources, including electricity and heat.
Sources: EPA (2021a)

2.2 The landfill methane outreach program

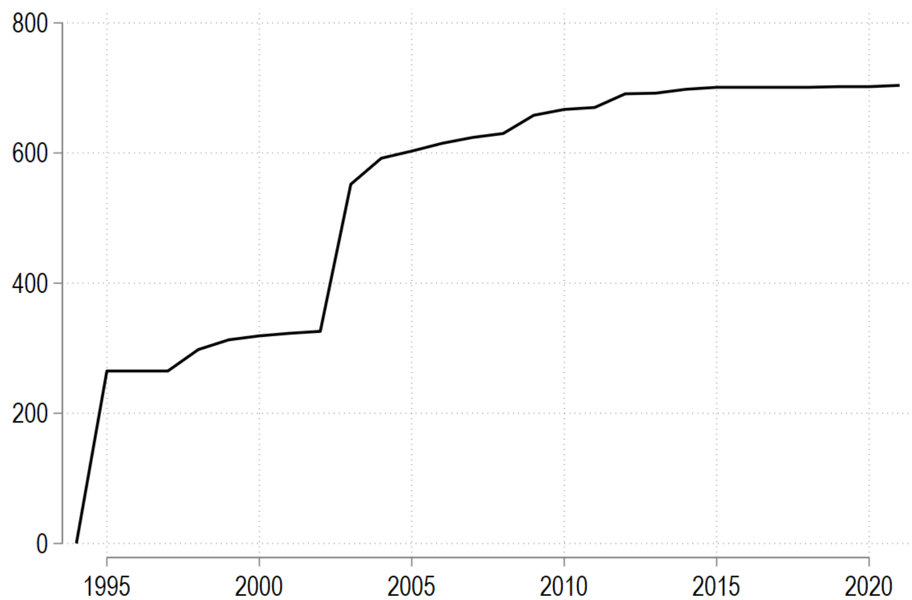
The EPA launched LMOP to promote the development of LFGE projects, cutting methane emissions from MSW landfills.[4] There is no specific requirement for joining LMOP; any organization that is willing to engage in LFGE project development can participate in the program through a Memorandum of Understanding (MOU) with the EPA. With confirmation from the EPA, the participant is assigned to one of the following partner types: Industry, Energy, State, Community, and Endorsers.[5] As of 2021, there are 1,053 program participants and 704 landfills are owned by 121 participating owners. Figure 4 illustrates how the number of landfills that are owned by LMOP participants changes over time. There are two noticeable spikes in 1995 and 2003, corresponding

[4]Carbon dioxide produced by landfill waste typically originates from biological sources and is deemed to be climate-neutral. (IPCC, 2006; Yang et al., 2013; Manfredi et al., 2009).

[5]Private landfill owners and LFGE project developers are considered as Industry partners energy partners include power providers and energy buyers. Community partners involve local governments and public landfill owners while State partners include local environmental departments involved in relevant regulation. Any nonprofit organizations that wish to promote LFGE projects are recognized as Endorsers (EPA, 2023b).

to the enrollment into LMOP of two major private firms that own more than 200 landfills each.[6]

Figure 4: Number of LMOP landfills.



Notes: This figure illustrates the number of LMOP landfills between 1994 and 2021. Any landfill owned by an LMOP partner is considered an LMOP landfill.

Participants are typically required to appoint an LMOP coordinator and report to the EPA about the LFGE projects they have been involved in although the specific responsibilities of the participants differ based on their partner types. Industry partners, for instance, are additionally expected to contribute to the development of case studies showcasing successful landfill gas recovery; state partners are suggested to review state policies to address obstacles to developing LFGE projects. In exchange, LMOP provides participants with technical assistance and information throughout the process of LFGE project development, which includes estimating the costs of LFGE projects at specific sites and identifying financing opportunities, although these benefits are accessible to non-participants as well upon request. In addition to individual assistance, LMOP offers general practical guidance, including technical application, regulatory changes, federal funding, and case studies, through regular webinars and workshops.

[6]WM (formerly Waste Management) owned 237 landfills and Republic Services owned 218 when they joined the program in 1995 and 2003, respectively. Other than landfills owned by WM and Republic Services, the number of private LMOP landfills has increased from 1 to 60 while the number of public landfills has increased from 12 to 172 between 1995 and 2021.

LMOP shares common features with other EPA-sponsored VEPs such as the 33/50 program (Khanna and Damon, 1999; Innes and Sam, 2008). VEPs have been adopted as complements to traditional command-and-control approaches for internalizing environmental externalities in the United States since the early 1990s. They have a number of advantages for both regulators and regulated entities. Regulators benefit with reduced monitoring and enforcement costs and participants obtain flexibility regarding the abatement of some of their emissions, public recognition of pro-environmental commitment, technical information, regulatory relief, and interaction opportunities with regulators or other participants (Segerson, 2013; Lyon and Maxwell, 2007; Borck and Coglianese, 2009; Bi and Khanna, 2012; Prakash and Potoski, 2012). Numerous studies suggest that VEPs reduce pollutant emissions (Zhou et al., 2020; Hoang et al., 2018; Bi and Khanna, 2012; Sam et al., 2009), promote environmental investment and innovation (Carrión-Flores and Innes, 2010; Carrión-Flores et al., 2013; Chang and Sam, 2015; Brouhle et al., 2023) and improve efficiency (Sam and Song, 2022).

In particular, for VEPs aiming to address climate change, such as Energy Star, Climate Wise, and SmartWay, empirical findings on their effectiveness in mitigating climate change are mixed. Some studies find the positive effects of the program participation on the reduction of carbon dioxide intensity (Kube et al., 2019), environmental innovation (Brouhle et al., 2013), and adopting cleaner technologies (Moon and Ko, 2013; Scott et al., 2023). Scott et al. (2023), for instance, suggest that the SmartWay program, which promotes cleaner truck investment in freight transportation, led a to a reduction of 25.2 MMTCO2e emissions between 2012 and 2019. Other studies find no significant evidence that these programs contribute to lessening greenhouse gas emissions (Pizer et al., 2011; Delmas and Montes-Sancho, 2009; Kim and Lyon, 2011). Although a number of studies scrutinize landfill gas management and its effects on methane releases from MSW landfills (Yang et al., 2013; Manfredi et al., 2009; Yao et al., 2019; Purmessur and Surroop, 2019; Pour et al., 2018; Jaramillo and Matthews, 2005), evaluation of policy interventions that promote landfill gas recovery is limited (Li et al., 2015; Jaramillo and Matthews, 2005; Melvin et al., 2016). We aim to fill this gap in the literature by evaluating the effectiveness of a government-sponsored program (LMOP) specifically conceived to addresses methane emissions from landfills.

3 Hypotheses

LMOP does not directly require landfill owners to cut their methane releases. Instead, it promotes the development of LFGE projects, which in turn result in reduced emissions through the capture and conversion of landfill gas into energy sources. Some landfill owners often hesitate to recover their landfill gas due to multiple obstacles, including insufficient methane generation, lack of information, and unfamiliarity with engineering technology (Trisolini, 2012; Hogan, 1996). While LMOP does not offer direct financial support, it provides participants with valuable information, including the feasibility analysis of an LFGE project and technical guidance (EPA, 2021a). These benefits are not exclusive to participants; non-participants can also access information and technical guidance. For instance, the LFGcost-Web model–which estimates the costs of LFGE projects–and past information-sharing webinars are publicly available online. Although the number of non-participants obtaining information from the program is not observed, the potential spillover of the program to non-participants may lead to an underestimation of its effects.

> *Hypothesis 1A.* LMOP participation increases the probability of LFGE project development.

In addition, we expect that barriers for LFGE project development faced by landfill owners vary depending on their circumstances, and the assistance and information provided by LMOP may play a more significant role for those facing higher barriers. We therefore explore the heterogeneous impacts of LMOP on LFGE project development based on previous experience with LFGE projects and ownership. We first divide LMOP landfills into two groups based on their previous experience of recovering landfill gas when they joined the program. If an LMOP landfill had any LFGE project before the participation, it is considered a landfill with prior experience. Approximately 89.9% of LMOP landfills had no previous experience with landfill gas recovery, and 41.0% of them ended up having LFGE projects after their program participation (See Figure A.1). Considering that one of the benefits the participants can receive is technical assistance for landfill gas recovery, the experience in recovering landfill gas and relevant knowledge would limit the impacts of the technical information.

Moreover, public landfill owners typically manage single landfill sites rather than multiple sites, and they are often perceived to have a lower level of expertise compared to private landfills (Trisolini, 2012).[7]. Single public landfill owners, in particular, have only one site to recover landfill gas from using new technology, implying a lower expected return on investment. In contrast, the owners of multiple landfills can leverage the new knowledge they have acquired across multiple sites, providing them with numerous opportunities to generate additional income (Trisolini, 2012). Also, transferring individual engineers with expertise from one site to other sites might promote knowledge sharing and learning economies as well (Stadler et al., 2022). Besides, public landfills are not eligible for tax benefits related to generating new energy sources, such as the Investment Tax Credit and Production Tax Credit, and the revenue from the sale of energy sources usually goes to the municipality's budget (Li et al., 2015), creating less financial incentives for LFGE projects compared to private landfills.

> *Hypothesis 1B.* The Effect of LMOP on the likelihood of LFGE project development is stronger among landfills without prior experience and public landfills.

An LFGE project may not lead to the reduction of fugitive methane releases considering that it is the GCCS, not the LFGE project, that collects landfill gas, resulting in a corresponding decline in methane emissions regardless of LFGE project development (Yang et al., 2013; Manfredi et al., 2009; Jaramillo and Matthews, 2005). For instance, if a landfill with a GCCS captures and flares landfill gas, the potential for reducing methane emissions through LFGE projects would be limited. On one hand, LFGE projects might contribute to reducing methane emissions by increasing the amount of landfill gas collected. The financial incentive for landfill owners that can generate additional income through the sale of energy may motivate them to capture more landfill gas. This could involve installing additional extraction wells or improving the efficiency of gas collection, leading to a reduction in fugitive emissions. On the other hand, it's possible for LFGE projects to result in higher fugitive emissions; some landfill owners with LFGE projects might intentionally elevate moisture levels by recirculating leachate and delaying the installation of soil cover, which boosts waste decomposition and maximizes landfill gas generation (Sierra Club, 2010; Trisolini, 2012). Given that it is practically hard to capture 100% of the landfill gas generated and approximately

[7] In our dataset, as of 2021, the number of public landfills is 1,222, representing 62.1% of the total MSW landfills, and there are 745 private landfills. The average design capacities of public and private landfills are 13.5 and 28.8 million tons, respectively. On average, public landfill owners have 2.3 landfills while private owners own 146.4 landfills. Excluding WM and Republic Services that own 442 out of 710 private landfills, the average number of landfills owned by private organizations is 8.8, still exceeding the average number for public landfills.

25-50% of landfill gases escape into the atmosphere (Anshassi et al., 2022; Pour et al., 2018; Manfredi et al., 2009; Themelis and Bourtsalas, 2021), the efforts to enhance the generation of landfill gas may result in additional fugitive methane emissions. Broun and Sattler (2016), for instance, suggest that landfills with both LFGE projects and a bioreactor that enhances leachate recirculation emit more methane compared to landfills with LFGE projects but without a bioreactor.

Hypothesis 2A. LFGE projects do not reduce fugitive methane emissions.

LFGE projects generate new energy, which mitigates carbon emissions by offsetting the use of fossil fuels. Many engineering studies provide life cycle assessment results showing that LFGE projects contribute to reducing greenhouse gas emissions because of energy generation, displacing fossil fuel usage (Yang et al., 2013; Liu et al., 2017; Manfredi et al., 2009; Wanichpongpan and Gheewala, 2007). For instance, Manfredi et al. (2009) suggest that both landfills with and without an LFGE project emit the same level of fugitive greenhouse gas emissions, and the overall net greenhouse gas emissions, which factor in the offsetting effects of energy production, are significantly lower in landfills with LFGE projects compared to those without.

Hypothesis 2B. LFGE projects reduce net greenhouse gas emissions.

4 Data

We have assembled a panel of Municipal Solid Waste landfills covering the period of 1994 to 2021, drawing on the EPA's Landfill Methane Outreach Program (LMOP) database. The database contains individual landfill characteristics such as geographical location, the year the landfill opened, whether it is public or private, and historical LFGE project development. To determine LFGE project operation status each year, we adopt a 183-day rule, i.e. an LFGE project is recorded as operating in a particular year if it is operated 183 days or more in the year.[8] The LMOP database also provides information about whether a landfill has a GCCS and the amount of landfill gas collected through GCCS for a given year between 2013 and 2021.

Besides, the EPA provides LMOP participant information, including the partner type and the year in which the organization joined the program. LMOP participation is recorded at the parent

[8]LFGE projects that operate less than 183 days in the year account for 3.4% of the total projects. The mean and median values of the LFGE project duration are 352.3 and 365 days, respectively.

organization level, not at the landfill level, and we posit that every landfill owned by an LMOP participant also joins the program in the year in which the parent organization participates in the program.[9] This assumption aligns with common practice in studies evaluating the impact of VEPs. Many such studies, including those examining participation in the ISO 14001 program (Tambunlertchai et al., 2013; Nishitani et al., 2012; Sam and Song, 2022) and the EPA's 33/50 program (Innes and Sam, 2008; Hoang et al., 2018), adopt a similar approach. Despite actual participation occurring at the facility level, these studies assess the effectiveness of VEP participation on firm-level outcomes, recognizing that the decision to embrace a voluntary program is typically made by the corporate management at the parent company level.

We obtain landfill-level fugitive methane emission data from the GHGRP, which also provides geolocation, industry type, and greenhouse gas emissions from 2010 to 2021. The methane emissions from GHGRP are the estimated methane released into the air based on the types of wastes, methane fraction of landfill gas, and landfill gas collection efficiency; they do not include the estimated methane either recovered by LFGE projects or destroyed through flaring (Jain et al., 2021; EPA, 2023a). The GHGRP requires landfill owners to report their methane releases if the annual greenhouse gas emission level is over 25,000 metric tons of carbon dioxide equivalent. Landfills that are not subject to this GHGRP rule account for approximately 64.5% of the total MSW landfills in the data. In the analysis of the effects of LFGE projects on methane emissions, we focus only on landfills that disclose their annual methane emissions. The LMOP database also contains the amount of avoided carbon emissions between 2013 and 2021; these represent estimates of carbon emissions offset by the use of energy generated through LFGE projects. Both fugitive methane emissions and avoided carbon emissions are recorded in the same unit, i.e., MMTCO2e, and we calculate net greenhouse gas emissions by subtracting the avoided carbon emissions from fugitive methane emissions following the life cycle assessment employed by Manfredi et al. (2009) and Yang et al. (2013).

Methane generation depends on various factors, including organic waste composition, tempera-

[9] This assumption implies that all landfills owned by LMOP parent organizations enjoy the benefits of the program, which may not be the case. Some landfills recorded as participants due to the participation of their parent organizations may not have been involved in the program, which would lead to the underestimation of the beneficial effects. In other words, this assumption likely biases the estimated effect of LMOP against our hypotheses. For a landfill that is first opened after its parent organization joined LMOP, the landfill is assumed to join the program in the year in which it is opened.

ture, moisture, atmospheric condition, nutrients, alkalinity, and waste age and density (Purmessur and Surroop, 2019; Rajaram et al., 2011; Tchobanoglous et al., 1993; Nanda and Berruti, 2021). We control landfill age and openness, which are calculated based on both opening and closing years of the landfill, to control the speed of waste decomposition and fugitive landfill gas emissions.[10] Until a landfill becomes full and closed with final covers, the site continues to accept new waste, resulting in more active biochemical reaction and landfill gas generation (Purmessur and Surroop, 2019). Daily and intermediate covers in active landfills lead to lower efficiency of landfill gas collection than final cover soils due to less thickness (Jain et al., 2021; Anshassi et al., 2022), which contributes to more fugitive methane emissions.

In addition, socioeconomic factors, including population, income, and education, also determine the level of MSW generation (Kolekar et al., 2016; Lebersorger and Beigl, 2011; Ojeda-Benítez et al., 2008; Beigl et al., 2004). Population and income growths are expected to raise the amount of MSW (Ali Abdoli et al., 2012; Keser et al., 2012). These changes can also shift lifestyles and consumption habits, potentially resulting in a decrease in organic waste(Nanda and Berruti, 2021; Ozcan et al., 2016). To account for such socioeconomic factors, we control for county GDP and population which were obtained from the Bureau of Economic Analysis, and the county unemployment rate, collected from the Economic Research Service. The political preference of local politicians may also affect state environmental protection spending (Raff et al., 2022), pollution level (Fowler and Kettler, 2021), and regulatory enforcement behavior (Innes and Mitra, 2015). Thus, we include in our models the ratio of Republican congressional representatives in each state, obtained from the Biographical Directory of the United States Congress, and governors' political party affiliation collected by scraping the National Governors Association website. Moreover, higher moisture and temperature spur landfill gas generation by speeding up bacterial decomposition (Purmessur and Surroop, 2019; Rajaram et al., 2011; Jain et al., 2021). We include mean temperature and precipitation level in the county obtained from the PRISM (Parameter-elevation Regressions on Independent Slopes Model) database. Finally, electricity and natural gas prices should affect a landfill's decision to operate LFGE projects for electricity generation (Li et al., 2015). We include the average retail price of electricity and the natural gas industrial price at the state level between 2001 and 2021.

[10]The average landfill ages at the time of program participation and project development are 25.8 and 30.4 years old, respectively. The average duration of LFGE project operations is 5.4 years for open landfills and 12.1 years for closed landfills.

Both are collected from the Energy Information Administration. We drop all observations where the control variables are missing.

Table A.1 displays landfill-level descriptive statistics. The final dataset consists of 41,924 observations between 2001 and 2021. The percentage of LFGE project development is 37.9% for LMOP landfills, which is significantly higher than that of non-participants (14.2%). The non-participants have a slightly higher average methane emissions (0.077 MMTCO2e) than the participants (0.074 MMTCO2e) although the difference is insignificant. Net greenhouse gas emissions, which accounts for avoided carbon emissions, are 0.059 and 0.071 MMTCO2e for LMOP and non-LMOP landfills, respectively. LMOP landfills are more likely to be opened and are typically located in counties with higher GDP and population levels than non-LMOP landfills.

5 Econometrics

The identification of the causal impact of LMOP participation on methane emissions requires an empirical strategy that addresses the endogeneity and the staggered nature of the decision to participate. Endogeneity arises from self-selection into LMOP and is a well-know feature in VEPs (see e.g., Sam et al. (2009); Zhou et al. (2020)). For example, in our context, unobserved environmental preferences of corporate leadership might influence both the choice to participate in LMOP and the decision to initiate an LFGE project. Companies led by individuals with a strong commitment to environmental sustainability might pursue LFGE projects and reduce methane emissions even in the absence of LMOP. These organizations are also more inclined to leverage the LMOP platform to highlight their commitment to environmental stewardship. To account for factors that determine the decision to join the program and LGFE development/emission behavior, we control for several potential confounders such as landfill and socioeconomic characteristics, and we include landfill and year-fixed effects. We first test whether LMOP participation increases the probability of LFGE project development between 2001 and 2021 (*Hypothesis 1A* and *Hypothesis 1B*), based on the following regression equation:

$$\text{LFGE Project}_{it} = \alpha + \beta \text{LMOP}_{it} + \mu X_{it} + \chi_i + \psi_t + \epsilon_{it} \tag{1}$$

where LFGE Project_{it} is a dummy indicator of whether a landfill i operates an LFGE project in the year t. LMOP_{it} equals 1 if a landfill participates in LMOP in the year. X_{it} represents time-varying cotrol variables. χ_i and ψ_t represent landfill and year fixed effects, respectively. ϵ_{it} represents the error term. The coefficient of interest β indicates the average treatment effect on the treated of LMOP participation on the probability of LFGE project development. However, recent advances in panel data estimation have shown that the two-way fixed effects displayed in Equation (1) may generate a biased treatment effect when the timing of the treatment varies across participants (de Chaisemartin and D'Haultfœuille, 2020; Goodman-Bacon, 2021; Roth et al., 2023). To overcome the potential pitfalls of two-way fixed effects estimation, we adopt a staggered difference-in-differences estimator developed by Callaway and Sant'Anna (2021), which provides a group-time average treatment effects on the treated. The Callaway and Sant'Anna (2021) estimator is well suited to our research setting in that LMOP participants have been joining the program in different years over the period of study (1994-2021).[11]. The comparison group is a landfill that never joins LMOP unless specified otherwise. Equation 3 presents the equation to estimate the group-time average treatment effects of LMOP participation:

$$\text{ATT(g, t)} = E[Y_t(g) - Y_t(0) | G_g = 1], \quad t \geq g \tag{2}$$

where G_g is a cohort indicator; $G_g = 1$ if a landfill first joins the program in year g. $Y_t(g)$ denotes the outcome for a treated landfill in the cohort group g in year t while $Y_t(0)$ indicates the untreated potential outcome (counterfactual) in year t. The Callaway and Sant'Anna (2021) estimator aggregates the group-time average treatment effects to estimate the overall effects of LMOP participation on the probability of LFGE project development.[12] Let $C = 1$ if a landfill has not participated in LMOP within the study period; 0 otherwise. In the absence of covariates, the average treatment is estimated based on a post-treatment parallel trends assumption as follows:

$$\widehat{\text{ATT}}\text{(g, t)} = E[Y_t - Y_{g-1} | G_g = 1] - E[Y_t - Y_{g-1} | C = 1] \tag{3}$$

In the presence of covariates, the treatment effects are estimated based on a doubly-robust approach

[11]Any participant who left the program before 2022 is not directly observed and treated as a non-participant in our analysis. This sample selection may lead to either overestimation (they left because they decided not to develop the LFGE project) or underestimation (they left because they developed the LFGE project) of the true effects.

[12]We use the Stata community-contributed command *CSDID* developed by Rios-Avila et al. (2023).

that combines inverse probability weighting and regression adjustment. Equation 4 represents the two-way fixed effects model to test whether LFGE project development reduces fugitive methane emissions (*Hypothesis 2A*) and net greenhouse gas emissions (*Hypothesis 2B*) from landfills.

$$\text{Log Emissions}_{it} = \tau + \gamma\text{LFGE Project}_{it} + \rho X_{it} + \sigma_i + \kappa_t + \eta_{it} \tag{4}$$

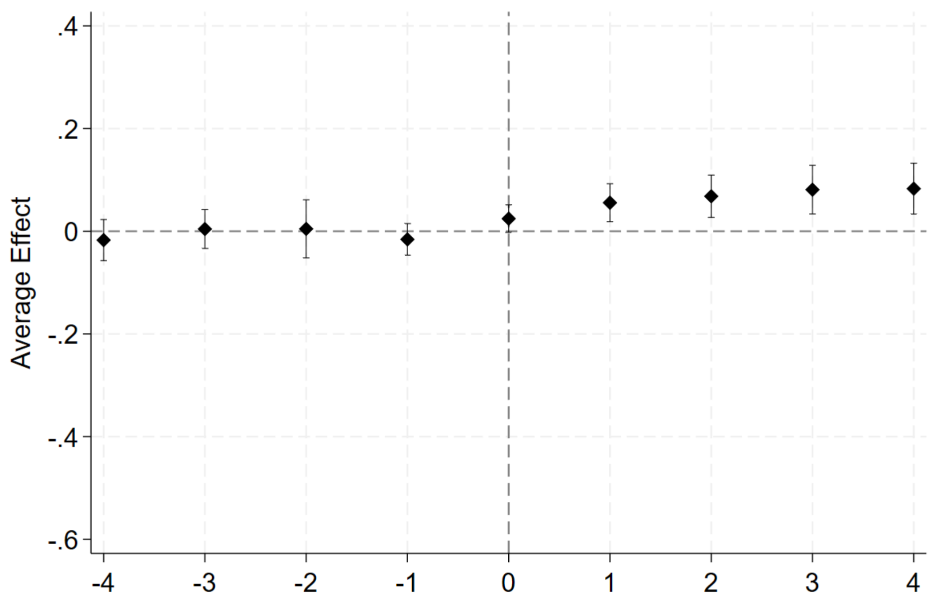
where Log Emissions$_{it}$ denotes the outcome variables–log methane emissions and log net greenhouse gas emissions– and X_{it} indicates time-varying control variables; σ_i and κ_t represent landfill and year fixed effects, respectively; η_{it} is the error term. We use Callaway and Sant'Anna (2021) to estimate the overall effects of LFGE projects on emissions based on the Equation 3. Due to limited availability of emissions data, we only observe the impact of LFGE project development on methane emissions between 2010 and 2021 and on net greenhouse gas emissions from 2013 to 2021.

6 Results

6.1 Effects of LMOP on LFGE project development

Figure 5 presents the event study plot of the average effects of LMOP participation on the probability of LFGE project development between 2001 and 2021 (*Hypothesis 1A*) using the Callaway and Sant'Anna (2021) estimator. The horizontal axis indicates the number of years since LMOP participation (positive values) or the number of years before (negative values) with zero being the year of participation. Compared to non-participation, LMOP participation significantly increases the probability of developing an LFGE project by 5.6 percentage points in the first year. The effects persist and gradually increase over multiple years such that by year 4 post-participation, the cumulative effects reach 8.3 percentage points. No statistically significant effects are detected before participation, as expected. The significant effects of LMOP on the likelihood of take-up of an LFGE project demonstrate that the program has achieved its main goal: promoting LFGE project development. To gauge the comparative impact of these effects, we calculate the corresponding proportional marginal effects based on the mean value of the probability of LFGE project development among non-LMOP participants (13.9%). We find that the estimated coefficients of 5.6 percentage points in the first year and 8.3 percentage points in the fourth year equate to proportional marginal effects or relative increases of 40.3% (5.6/13.9) and 59.7% (8.3/13.9), respectively.

Figure 5: The effect of LMOP on the probability of LFGE project development.

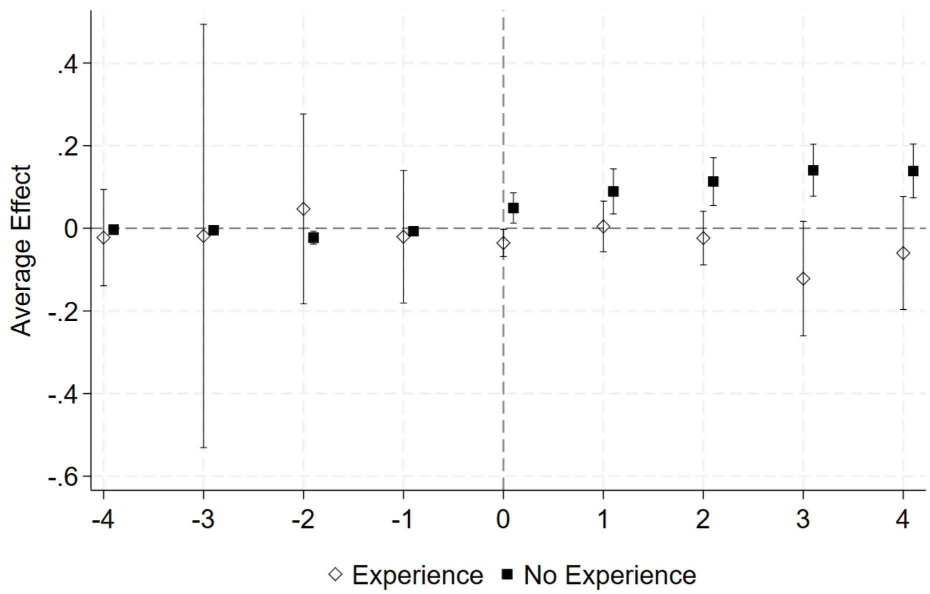


Notes: This figure illustrates the estimated effects of LMOP participation (diamonds) with 95% confidence intervals (vertical lines) on the probability of LFGE project development between 2001 and 2021. The control group is made up of never-treated landfills. In addition to landfill and year fixed effects, landfill operation status and age, county GDP, unemployment rate, population, temperature, precipitation, Republican representatives ratio in states, Republican governor, and electricity and natural gas prices in states are controlled for. The mean value of the probability of LFGE project development in the control group is 13.9%. The number of observations is 35,359.

We further explore potential heterogeneity in the effects of LMOP participation based on prior experience with LFGE projects and landfill ownership (*Hypothesis 1B*). Figure 6 shows the effects on the probability of LFGE project development in landfills with previous experience in LFGE projects and those without such experience before participation. The positive effects of LMOP participation on LFGE project development discussed above are mostly driven by landfills with no previous experience. LMOP participation increases the probability of LFGE project development for said landfills by 8.9 percentage points in year 1, equivalent to a 64% proportional marginal effect relative to non-participants. The effects become stronger over time; the cumulative effect by the year 4 is 13.9 percentage points, equivalent to 100% proportional increase. Considering that owners without prior experience in landfill gas recovery may lack the necessary technological knowledge for

LFGE project development, the information and assistance offered by LMOP appear to serve as an effective catalyst. For landfills that have any prior experience with LFGE project development, we find no significant evidence that LMOP participation increases the probability of LFGE project development, compared to non-participants.

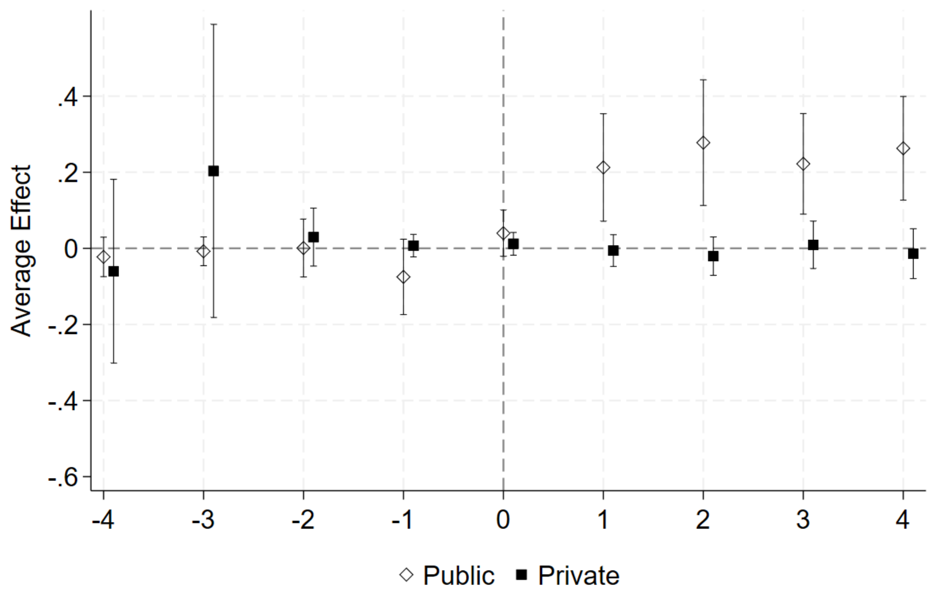
Figure 6: The effect of LMOP on the probability of LFGE project development by prior experience.



Notes: This figure illustrates the effects of LMOP participation with 95% confidence intervals (vertical lines) on the probability of LFGE project development by prior experience of LFGE projects before LMOP participation between 2001 and 2021. The control group is made up of never-treated landfills. If LMOP participants have prior experience with LFGE project before the participation, they are recorded as experienced landfills (diamonds), otherwise non-experienced ones (squares). In addition to landfill and year fixed effects, landfill operation status and age, county GDP, unemployment rate, population, temperature, precipitation, Republican representatives ratio in states, Republican governor, and electricity and natural gas prices in states are controlled for. The mean value of the probability of LFGE project development in the control group is 13.9%. The numbers of observations are 30,219 and 33,579 for the Experience and No Experience landfill samples, respectively.

Figure 7 shows that LMOP increases the probability of landfill gas recovery for public landfills by approximately 21.3 percentage points in the first year following participation, while no significant effects are observed among private landfills. Given that 13.0% of non-LMOP public landfills have LFGE projects, the estimated coefficient of 21.3 is equivalent to a proportional marginal effect of 163.8%. The effects continue to persist, and the cumulative effect in year 4 is 26.3 percentage points, equivalent to a proportional increase of 202.3%. The significant impacts may be partially attributed to the fact that, unlike private landfills, the majority of public landfills are owned by a single owner, who might be less inclined to adopt a new technology without technical assistance.[13] Figure A.2 shows that landfills owned by single owners (generally public landfills) are more likely to respond to the program in terms of LFGE project development than owners of multiple landfills.

Figure 7: The effect of LMOP on the probability of LFGE project by landfill ownership



Notes: This figure illustrates the effects of LMOP participation with 95% confidence intervals (vertical lines) on the probability of LFGE project development by landfill ownership between 2001 and 2021. The horizontal axis represents the relative year of LMOP participation. The control group is made up of never-treated landfills. In addition to landfill and year fixed effects, landfill operation status and age, county GDP, unemployment rate, population, temperature, precipitation, Republican representatives ratio in states, Republican governor, and electricity and natural gas prices in states are controlled for. The mean values of the probability of LFGE project development in the control group for public and private landfills are 13.0% and 20.6%, respectively. The numbers of observations are 23,981 and 10,270 for public and private landfills, respectively.

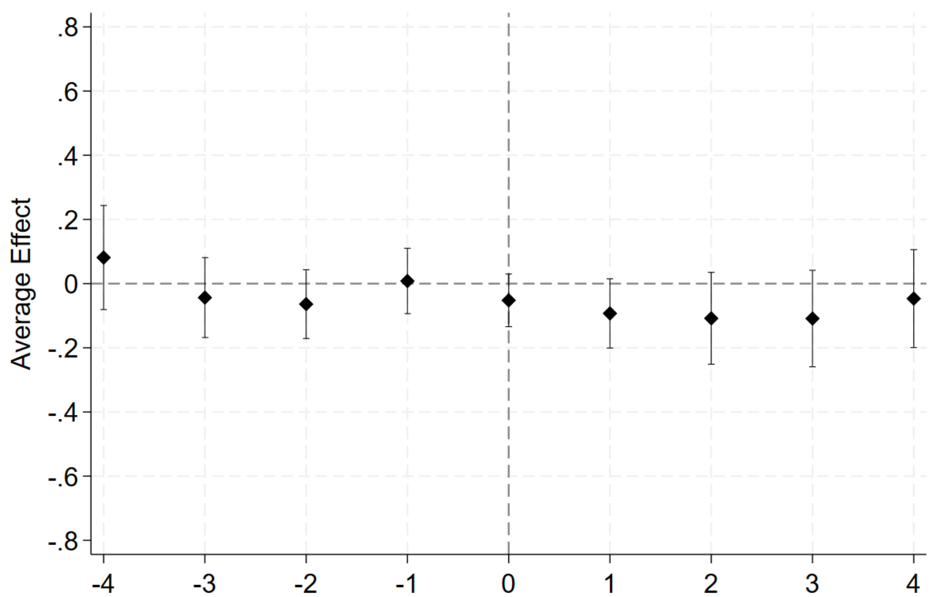
6.2 Effects of LFGE project development on methane emissions

Figure 8 illustrates how the development of an LFGE project affects methane emissions over the 2010-2021 period (*Hypothesis 2A*). We do not find any significant evidence that LFGE project development reduces fugitive methane emissions. The results confirm previous studies suggesting

[13]Table A.2 presents the descriptive statistics by single and multiple site ownership; 84% of landfills owned by a single site owner are public landfills.

that landfills with or without LFGE projects exhibit similar levels of fugitive emissions as long as they have GCCS (Manfredi et al., 2009; Jaramillo and Matthews, 2005). The impact of LFGE projects on methane emissions is constrained when a GCCS is already in place, capturing landfill gas prior to project development. When a GCCS effectively reduces methane emissions, the only viable avenues for an LFGE project to achieve further reductions involve either augmenting the quantity of landfill gas collected through the installation of additional extraction wells or enhancing the efficiency of the existing GCCS.

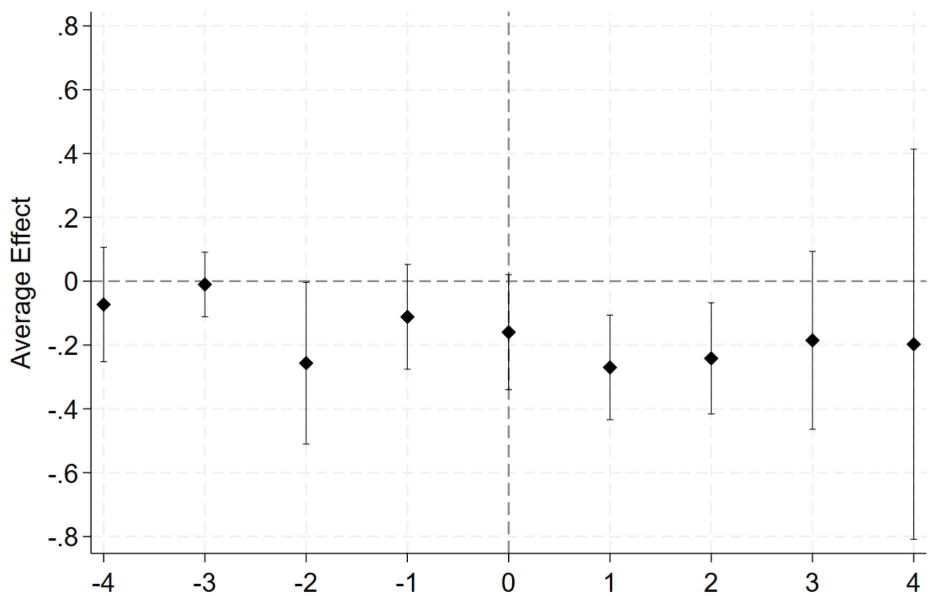
Figure 8: The effect of LFGE project development on log methane emissions



Notes: This figure illustrates the effects of LFGE project development (diamonds) with 95% confidence intervals (vertical lines) on log methane emissions between 2010 and 2021. The control group made of never-treated landfills. In addition to landfill and year fixed effects, landfill operation status and age, county GDP, unemployment rate, population, temperature, precipitation, Republican representatives ratio in states, Republican governor, and electricity and natural gas prices in states are controlled for. The mean value of the methane emissions in the control group is 0.06 MMTCO2e. The number of observations is 7,942.

We first look into whether GCCS alone reduces methane emissions in the absence of LFGE projects. We limit the sample by excluding landfills with LFGE projects to rule out the potential effects of LFGE project development on methane emissions. Figure 9 shows that among landfills without LFGE projects, from 2013 to 2021, the development of GCCS significantly reduces methane emissions by 23.6% in the year following GCCS installation, which confirms our expectation that GCCS reduces methane emissions. We also examine whether LFGE projects affect the additional reduction of methane releases on top of the reduction achieved by GCCS. We find that LFGE project does not significantly affect the amount of landfill gas collected (Figure A.4) nor reduce fugitive methane emissions among landfills that already have GCCS (Figure A.3). Overall, given that GCCS is a prerequisite of LFGE projects, the insignificant results shown in Figure 8 are be explained by the significant reduction of methane emissions from GCCS installation and insignificant effects of LFGE projects on landfill gas collected.

Figure 9: The effects of GCCS without LFGE project development on log methane emissions

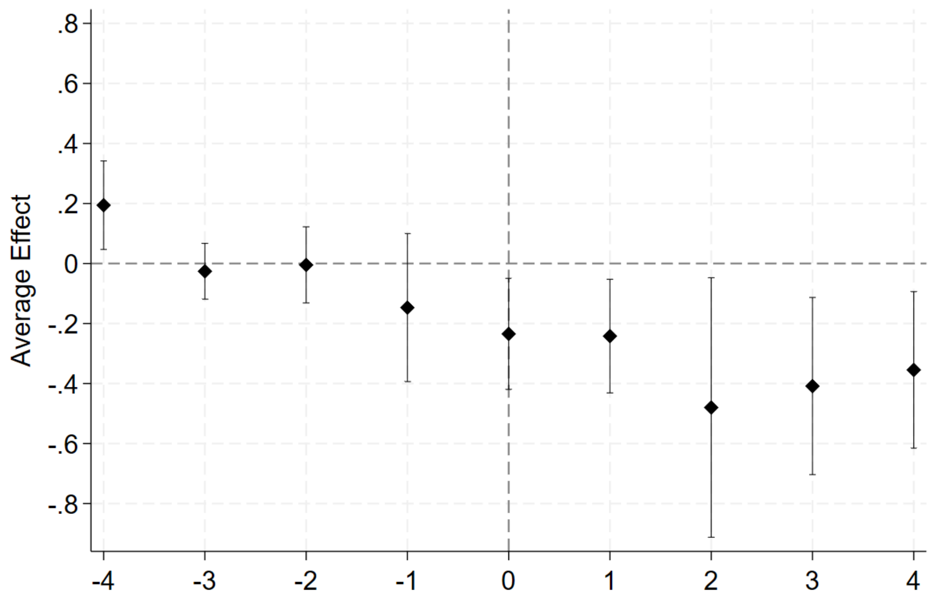


Notes: This figure illustrates the effects of GCCS development (diamonds) with 95% confidence intervals (vertical lines) on log methane emissions between 2013 and 2021. The control group is never-treated landfills. In addition to landfill and year fixed effects, landfill operation status and age, county GDP, unemployment rate, population, temperature, precipitation, Republican representatives ratio in states, Republican governor, and electricity and natural gas prices in states are controlled for. The mean value of the methane emissions in the control group is 0.06 MMTCO2e. The number of observations is 8,041.

Figure 10 shows that LFGE projects significantly reduce net greenhouse gas emissions by 21.5%, compared to landfills without LFGE projects, in the first year following LFGE project development (*Hypothesis 2B*). The effects persist over time; for instance, in year 4, the coefficient of -29.9%

remains significant. The post treatment average effect stands at -31.4%. Since we take the log of net greenhouse gas emissions, the negative net emissions—avoided emissions are higher than fugitive emissions—are dropped, likely leading to underestimated effects.[14]

Figure 10: The effects of LFGE project development on log of net greenhouse gas emissions



Notes: This figure illustrates the effects of LFGE project development (diamonds) with 95% confidence intervals (vertical lines) on log net greenhouse gas emissions between 2013 and 2021. The horizontal axis represents the relative year of GCCS development. The control group is made of never-treated landfills. In addition to landfill and year fixed effects, landfill operation status and age, county GDP, unemployment rate, population, temperature, precipitation, Republican representatives ratio in states, Republican governor, and electricity and natural gas prices in states are controlled for. The mean value of the net greenhouse gas emissions in the control group is 0.06 MMTCO2e. The number of observations is 5,238.

Our estimation results show that LFGE projects contribute to the reduction of greenhouse gas emissions not by reducing fugitive emissions but mainly through the generation of new energy. Hence, LMOP contributes to cutting greenhouse gas emissions by promoting LFGE projects that generate new energy sources. Considering the program's inception in 1994 and the fact that benefits of LMOP may wane over time, it is important to note that our estimation of the effects of LFGE projects on fugitive emissions is confined to the period between 2010 and 2021 due to data

[14]Four hundred and ninety observations are dropped out of 9,770 observations, representing 5% of the sample. LMOP participants account for 74.1% of the dropped data (363 observations). Landfills with LFGE projects account for 87.4% of the dropped sample (428 out of 490 observations).

limitations regarding methane releases. Furthermore, given that a substantial portion of participants joined the program before 2010 (Figure 4), it's likely that we would have detected a more substantial impact of LFGE projects on methane releases if we had the ability to observe fugitive methane emissions since 1994.

Moreover, LMOP may induce landfills exempted from the NSPS and EG to develop LFGE projects. If so, the program would contribute to the installation of a GCCS (essential for landfill gas recovery) for those who are not required to capture landfill gas. Since we do not directly observe in our data whether a landfill is regulated under the NSPS/EG in any given year, we utilize design capacity to create a proxy for exemption of NSPS/EG regulation. To do so, we assume that the design capacity remains constant over time and classify landfills with a design capacity of less than 2.5 million megagrams, as of 2021, as exempt from the NSPS and EG.[15] In our dataset, regulated landfills account for 82.3% of total landfills, and we do not find significant evidence that LMOP increases the likelihood of LFGE projects among landfills not regulated by the NSPS and EG while significant positive effects are observed for regulated landfills (Figure A.5). A cautionary note in interpreting this result is that certain landfills may undergo expansions in their design capacity. This implies that some previously unregulated landfills might be incorporated into the regulated group. As we do not have information on yearly changes in design capacity, potential expansions may lead to an underestimation of the effects of LMOP on LFGE projects among exempted landfills given the significant effects detected among the regulated group.[16]

6.3 Sensitivity bounds

Despite incorporating landfill and year-fixed effects alongside various confounders, our analysis remains susceptible to omitted variable bias. The decision to engage in the LMOP is inherently endogenous, potentially influenced by unobserved factors that simultaneously affect the choice to participate and emissions outcomes. For example, non-inclusion of variables such as a landfill's financial health could introduce omitted variable bias. To assess the influence of potentially omitted

[15] If a landfill releases less than 34 metric tons of NMOC, it is not required to control landfill gas, even if the design capacity is above 2.5 million megagrams. Due to the unavailability of individual NMOC emissions data, we solely use design capacity for our analysis. The unit for design capacity in the data is U.S. short tons while the NSPS and EG use megagram or metric tons. Consequently, we classify landfills with a design capacity exceeding 2.75 U.S. short tons as regulated based on the following conversion rule: 1 megagram=1.1 U.S. short tons.

[16] The regulated group is likely inflated by our data-dictated conservative approach of categorizing regulatory exemption based on the most recent design capacity.

variables, we employ the sensitivity analysis framework proposed by Cinelli et al. (2020). This approach enables the estimation of the extent to which omitted variables could impact the estimated effects and their statistical significance relative to observed controls. The sensitivity analysis results, displayed in Table A.3, detail findings from two principal regressions: the average impact of LMOP on LFGE project development (Panel A) and the impact of LFGE project development on the logarithm of net greenhouse gas emissions (Panel B). According to Panel A, any omitted variables that fail to account for at least 6.9% (robustness value) of the residual variance in both the LFGE project and LMOP participation are insufficient to nullify the estimated treatment effects. Similarly, the estimated impact of LFGE projects on net greenhouse gas emissions cannot be driven to zero provided that potential confounders do not account for more than 6.6% of the residual variance in both the LFGE project and net greenhouse gas emissions, as shown in Panel B.

Furthermore, we can compare the effects of omitted variables on the estimates with observed control variables. We use landfill openness as a benchmark covariate. Table A.3 (A) provides that the estimated effects of LMOP on the probability of LFGE project would not be affected by unobserved confounders, even if the confounders are five times stronger than landfill openness in terms of explanatory power (For visualization, see Figure A.6). Besides, Table A.3 (B) shows that the estimated effects of LFGE project on net greenhouse gas emissions are also not sensitive even with the omitted variables that are five times as strong as landfill openness (For visualization, see Figure A.7).

6.4 Robustness checks

Different measurements of variables

LMOP participation: Some landfills often make a contract with a private firm to operate landfills, and 32.6% of landfills are operated by an organization that is not their owner. While the decision to develop an LFGE project would be made by the landfill owner, it is likely that the landfill operator influences the decision as they would be responsible for the practical implementation of the project. Figure A.8 shows that defining LMOP participation based on the participation status of the operator provides similar results, with a slightly lower probability of LFGE project development in all post-participation years of participation.

LFGE Project: Instead of the 183-day rule for determining LFGE project status for each year, we adopt 1-day and 365-day rules. Figure A.9 shows that the effects of LMOP on the probability of LFGE projects with 1-day and 365-day rules are consistent with the main findings with the 183-day rule although the estimation results with the 1-day rule provide insignificant effects in the first two years post-participation.

Not-yet-treated group as control group

Unlike the main analysis where we adopt Callaway and Sant'Anna (2021) estimator with never-treated landfills as a control group, here we use the not-yet-treated group as a control group. Overall, the estimation results with the not-yet-treated group are consistent with our previous findings with never-treated groups. The effects of LMOP on the probability of LFGE project development are shown in Figure A.10. The effects of LFGE projects and GCCS on log methane emissions are displayed in Figure A.11 and Figure A.12, respectively. Figure A.13 presents the effects of LFGE projects on log net greenhouse gas emissions.

Alternative estimators and lagged LMOP participation

Besides the Callaway and Sant'Anna (2021) estimator, we consider the estimators proposed by Sun and Abraham (2021) and de Chaisemartin and D'Haultfœuille (2020) that are also designed to overcome the potential bias of the conventional two-way fixed effects estimator in the presence of staggered treatment. Our main findings are robust to these alternative estimators. The effects of LMOP on the probability of LFGE project development are shown in Figure A.14, and Figure A.15 illustrates the effects of GCCS on log methane emissions among landfills without LFGE projects. The effects of LFGE projects on log methane emissions and log of net greenhouse gas emissions are presented in Figure A.16 and Figure A.17, respectively. To rule out the possibility of potential reverse causality, we use lagged LMOP participation. Figure A.18 illustrates the effects of LMOP on the probability of LFGE projects using 1-year-lagged LMOP participation, and the results are consistent with the findings based on contemporaneous LMOP participation.

7 Conclusion

This study analyses the Landfill Methane Outreach Program (LMOP) and its efficacy in spurring the development of landfill gas-to-energy (LFGE) projects and methane abatement within the context of municipal solid waste (MSW) landfills in the United States. Using a staggered difference-in-differences analytical framework and robustness checks, we find evidence that LMOP significantly increases the likelihood of LFGE project development, particularly among landfills lacking prior experience and those owned by public entities. This finding highlights the LMOP's important role in encouraging the adoption of green technologies that convert landfill gas into renewable energy sources.

Despite the program's success in promoting LFGE project development, we did not detect a significant reduction in fugitive methane emissions due to LFGE projects. Hence, the mere development of an project, while beneficial for energy generation, may not directly reduce fugitive methane emissions, possibly due to the pre-existing installation of landfill gas collection and control systems that operate independently of LFGE initiatives. Nonetheless, the positive impact of LFGE projects on net greenhouse gas emissions, with a notable reduction of 31.4%, highlights the critical contribution of these projects to climate change mitigation efforts by offsetting carbon emissions through the generation of alternative energy sources.

Additionally, the non-exclusive nature of information from LMOP, accessible to both LMOP and non-LMOP landfills, may lead to a spillover effect, akin to other VEPs (Zhou et al., 2020). Exploring how LMOP information is shared among participants and disseminated across all landfills is a prospective avenue for future research. Moreover, delving into the motivations behind the development of LFGE projects is crucial. The factors influencing the decision to recover landfill gas have been inadequately explored (Li et al., 2015). Further investigations into the determinants that drive landfills to recover their landfill gas are essential for designing and implementing policies that effectively promote gas recovery.

Our study fills a gap in literature regarding the empirical evaluation of voluntary environmental programs (like LMOP) within the framework of climate change strategies in the waste management sector. It underscores the necessity of considering both direct and indirect environmental benefits of such programs, offering a more comprehensive understanding of their efficacy. The findings accentuate the importance of policy incentives, such as Investment Tax Credits, Renewable Energy Certificates, and state grants, in making LFGE projects financially viable and environmentally beneficial.

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A Appendix

Table A.1: Descriptive statistics by LMOP

	LMOP (a)	Non-LMOP (b)	Difference (a-b)
LFGE Projects (=1)	0.38	0.14	0.24***
	(0.00)	(0.00)	(0.00)
Fugitive Methane Emissions (MMTCO2e)	0.07	0.08	-0.00
	(0.00)	(0.00)	(0.00)
Net Greenhouse Gas Emissions (MMTCO2e)	0.06	0.07	-0.01***
	(0.00)	(0.00)	(0.00)
Open (=1)	0.70	0.47	0.23***
	(0.00)	(0.00)	(0.01)
Landfill Age (Years)	34.54	36.04	-1.50***
	(0.13)	(0.09)	(0.16)
GDP (billion US$)	42.70	24.48	18.21***
	(0.95)	(0.39)	(0.86)
Unemployment Rate (%)	6.34	6.25	0.09***
	(0.02)	(0.02)	(0.03)
Population (million)	0.71	0.46	0.26***
	(0.02)	(0.01)	(0.01)
Mean Temperature (°C)	13.43	13.21	0.22***
	(0.04)	(0.02)	(0.05)
Mean Precipitation (meter)	1.04	1.05	-0.00
	(0.00)	(0.00)	(0.00)
Republican Representative Ratio	0.55	0.54	0.01***
	(0.00)	(0.00)	(0.00)
Republican Governor (=1)	0.56	0.55	0.01
	(0.00)	(0.00)	(0.01)
Electricity Prices (US cents/kWh)	9.61	9.63	-0.02
	(0.02)	(0.02)	(0.03)
Natural Gas Prices (US$/thousand cubic feet)	7.06	7.22	-0.16***
	(0.02)	(0.01)	(0.02)

Note: This table presents the descriptive statistics by LMOP participation. LMOP landfill is a landfill owned by LMOP participants. LFGE project is equal to 1 if a landfill operates LFGE project more than 183 days in a year. GDP, unemployment rate, population, mean temperature, and mean precipitation are at the county level. The Republican representative ratio is the ratio of Republican congressional representatives in each state, and the Republican governor is equal to 1 if a landfill is located in a state led by a Republican governor. Electricity and natural gas prices are average retail prices and industrial prices, respectively, at the state level. The numbers of observations of LMOP and non-LMOP landfills are 12,192 and 29,732, respectively. Regarding methane emissions, there are 6,392 observations for LMOP and 6,816 for non-LMOP landfills. For net greenhouse gas emissions, the respective observation numbers are 4,755 and 5,015, respectively. * $p<0.10$, ** $p<0.05$, *** $p<0.01$.

Table A.2: **Descriptive statistics by single and multiple site ownership**

	Single (a)	Multiple (b)	Difference (a-b)
LMOP Participation (=1)	0.05	0.58	1.00***
	(0.00)	(0.00)	(0.00)
LFGE Projects (=1)	0.16	0.28	0.24***
	(0.00)	(0.00)	(0.00)
Fugitive Methane Emissions (MMTCO2e)	0.07	0.08	-0.00
	(0.00)	(0.00)	(0.00)
Net Greenhouse Gas Emissions (MMTCO2e)	0.07	0.06	-0.01***
	(0.00)	(0.00)	(0.00)
Public (=1)	0.84	0.39	-0.59***
	(0.00)	(0.00)	(0.00)
Open (=1)	0.49	0.62	0.23***
	(0.00)	(0.00)	(0.01)
Landfill Age (Years)	36.37	34.40	-1.50***
	(0.10)	(0.11)	(0.16)
GDP (billion US$)	19.15	42.54	18.21***
	(0.44)	(0.69)	(0.86)
Unemployment Rate (%)	6.17	6.42	0.09***
	(0.02)	(0.02)	(0.03)
Population (million)	0.34	0.75	0.26***
	(0.01)	(0.01)	(0.01)
Mean Temperature (°C)	12.99	13.79	0.22***
	(0.03)	(0.03)	(0.05)
Mean Precipitation (meter)	1.10	0.98	-0.00
	(0.00)	(0.00)	(0.00)
Republican Representative Ratio	0.56	0.54	0.01***
	(0.00)	(0.00)	(0.00)
Republican Governor (=1)	0.55	0.56	0.01
	(0.00)	(0.00)	(0.01)
Electricity Prices (US cents/kWh)	9.55	9.70	-0.02
	(0.02)	(0.02)	(0.03)
Natural Gas Prices (US$/thousand cubic feet)	7.20	7.10	-0.16***
	(0.02)	(0.02)	(0.02)

Note: This table presents the descriptive statistics by single and multiple site ownership. LMOP landfill is a landfill owned by LMOP participants. LFGE project is equal to 1 if a landfill operates LFGE project more than 183 days in a year. GDP, unemployment rate, population, mean temperature, and mean precipitation are at the county level. The Republican representative ratio is the ratio of Republican congressional representatives in each state, and the Republican governor is equal to 1 if a landfill is located in a state led by a Republican governor. Electricity and natural gas prices are average retail prices and industrial prices, respectively, at the state level. The numbers of observations of landfills owned by single and multiple site owners are 21,243 and 19,176, respectively. Regarding methane emissions, there are 5,245 observations for single and 7,963 for multiple sites landfills. For net greenhouse gas emissions, the respective observation numbers are 3,900 and 5,870, respectively. * $p<0.10$, ** $p<0.05$, *** $p<0.01$.

Table A.3: Sensitivity Test: Cinelli et al. (2020)

Panel A
Outcome: *LFGE project*

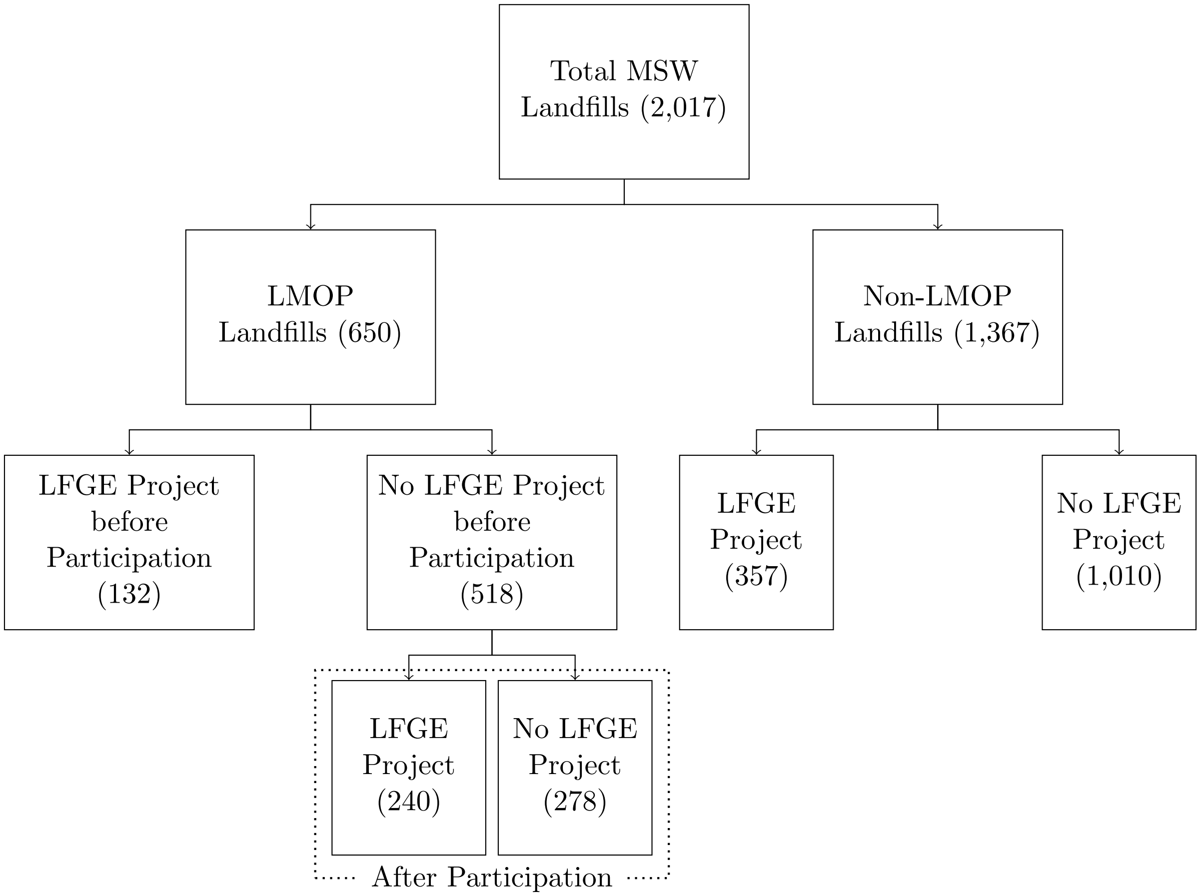
Treatment:	Est.	S.E.	t(H0=0)	$R^2_{Y\sim D\mid\mathbf{X}}$	$RV_{q=1}$	$RV_{q=1,\alpha=.05}$
LMOP	.117	.008	14.273	.51%	6.9 %	5.98%
df = 39876		*Bound (1x open)*: $R^2_{Y\sim Z\mid\mathbf{X},D} = .15\%$, $R^2_{D\sim Z\mid\mathbf{X}} = .01\%$				
		Bound (2x open): $R^2_{Y\sim Z\mid\mathbf{X},D} = .3\%$, $R^2_{D\sim Z\mid\mathbf{X}} = .03\%$				
		Bound (3x open): $R^2_{Y\sim Z\mid\mathbf{X},D} = .44\%$, $R^2_{D\sim Z\mid\mathbf{X}} = .04\%$				

Panel B
Outcome: *Log net greenhouse gas emissions*

Treatment:	Est.	S.E.	t(H0=0)	$R^2_{Y\sim D\mid\mathbf{X}}$	$RV_{q=1}$	$RV_{q=1,\alpha=.05}$
LFGE project	-.202	.033	-6.126	.46%	6.59 %	4.53%
df = 8081		*Bound (1x open)*: $R^2_{Y\sim Z\mid\mathbf{X},D} = .33\%$, $R^2_{D\sim Z\mid\mathbf{X}} = .33\%$				
		Bound (2x open): $R^2_{Y\sim Z\mid\mathbf{X},D} = .67\%$, $R^2_{D\sim Z\mid\mathbf{X}} = .66\%$				
		Bound (3x open): $R^2_{Y\sim Z\mid\mathbf{X},D} = 1\%$, $R^2_{D\sim Z\mid\mathbf{X}} = .98\%$				

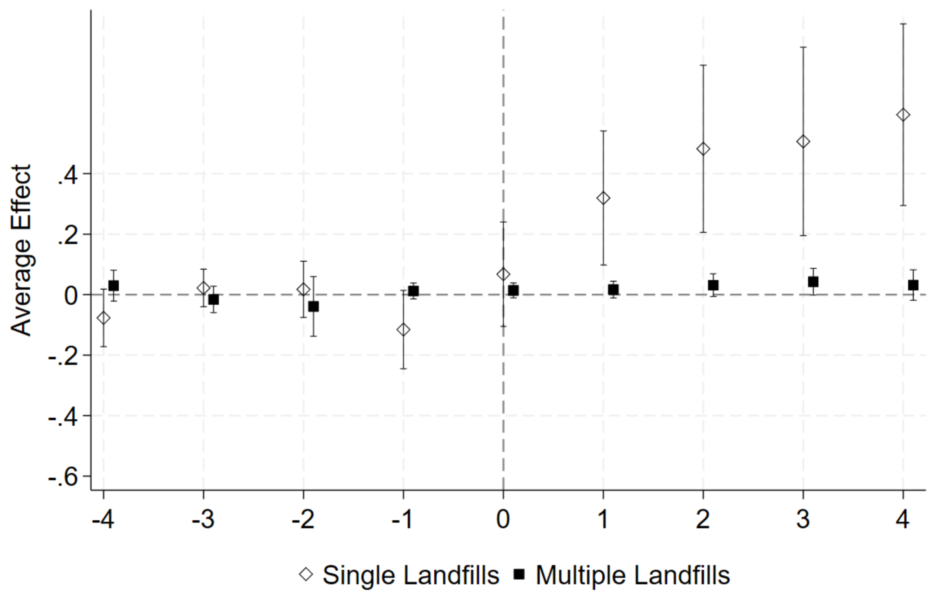
Note: This table shows the sensitivity test developed by Cinelli and Hazlett (2020). Stata community-contributed command *sensemakr* developed by Cinelli et al. (2020) is used. Panel A shows the test results on the regression of the probability of LFGE project on LMOP. Panel B shows the test results on the regression of net greenhouse gas emissions on LFGE project development. In both panel A and panel B tests, two-way fixed effects models are adopted, and the landfill openness is used as benchmark covariates. D and Y represent treatment variable and outcome variables, respectively. Z denotes unobserved confounders. $R^2_{Y\sim D}$ represents the partial R^2 of D with Y. $RV_{q=1}$ represents the robustness value for confounders to bring the estimated effect to zero. $RV_{q=1,\alpha=.05}$ represents the robustness value for confounders to eliminate the significance of the estimated effect.

Figure A.1: Number of landfills by LFGE project experience



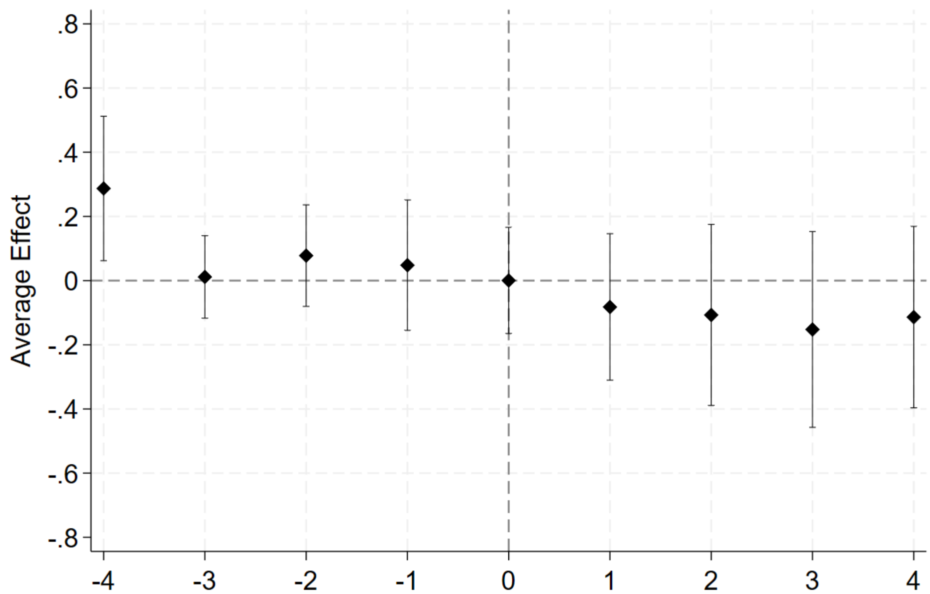
Note: This table presents the number of MSW landfills based on their LMOP participation and LFGE project status as of 2021. The number in parentheses denotes the number of landfills that belong to each category. LMOP landfills are landfills that are owned by LMOP participants; non-LMOP landfills are landfills that are never owned by LMOP participants. Among LMOP landfills, the landfills that have ever developed an LFGE project prior to their program participation are considered as "LFGE Project before Participation". The "No LFGE Project before Participation" refers to LMOP landfills that have never developed an LFGE project before they joined the program, which consists of two subgroups based on their LFGE project development after their program participation. Among "Non-LMOP Landfills", the landfills that have ever developed an LFGE project belong to the group "LFGE project"; they are included in the group "No LFGE Project", otherwise.

Figure A.2: The effect of LMOP on the probability of LFGE project development by single and multiple site ownership



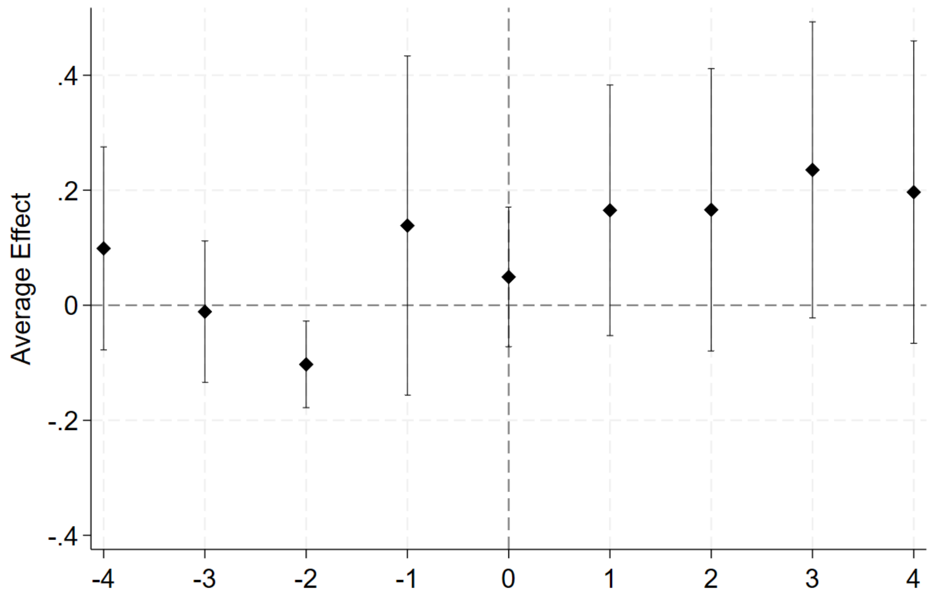
Notes: This figure illustrates the effect of LMOP participation with 95% confidence intervals (vertical lines) on the probability of LFGE project development by whether a landfill is owned by single (diamonds) or multiple (squares) site owner between 2001 and 2021. The horizontal axis represents the relative year of LMOP participation. A landfill is recorded as 'multiple' if it is owned by an organization with more than one landfill site; otherwise, it is recorded as a 'single' landfill. The control group is made up of never-treated landfills. In addition to landfill and year fixed effects, landfill operation status and age, county GDP, unemployment rate, population, temperature, precipitation, Republican representatives ratio in states, Republican governor, and electricity and natural gas prices in states are controlled for. The mean values of the probability of LFGE project development in the control group for single and multiple landfills are 0.14% and 0.16%, respectively. The numbers of observations are 20,843 and 13,043 for single and multiple site landfills, respectively.

Figure A.3: The effects of LFGE Project development on log methane emissions among landfills with GCCS



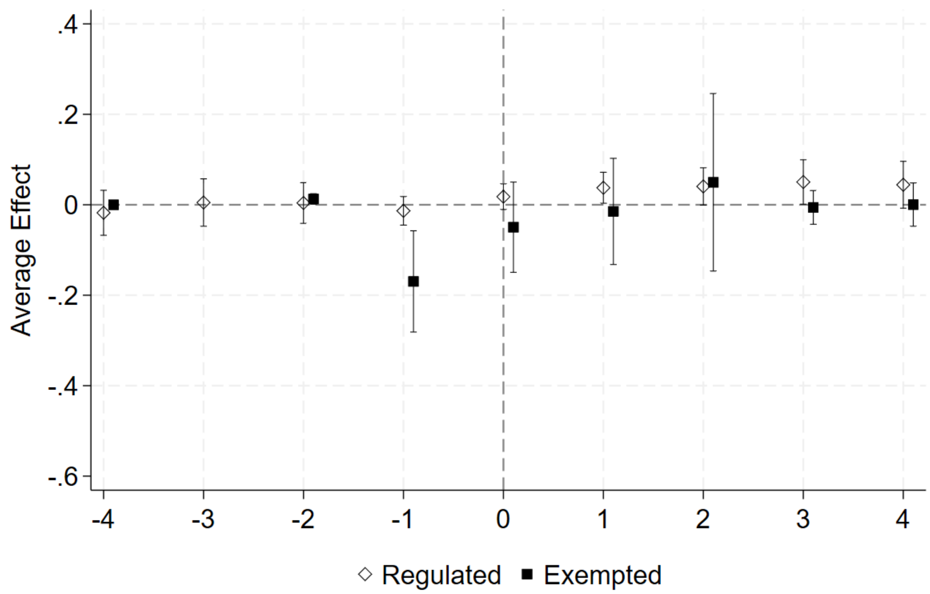
Notes: This figure illustrates the effects of LFGE project development (diamonds) with 95% confidence intervals (vertical lines) on log methane emissions among landfills with GCCS between 2013 and 2021. The horizontal axis represents the relative year of LFGE project development. The control group is made up of never-treated landfills. In addition to landfill and year fixed effects, landfill operation status and age, county GDP, unemployment rate, population, temperature, precipitation, Republican representatives ratio in states, Republican governor, and electricity and natural gas prices in states are controlled for. The mean value of the methane emissions in the control group is 0.06 MMTCO2e. The number of observations is 2,669.

Figure A.4: The effects of LFGE project development on log landfill gas collected



Notes: This figure illustrates the effects of LFGE project development (diamonds) with 95% confidence intervals (vertical lines) on log landfill gas collected between 2013 and 2021. The horizontal axis represents the relative year of LFGE project development. The control group is made up of never-treated landfills In addition to landfill and year fixed effects, landfill operation status and age, county GDP, unemployment rate, population, temperature, precipitation, Republican representatives ratio in states, Republican governor, and electricity and natural gas prices in states are controlled for. The mean value of the methane emissions in the control group is 0.23 million standard cubic feet per day. The number of observations is 3,524.

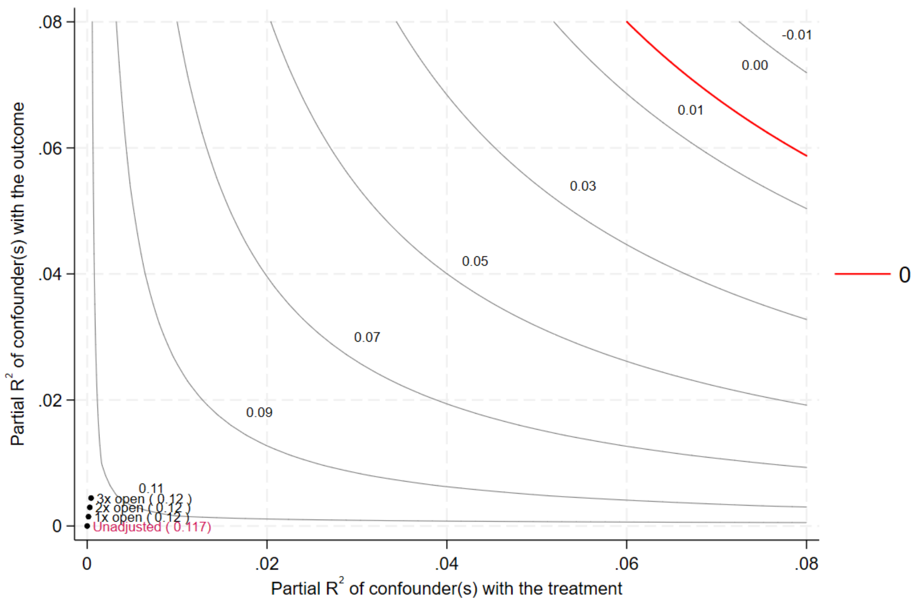
Figure A.5: The effects of LMOP on the probability of LFGE project by being regulated by the NSPS and EG



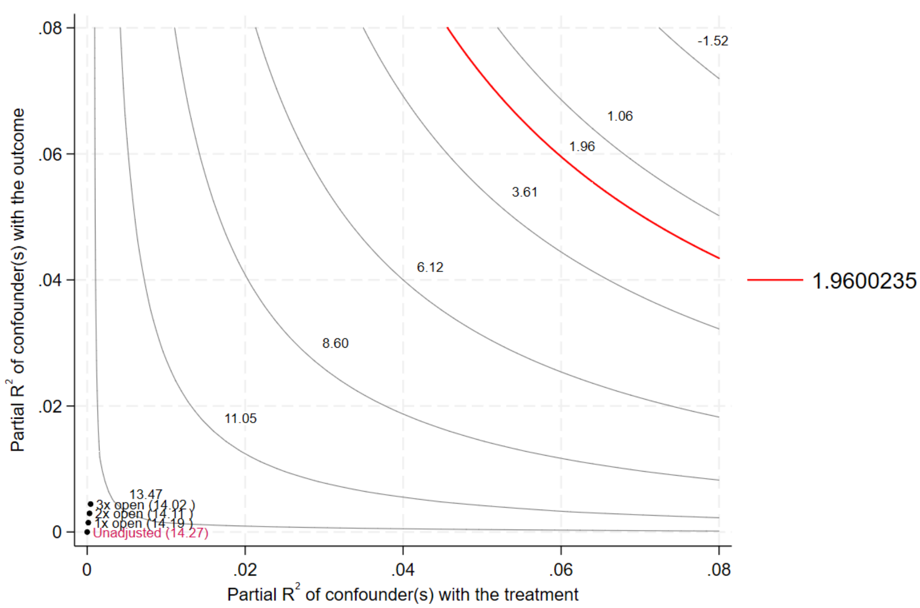
Notes: This figure describes the effect of LMOP participation with 95% confidence intervals (vertical lines) on the probability of LFGE project development by whether landfills are regulated by the NSPS and EG between 2001 and 2021. The horizontal axis represents the relative year of LMOP participation. A landfill is classified as regulated if its design capacity is greater than or equal to 2.75 million; otherwise, it is recorded as an exempted landfill. The control group is made up of never-treated landfills In addition to landfill and year fixed effects, landfill operation status and age, county GDP, unemployment rate, population, temperature, precipitation, Republican representatives ratio in states, Republican governor, and electricity and natural gas prices in states are controlled for. The mean values of the probability of LFGE project development in the control group for regulated and exempted landfills are 27.2% and 3.2%, respectively. The numbers of observations are 15,525 and 3,893 for regulated and exempted landfills, respectively.

Figure A.6: Sensitivity test contour plots: effects of LMOP on the probability of LFGE project development

(a)



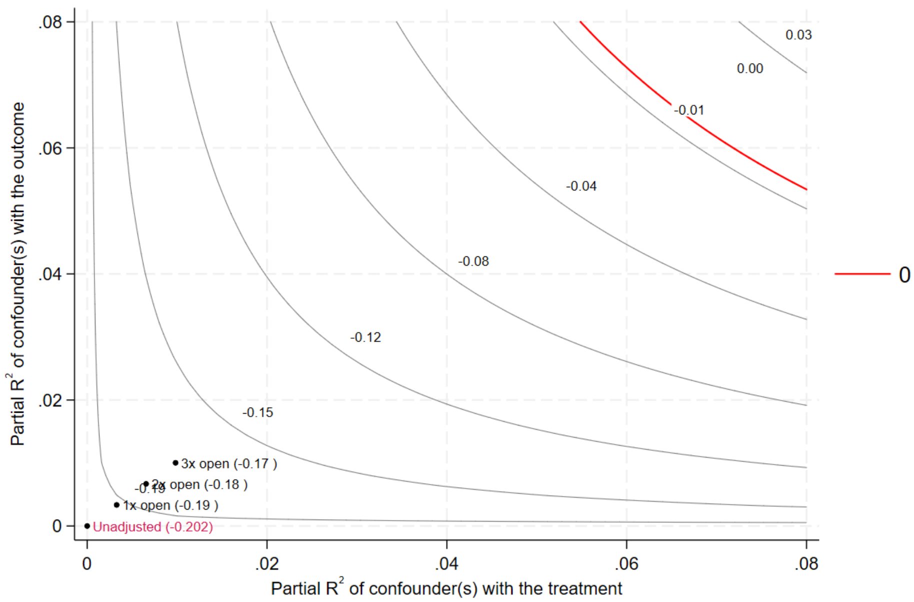
(b)



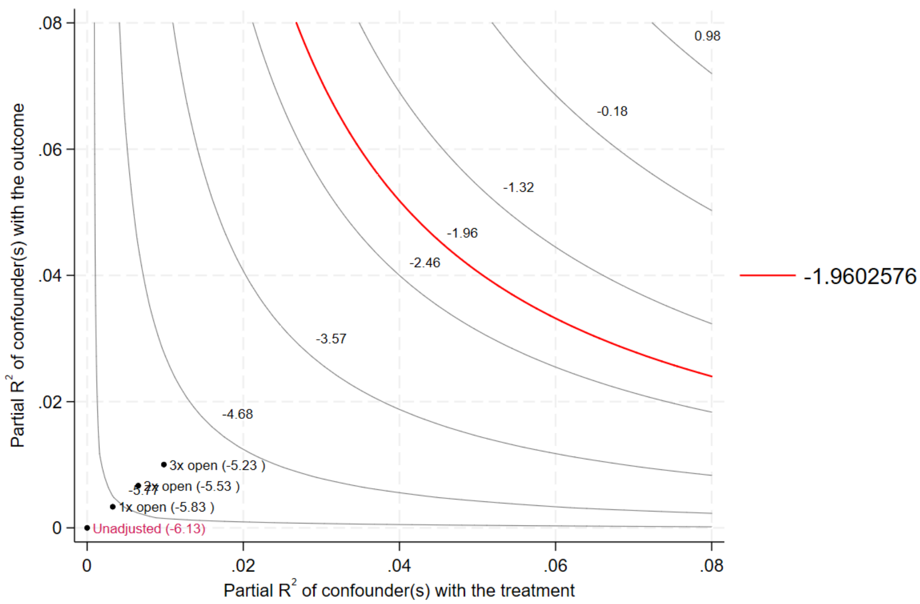
Notes: These contour plots describe the effects of omitted variables on the coefficient (Figure (a)) and 5% significance (Figure (b)) of the estimated effect of LMOP on the probability of LFGE project development, based on Cinelli et al. (2020) sensitivity test.

Figure A.7: Sensitivity test contour plots: effects of LFGE project development on log net greenhouse gas emissions

(a)

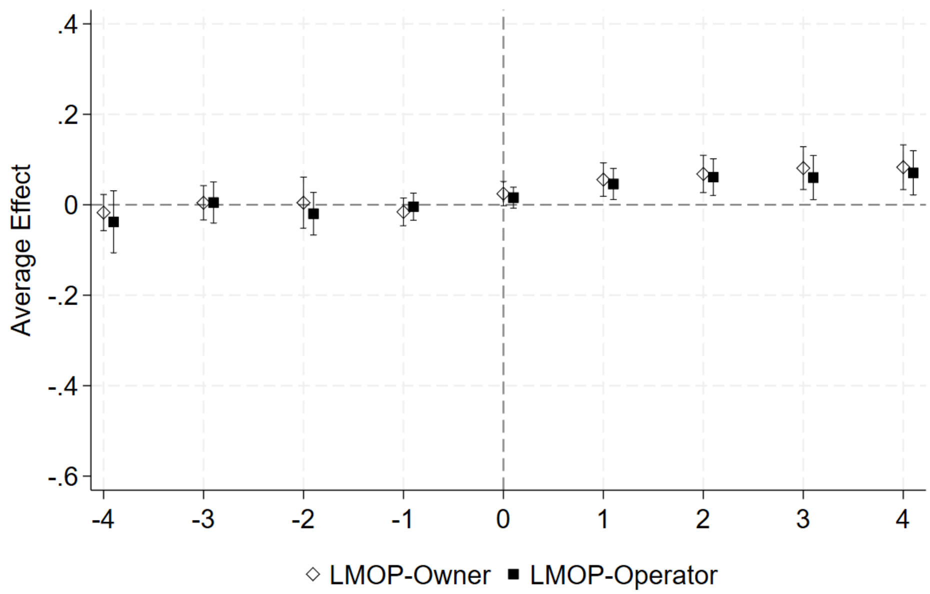


(b)



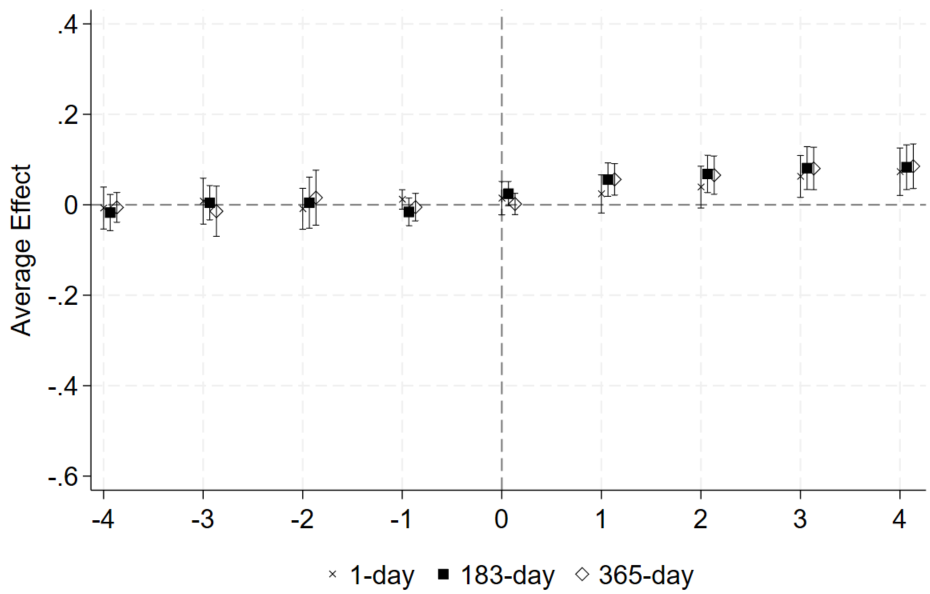
Notes: These contour plots describe the effects of omitted variables on the coefficient (Figure (a)) and 5% significance (Figure (b)) of the estimated effect of LFGE project development on log net greenhouse gas emissions, based on Cinelli et al. (2020) sensitivity test.

Figure A.8: The effects of LMOP on the probability of LFGE project development using different measurement of LMOP participation.



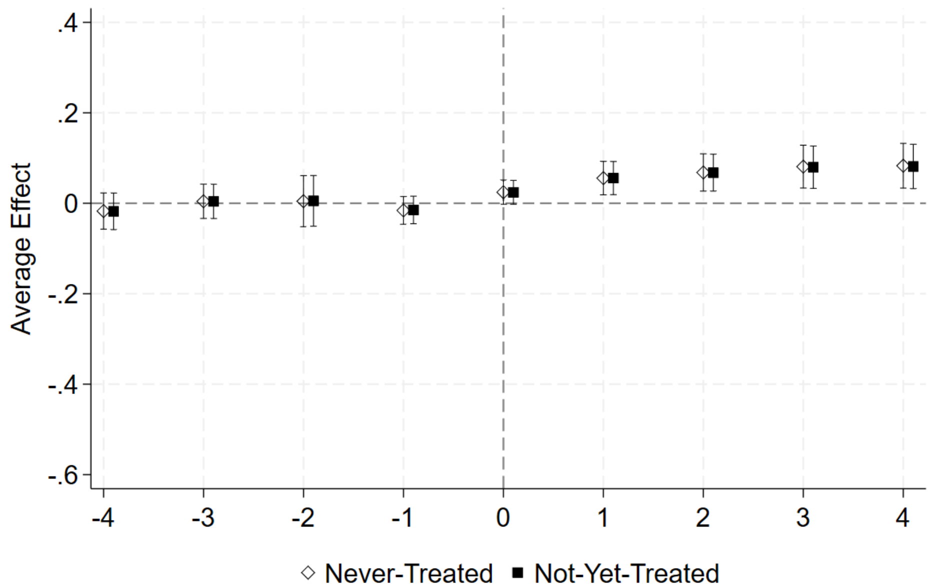
Notes: This figure illustrates the effect of LMOP participation with 95% confidence intervals (vertical lines) on the probability of LFGE project development using different measurements of LMOP participation between 2001 and 2021. The horizontal axis represents the relative year of LMOP participation. The 'LMOP-Operator' indicates that the LMOP participant is determined based on its operator's participation decision. The control group is made up of never-treated landfills In addition to landfill and year fixed effects, landfill operation status and age, county GDP, unemployment rate, population, temperature, precipitation, Republican representatives ratio in states, Republican governor, and electricity and natural gas prices in states are controlled for. The mean values of the probability of LFGE project development in the LMOP-Owner and LMOP-Operator control groups are 13.9% and 13.4%, respectively. The numbers of observations are 35,359 and 35,514 for LMOP-Owner and LMOP-Operator samples, respectively.

Figure A.9: The effects of LMOP on the probability of LFGE project development using different measurements of LFGE project.



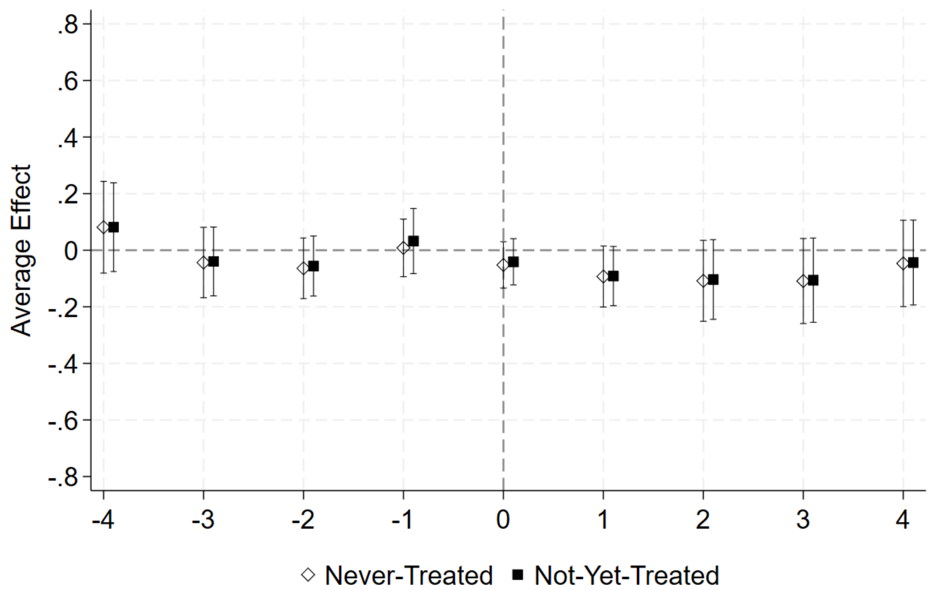
Notes: This figure describes the effect of LMOP participation with 95% confidence intervals (vertical lines) on the probability of LFGE project development using different measurements of LFGE projects between 2001 and 2021. The horizontal axis represents the relative year of LMOP participation. An LFGE project is recorded as operated if the number of any LFGE project operation days is at least 1 (x), 183 (squares), and 365 (diamonds) days in a given year, for 1-day, 183-day, and 365-day rules, respectively. The control group is made up of never-treated landfills In addition to landfill and year fixed effects, landfill operation status and age, county GDP, unemployment rate, population, temperature, precipitation, Republican representatives ratio in states, Republican governor, and electricity and natural gas prices in states are controlled for. The mean values of the probability of LFGE project development in the 1, 183, and 365 days control group are 14.4%, 13.9%, and 13.4%, respectively. The numbers of observations are 35,359.

Figure A.10: Effects of LMOP on the probability of LFGE project development with not-yet-treated control group.



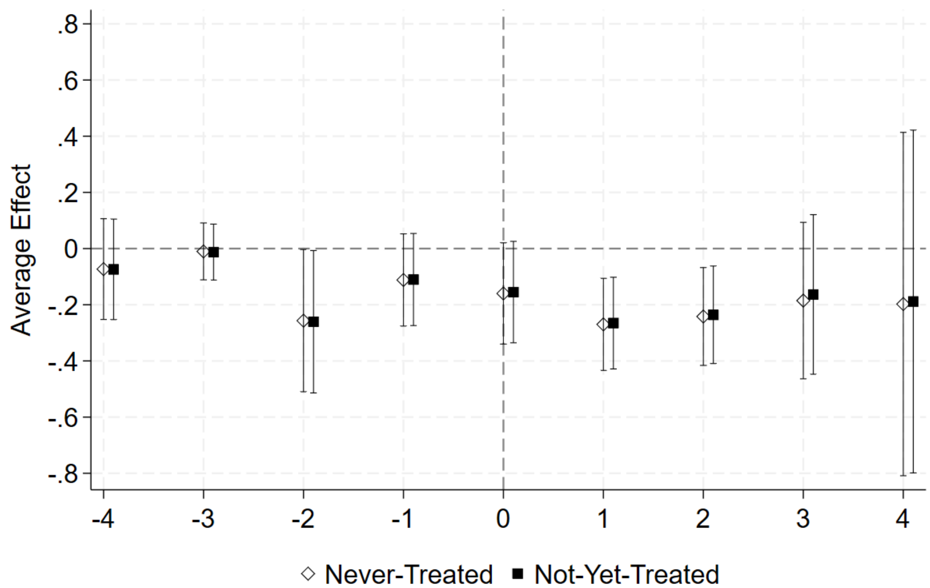
Notes: This figure illustrates the effects of LMOP participation with 95% confidence intervals (vertical lines) on the probability of LFGE project development, with never-treated (squares) and not-yet treated (diamonds) landfills as control groups between 2001 and 2021. The horizontal axis represents the relative year of LMOP participation. In addition to landfill and year fixed effects, landfill operation status and age, county GDP, unemployment rate, population, temperature, precipitation, Republican representatives ratio in states, Republican governor, and electricity and natural gas prices in states are controlled for. The number of observations for never-treated and not-yet-treated groups are 35,359 and 35,387, respectively.

Figure A.11: Effects of LFGE project development on log methane emissions with not-yet-treated control group.



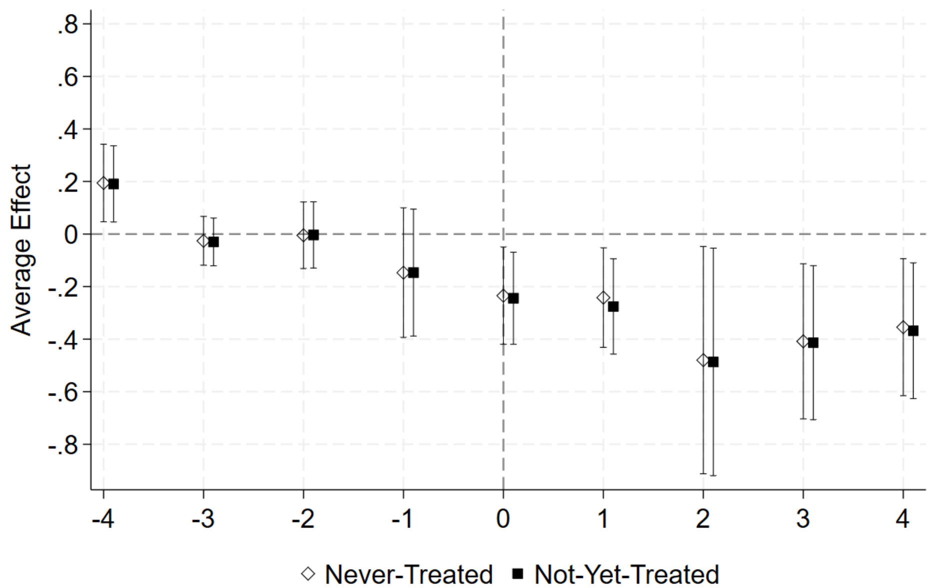
Notes: This figure illustrates the effects of LFGE project development with 95% confidence intervals (vertical lines) on log methane emissions, with never-treated (squares) and not-yet treated (diamonds) landfills as control groups between 2010 and 2021. The horizontal axis represents the relative year of LFGE project development. In addition to landfill and year fixed effects, landfill operation status and age, county GDP, unemployment rate, population, temperature, precipitation, Republican representatives ratio in states, Republican governor, and electricity and natural gas prices in states are controlled for. The number of observations for never-treated and not-yet-treated groups are 7,942 and 7,944, respectively.

Figure A.12: Effects of GCCS development on log methane emissions with not-yet-treated control group.



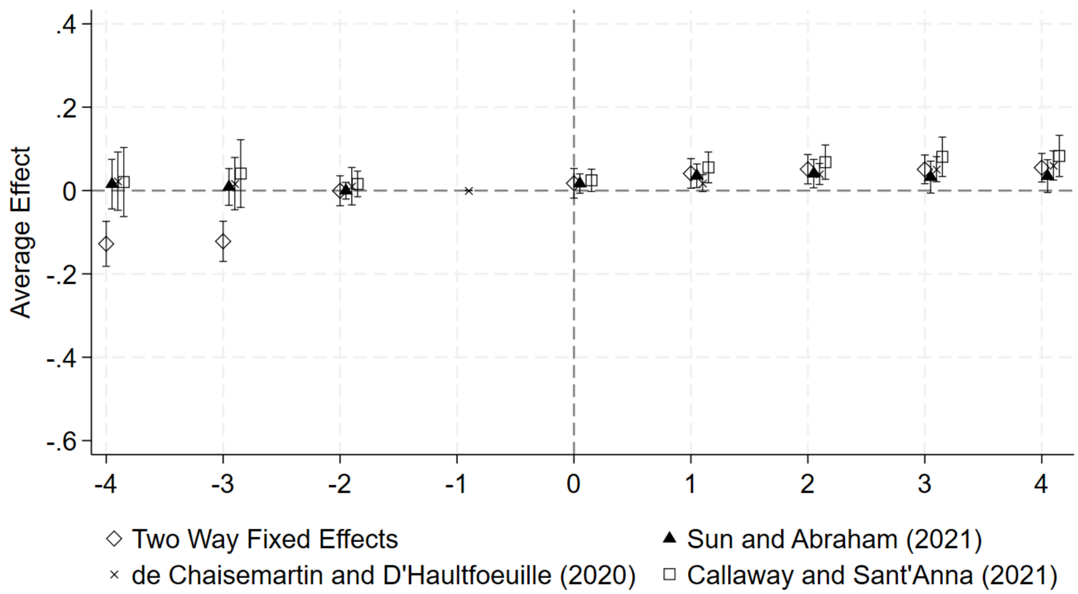
Notes: This figure illustrates the effects of GCCS development with 95% confidence intervals (vertical lines) on log methane emissions, with never-treated (squares) and not-yet treated (diamonds) landfills as control groups between 2013 and 2021. The horizontal axis represents the relative year of GCCS development. In addition to landfill and year fixed effects, landfill operation status and age, county GDP, unemployment rate, population, temperature, precipitation, Republican representatives ratio in states, Republican governor, and electricity and natural gas prices in states are controlled for. The number of observations is 8,041.

Figure A.13: Effects of LFGE development on log of net greenhouse gas emissions with not-yet-treated control group.



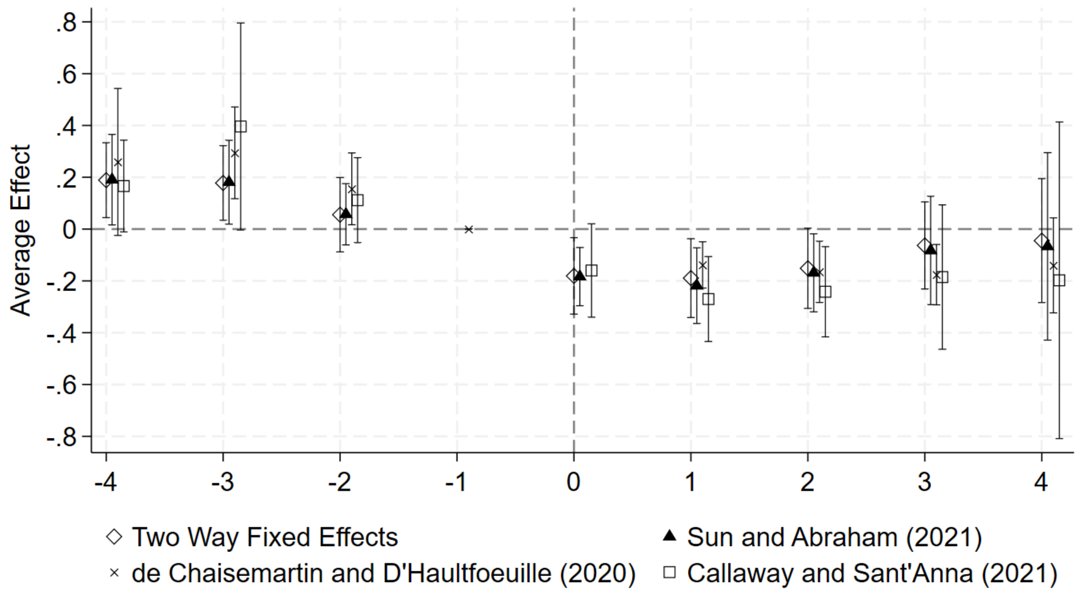
Notes: This figure illustrates the effects of LFGE project development with 95% confidence intervals (vertical lines) on log net greenhouse gas emissions, with never-treated (squares) and not-yet treated (diamonds) landfills as control groups between 2013 and 2021. The horizontal axis represents the relative year of GCCS development. In addition to landfill and year fixed effects, landfill operation status and age, county GDP, unemployment rate, population, temperature, precipitation, Republican representatives ratio in states, Republican governor, and electricity and natural gas prices in states are controlled for. The number of observations for never-treated and not-yet-treated groups are 5,238 and 5,267, respectively.

Figure A.14: Effects of LMOP on the probability of LFGE project development with alternative estimators.



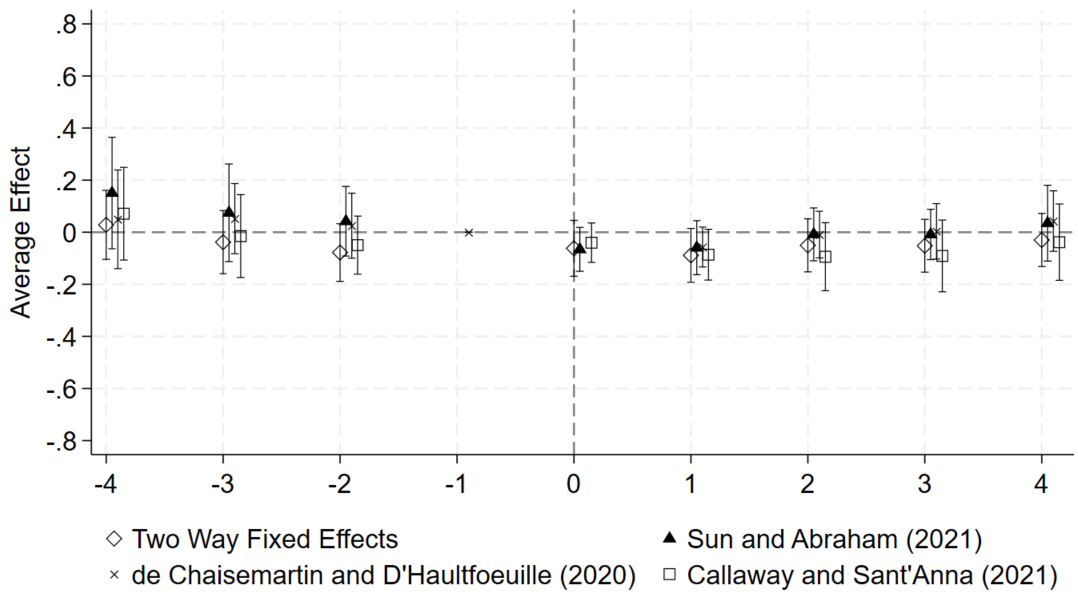
Notes: This figure illustrates the effects of LMOP participation with 95% confidence intervals (vertical lines) on the probability of LFGE project development using alternative estimators, including two-way fixed effects, Sun and Abraham (2021) and de Chaisemartin and D'Haultfœuille (2020), between 2001 and 2021. The horizontal axis represents the relative year of LMOP participation. The universal base period is employed. In addition to landfill and year fixed effects, landfill operation status and age, county GDP, unemployment rate, population, temperature, precipitation, Republican representatives ratio in states, Republican governor, and electricity and natural gas prices in states are controlled for. 35,347

Figure A.15: Effects of GCCS development on log of methane emissions with alternative estimators.



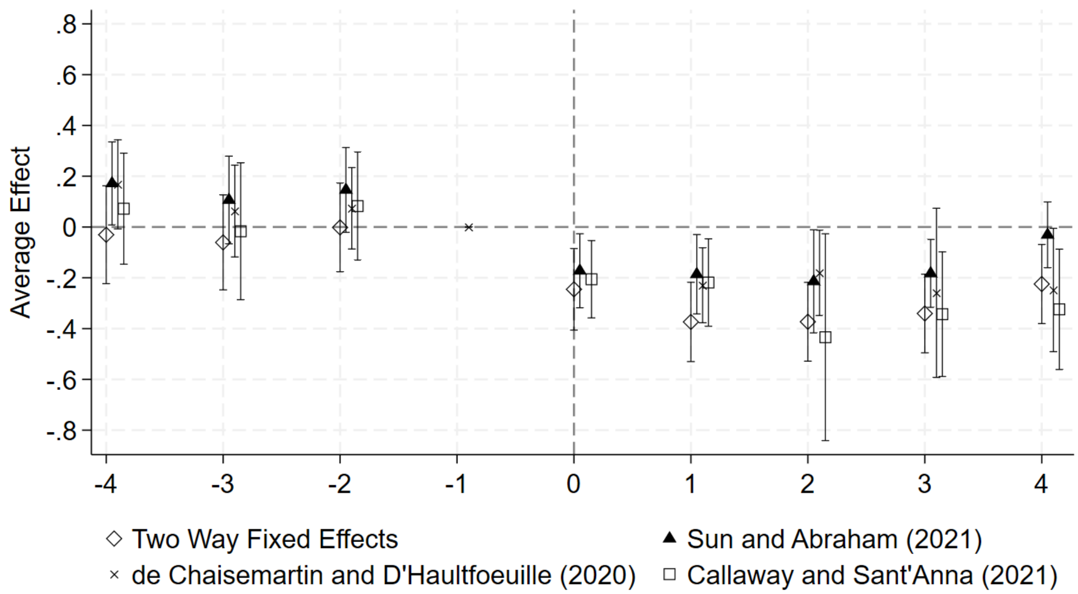
Notes: This figure illustrates the effects of GCCS development with 95% confidence intervals (vertical lines) on log methane emissions using alternative estimators, including two-way fixed effects, Sun and Abraham (2021) and de Chaisemartin and D'Haultfœuille (2020), between 2013 and 2021. The horizontal axis represents the relative year of GCCS development. The Universal base period is employed. In addition to landfill and year fixed effects, landfill operation status and age, county GDP, unemployment rate, population, temperature, precipitation, Republican representatives ratio in states, Republican governor, and electricity and natural gas prices in states are controlled for.

Figure A.16: Effects of LFGE project development on log of methane emissions with alternative estimators.



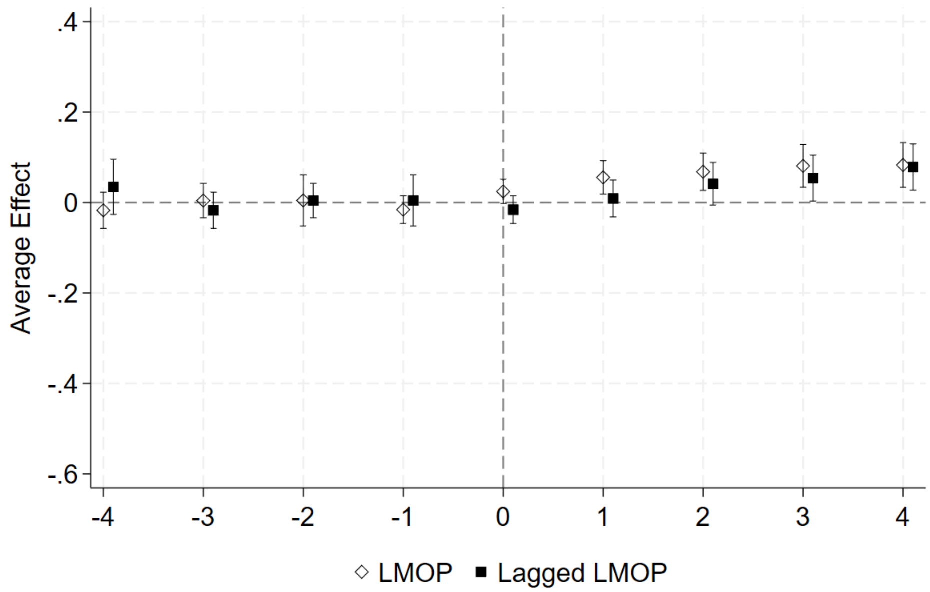
Notes: This figure illustrates the effects of LFGE project development with 95% confidence intervals (vertical lines) on log methane emissions using alternative estimators, including two-way fixed effects, Sun and Abraham (2021) and de Chaisemartin and D'Haultfœuille (2020), between 2010 and 2021. The horizontal axis represents the relative year of LFGE project development. The Universal base period is employed. In addition to landfill and year fixed effects, landfill operation status and age, county GDP, unemployment rate, population, temperature, precipitation, Republican representatives ratio in states, Republican governor, and electricity and natural gas prices in states are controlled for.

Figure A.17: Effects of LFGE project development on log of net greenhouse gas emissions with alternative estimators.



Notes: This figure illustrates the effects of LFGE project development with 95% confidence intervals (vertical lines) on log net greenhouse gas emissions using alternative estimators, including two-way fixed effects, Sun and Abraham (2021) and de Chaisemartin and D'Haultfœuille (2020), between 2013 and 2021. The horizontal axis represents the relative year of LFGE project development. The Universal base period is employed. In addition to landfill and year fixed effects, landfill operation status and age, county GDP, unemployment rate, population, temperature, precipitation, Republican representatives ratio in states, Republican governor, and electricity and natural gas prices in states are controlled for.

Figure A.18: Effects of lagged LMOP participation on the probability of LFGE project development.



Notes: This figure illustrates the effects of LMOP participation with 95% confidence intervals (vertical lines) on the probability of LFGE project development with 1-year-lagged LMOP participation between 2001 and 2021. The horizontal axis represents the relative year of LMOP participation. The control group is made up of never-treated landfills. In addition to landfill and year fixed effects, landfill operation status and age, county GDP, unemployment rate, population, temperature, precipitation, Republican representatives ratio in states, Republican governor, and electricity and natural gas prices in states are controlled for. The mean value of the probability of LFGE project development in the control group is 13.9%. The numbers of observations are 35,359 and 35,337 for LMOP and lagged LMOP landfills, respectively.