

AVOIDING, DETECTING AND CAPTURING METHANE EMISSIONS FROM LANDFILLS

HEARING BEFORE THE COMMITTEE ON ENVIRONMENT AND PUBLIC WORKS UNITED STATES SENATE

ONE HUNDRED EIGHTEENTH CONGRESS

SECOND SESSION

JANUARY 31, 2024

Printed for the use of the Committee on Environment and Public Works



Available via the World Wide Web: <http://www.govinfo.gov>

U.S. GOVERNMENT PUBLISHING OFFICE

COMMITTEE ON ENVIRONMENT AND PUBLIC WORKS

ONE HUNDRED EIGHTEENTH CONGRESS
SECOND SESSION

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WEDNESDAY, JANUARY 31, 2024

U.S. SENATE,
COMMITTEE ON ENVIRONMENT AND PUBLIC WORKS,
Washington, DC.

The committee met, pursuant to notice, at 10:03 a.m. in room 406, Dirksen Senate Office Building, Hon. Thomas R. Carper (chairman of the committee) presiding.

Present: Senators Carper, Capito, Cardin, Whitehouse, Merkley, Markey, Kelly, Padilla, Ricketts, Sullivan.

OPENING STATEMENT OF HON. THOMAS R. CARPER, U.S. SENATOR FROM THE STATE OF DELAWARE

Senator CARPER. Good morning, everyone. We are pleased to call this hearing to order.

Today, as you know, we are going to be discussing a topic that is a priority for many of us on the Environment and Public Works Committee, and that is reducing methane emissions from landfills and how we can do that through deploying new and innovative technologies while improving waste management and increasing the use of existing solutions, like composting. We will also explore how addressing methane emissions can create new jobs, a lot of them, and provide new revenue streams for landfill operators.

Over the past couple of centuries, methane concentrations in the atmosphere have more than doubled. Methane, as many of you know, is roughly 80 times more potent as a greenhouse gas than carbon dioxide. As a result, this super-pollutant is responsible for roughly a third of the global warming our planet is currently experiencing. I am going to say that again: this super-pollutant is responsible for roughly a third of the global warming that our planet is currently experiencing, a third.

This makes cleaning up methane emissions one of the fastest ways to mitigate global warming. In fact, according to the Intergovernmental Panel on Climate Change, strong, rapid, and sustained methane reductions are critical to limiting near-term warming.

Two years ago, I traveled with some of our colleagues to Scotland for the United Nations (UN) Climate Change Conference (COP26), and also with members of our staff. That is when the United States and the European Union launched the Global Methane Pledge. This agreement represents a collective effort to reduce global methane emissions by at least 30 percent over the next 10 years.

Today, more than 150 countries have signed onto that pledge. One hundred fifty countries have signed onto that pledge. More re-

cently, I attended COP28 in Dubai with a bipartisan delegation of our colleagues led by Senator Cardin. There, governments and private industries renewed their commitments to reduce methane emissions.

As an original signatory of the Global Methane Pledge and significant contributor to global methane emissions, the United States must continue to do its part, our part, to drive domestic methane reductions. In short, we need to provide what I call, and what you probably call, leadership by example.

So, why should we focus on reducing methane emissions? To answer that question, let me begin by sharing the age-old story of Willie Sutton, whom as many of you will recall and members of our committee have heard me say more than they want to remember, I suspect, but he was a notorious bank robber during the Great Depressions. In fact, he robbed a lot of banks.

Finally, he was caught and taken to trial. They stood before the judge, and the judge famously asked him, "Mr. Sutton, why do you rob banks?" He replied, famously, "Because, Your Honor, that is where the money is." We can apply the same logic to today's hearing. We have to go where the emissions are and then find ways to reduce them.

The good news is that we are well on our way to doing just that. Thanks to the Methane Emissions Reductions Program in the Inflation Reduction Act, the United States is advancing technologies to detect and capture methane emissions from the oil and gas sector, as well.

Not only will these investments help us reduce emissions, but they will also help us create jobs while recovering wasted energy, enough to power nearly seven million homes every year. Let me say that again: that is enough to power seven million homes every year. That is a win-win for our communities, and it is a win-win for our planet.

For this hearing, though, we are going to focus on the next frontier of mitigating methane emissions, and that is landfills. In other words, we are going to, my staff wrote this out for me, they like this, we are going to talk trash. That is pretty good, isn't it?

[Laughter.]

Senator CARPER. You may ask yourself, why are we concerned about methane emissions from landfills? Landfills and their emissions are largely out of sight and largely out of mind for most people. However, landfill methane emissions are the third, that is right, the third largest source of methane emissions in the United States and globally.

So, where is the methane coming from? In the United States, we send more food waste to landfills than any other materials. When organic material, like food, breaks down in landfills, as you know, it creates methane. If a landfill is not equipped to capture that methane, it simply escapes into our atmosphere.

As many of our colleagues know, I care deeply about finding meaningful ways to reduce our waste while promoting sustainability. To that end, I am working alongside Senator Boozman and Senator Capito to pass legislation that would strengthen our Nation's recycling and composting systems.

While composting and waste diversion are important tools to reduce methane emissions from landfills, it is also important that our landfills are equipped with technology that is necessary to mitigate emissions for years to come.

For example, in my home State of Delaware, where one of our witnesses has spent a little bit of time, a lot of time, actually, the Delaware Solid Waste Authority mitigates methane emissions from their landfills with collection systems. Local businesses then use the gas that is collected to power their operations. Many landfills across the Country use similar systems to capture what would otherwise be wasted energy.

As members of our committee have oftentimes heard me say, we need to find out what works and do more of that. In this case, we also need to find ways to improve upon what is already working. Deploying innovative methods and technologies to limit methane leakage will go a long way toward reducing landfill emissions across the United States.

Last, in order to fully address this problem, we must be able to identify where the largest releases of methane from landfills are occurring. In fact, over the last couple of years, new studies have begun to reveal the scale of that problem.

Satellite monitoring, flyovers, and other enhanced emissions monitoring technologies are playing a growing role in identifying methane emissions from landfills. These newer detection technologies can help landfill operators quickly respond to large emission events. We will need diverse strategies to detect landfill emissions going forward, because traditional methods have been unable to produce accurate emissions data for landfills.

Let me close by reminding everybody that if we take action to reduce landfill emissions, it would have an immediate positive impact on climate, on air quality, and on public health while also creating economic opportunity across our Country, especially in our rural areas.

My hope is that today's hearing will help us further our committee's understanding of how we can better detect and capture methane emissions from landfills and what strategies can keep methane-generating organic waste out of landfills in the first place.

Before we do that, I want to recognize our Ranking Member, Senator Capito, for her opening statement. Senator Capito, good morning.

**OPENING STATEMENT OF HON. SHELLEY MOORE CAPITO,
U.S. SENATOR FROM THE STATE OF WEST VIRGINIA**

Senator CAPITO. Good morning, and thank you, Mr. Chairman, and thanks for holding the hearing. Welcome to our panel of witnesses, and thanks for your willingness to testify.

As organic materials decompose in landfills, they produce landfill gas containing methane, as the Chairman talked about, the main compound found in natural gas. Due to the natural generation of methane in landfill gas, landfills are now the third largest source, I believe you said that, of methane emissions in the U.S. This may be an environmental problem, but it is also an economic one, as methane lost to the atmosphere could be used for energy or manufacturing.

While there is more work to be done, and improvements can be made, I want to acknowledge that the U.S. has made a lot of progress in reducing emissions from landfills. Through innovation thanks to the realization of its monetary value, the landfill sector has significantly improved its capacity to collect and manage landfill gas.

Since 1990, U.S. landfills have reduced their greenhouse gas emissions by 38 percent. Recycling rates are increasing, and composting programs are taking off nationwide, meaning less methane-producing materials are ending up in the landfills. Also, the number of landfills are decreasing due to increases in operational efficiencies and improved land use.

In considering solutions to address landfill methane that benefit the environment and economic development, it is essential that any regulations are achievable and that incentives are targeted. This is not what we have seen in the approach of this Administration, particularly from the Air Office at the Environmental Protection Agency (EPA), which has pursued punitive regulations that are impossible to achieve, such as Clean Power Plan 2.0 and the misnamed Good Neighbor regulations.

The Administration has also ladled our billions of funding for favored industries and causes which has been mired in red tape and have not delivered the promised results. We do not want to repeat those mistakes here, and it is important that Congress scrutinize proposed regulations coming out of the Air Office that deal with landfill methane.

Natural gas derived from landfill methane can be used to generate reliable electricity or be used as transportation of industrial fuels, all of which promotes energy independence while reducing emissions. I am concerned that the landfill sector is facing the same approach that the Biden and the Obama administrations have taken with regard to fossil fuels, where the goal is to make them uneconomic, and then the EPA then works backward to achieve that with crushing regulations.

For example, proposed changes to the Clean Air Act's New Source Review Program would create a burdensome regulatory landscape for landfills seeking to implement technology innovations to address fugitive methane emissions. Despite receiving increased enforcement scrutiny for methane emissions, landfills have not been able to access the emissions reductions tax credits by the so-called Inflation Reduction Act, and have been shut out from the EPA's implementation of the Renewable Fuel Standard.

Did I say the Renewable Fuel Standard? This is an ongoing joke with Mr. Nebraska over here.

[Laughter.]

Senator CAPITO. I am concerned this is the beginning and not the end of political targeting of an industry that is necessary for our economy, public health, and environmental risk management. Indeed, the EPA will be considering several burdensome rulemakings on landfills this year. The agency is currently evaluating multiple rules related to New Source Review to penalize fugitive emissions and require project emissions accounting in major permitting decisions.

The waste sector already experiences needless permitting delays for deploying renewable energy projects that the Administration supports. These rulemakings will only exacerbate the sector's frequent permitting obstacles, we see this across industries, and aggravate the Biden Administration's stated goal of reducing methane emissions.

The Administration will also need to review its New Source Performance Standards (NSPS) and Emission Guidelines for Municipal Solid Waste landfills under Section 111 of the Clean Air Act this year. Environmental groups are already petitioning the EPA to set more stringent air emissions standards on smaller municipal landfills.

There are bipartisan solutions in front of us today. There is broad bipartisan agreement about the difficulties of monitoring and measuring methane emissions from landfills. Development of new technologies is underway and is essential to better detect and quantify emissions.

Municipal landfills and local communities could benefit from additional support from the EPA to research and evaluate cutting edge technologies, but none of this will work if outdated regulations like New Source Review stymie those upgrades at existing facilities to recover methane and get it to the market.

I urge my colleagues to continue to work with me on permitting reform and updating out-of-date environmental regulations, areas within this committee's jurisdiction, so we can ensure that emissions-reducing technologies can actually get out to the market and make a difference.

Thank you again to the three witnesses here today. I look forward to our discussion.

Senator CARPER. Senator Capito, thanks for your statement.

I want to thank both minority and majority staff for your work in putting this hearing together. It does not just happen by magic. This is going to be, I think, an especially valuable hearing, a timely hearing, and we are grateful for our witnesses, but also for our staff in helping to make it happen.

Now, we are going to turn to our three witnesses. I am going to take a moment just to briefly introduce you. We are grateful, again, to all of you for helping us better understand and deal with what is an important challenge, but really a great opportunity as well.

We are going to be hearing, in this order, from these three witnesses, leading off with Mr. Tom Frankiewicz. Tom is a Subject Matter Expert, I understand, on waste sector methane at the Rocky Mountain Institute, a research organization known as RMI. In this role, Tom leads RMI's work on methane emissions mitigation and waste management and coordinates the organization's work with the global methane hub.

Before joining RMI, Mr. Frankiewicz worked in the Climate Change Division in the U.S. Environmental Protection Agency for over 16 years. He earned his M.B.A. from George Washington University School of Business, with a concentration in environmental and strategic management. Welcome.

Our second witness is Tia Scarpelli, a Research Scientist and the Waste Sector Lead for Carbon Mapper, a nonprofit organization that uses remote sensing to detect and quantify methane emissions

data. Dr. Scarpelli's research interests include investigating the characteristics of methane emissions at global landfills and dump sites and the role that satellite observation can play in informing the mitigation of waste sector emissions. She earned her Ph.D. in atmospheric chemistry at Harvard University, and she brings a wealth of knowledge of satellite observation and atmospheric modeling.

Third, last but not least, we have Anne Germain, Chief Operating Officer and Senior Vice President of Regulatory Affairs for the National Waste and Recycling Association. She has worked in the field of resource conservation and materials management for more than 30 years and has been with the National Waste and Recycling Association since 2013. Prior to joining the National Waste and Recycling Association, Ms. Germain worked for the Delaware Solid Waste Authority for 19 years, where she served as chief engineer.

Where did you live, did you live in Delaware?

Ms. GERMAIN. I actually lived in Caroline County, Maryland while I was there.

Senator CARPER. Okay. She is a board-certified environmental engineer with a master's in civil engineering from the University of Delaware.

I would just say to my colleagues, about a week ago, I happened to be visiting one of the Delaware solid waste facilities for environmental educational training for students. It is in Dover, and we have thousands of students that come every year. They learn about recycling, and actually, they learn about what we are talking about here today. It was just pure joy to be there. If your old colleagues had known that we were going to be with you today, I am sure they would all send their best.

We thank you all again for appearing before our committee today. We will now begin with our witnesses' testimony. Mr. Frankiewicz, you are our lead-off hitter. Please proceed with your statement when you are ready. Thank you, and again, welcome to everybody.

Welcome, especially, to Senator Markey. Please, go ahead.

**STATEMENT OF TOM FRANKIEWICZ, SUBJECT MATTER
EXPERT, WASTE METHANE, ROCKY MOUNTAIN INSTITUTE**

Mr. FRANKIEWICZ. Thank you, Chairman Carper, Ranking Member Capito, members of the committee, thank you for the opportunity to appear before you today.

Senator CARPER. Can you hold for just a second? We all serve on different committees. One of my committees, the Homeland Security Committee, is meeting right now. They are voting. They need me to come and join them, so I leave you all in good hands, right here. Thanks.

Senator CAPITO.

[Presiding.] I got it.

Senator CARPER. I will be back.

Mr. FRANKIEWICZ. Thank you. I have three key messages for you today: one, landfill methane pollution is a major threat to our climate and communities; we have viable solutions to cut emissions

today; and three, implementing these solutions will bring local benefits.

Landfills are a major source of methane. Methane has about 80 times the planet heating power of carbon dioxide over a 20 year time period. Thanks to its relatively short atmospheric life, cutting methane today offers an immediate opportunity to slow global warming and is essential to void the worst effects of climate change.

Each year, we send over 140 million tons of municipal solid waste to roughly 1,200 open landfills across the Country. The majority of the waste is organic, think banana peels and yard clippings, generating methane as it decomposes in the landfills. Some landfills capture their gas, but lots of methane still escapes into the atmosphere.

In 2021, the methane released from U.S. landfills had the same near-term warming impacts as driving 66 million cars for a year. The true total is likely higher, as recent aerial surveys suggest. We have viable solutions to address landfill methane: strengthen landfill emission controls and reduce organic waste disposal. It is time we modernized air emissions regulations for landfills, expanding gas collection, more comprehensive monitoring, and other common sense improvements can limit the release of methane to the atmosphere and protect communities from other harmful co-pollutants.

At the same time, we must invest in infrastructure to keep organics out of landfills. Waste prevention programs, food rescue, and composting all help to avoid future landfill methane generation and bring other local benefits.

On both fronts, we have seen State and local leadership. Strong landfill emissions standards in three States, organic recycling policies in nine, and curbside composting in hundreds of communities across the Country, and new commitments from the private sector, as well. Federal action is needed to ensure that methane reductions are achieved at scale. The EPA is statutorily required to revisit its Clean Air Act regulations for landfills this year. The agency should meet the challenge with Section 111 standards that reflect the latest best practices in methane monitoring and control while encouraging organics diversion.

Congress can also provide funds to catalyze landfill methane reductions. Building on the success of the Bipartisan Infrastructure Law and the Inflation Reduction Act, additional grant programs could prioritize local waste prevention programs, organic recycling infrastructure, and landfill methane capture. The methane abatement potential here is significant.

New EPA landfill standards can reduce emissions by amount one million metric tons of methane per year, or 80 million metric tons carbon dioxide equivalent. This is based on a preliminary analysis by the Environmental Integrity Project using EPA data. These efforts will help the U.S. meet its domestic climate goals while demonstrating global leadership.

A more sustainable waste management system would bring local benefits. Landfills release toxic, smog-forming gases and odors that harm the health and well-being of nearby communities. More effective landfill methane controls would also address these co-pollutants, improving local air quality and life. Keeping organic waste

out of landfills can bring further benefits, addressing food and security, creating job opportunities, and producing compost to improve soil health. For both stronger landfill emission controls and organics diversion programs, the cumulative benefits exceed the implementation costs.

In closing, I would like to leave you these three points: landfills are a major source of methane pollution, but we have solutions to reduce these emissions today. By acting now, through stronger standards, we can limit near-term warming and bring real benefits to communities.

Thank you, and I look forward to your questions.

[The prepared statement of Mr. Frankiewicz follows:]



Statement before the U.S. Senate Committee on Environment & Public Works
Avoiding, Detecting, and Capturing Methane Emissions from Landfills

Testimony of:
 Tom Frankiewicz
 Principal, Subject Matter Expert, Waste Methane
 RMI (Rocky Mountain Institute)

January 31, 2024

INTRODUCTION

Chairman Carper, Ranking Member Capito, and Members of the Committee: thank you for the opportunity to appear before you today.

My name is Tom Frankiewicz, and I lead Waste Sector Methane mitigation at RMI, an independent, non-partisan, nonprofit organization working to accelerate the clean energy transition and improve lives. Before joining RMI, I worked for more than sixteen years at the United States Environmental Protection Agency.

I am excited to speak with you today about the readily available, low-cost strategies to prevent and reduce landfill methane emissions. Fast action to curb landfill methane emissions will help to limit near-term warming, advance U.S. climate commitments, and deliver substantial benefits to local communities.

THE PROBLEM

Accelerated methane abatement is crucial to limit temperature rise over the near term and avoid the worst impacts of climate change. Methane is the second most abundant greenhouse gas after carbon dioxide, and the concentration of methane in the atmosphere has more than doubled over the past 200 years.¹ Scientists estimate that methane is responsible for about 30 percent of global warming since pre-industrial times.²

Methane has outsized impacts on near-term temperature rise. In the first twenty years after its release, methane has more than 80 times the heat-trapping power of carbon dioxide. But since methane only lingers in the atmosphere for about a decade, compared to centuries for CO₂, reducing methane emissions today provides an immediate opportunity to slow global warming and

¹ "Methane," NASA Global Climate Change, 2024, <https://climate.nasa.gov/vital-signs/methane/>.

² "Methane emissions are driving climate change. Here's how to reduce them.," United Nations Environment Programme (UNEP), August 2021, <https://www.unep.org/news-and-stories/story/methane-emissions-are-driving-climate-change-heres-how-reduce-them>.

limit the risk of dangerous climate tipping points.³ Pairing decarbonization with mitigation measures targeting short-lived climate pollutants like methane can slow the rate of warming a decade or two earlier than decarbonization alone.⁴

Our methane strategy must target the waste sector, a major source of heat-trapping emissions. Globally, the waste sector is responsible for about 20 percent of anthropogenic methane emissions.⁵ In the United States, municipal solid waste (MSW) landfills are the third-largest source of human-related methane emissions, accounting for 14 percent of the total.⁶ In 2021, U.S. MSW landfills emitted an estimated 3.7 million metric tons of methane according to the U.S. Environmental Protection Agency (EPA)'s inventories, or about 295 million metric tons of carbon dioxide equivalent (MMT CO₂e) on a 20-year time horizon. That's equivalent to the annual greenhouse gas pollution from 66 million gas-powered passenger vehicles or 79 coal-fired power plants.⁷ In 37 states, a landfill was the single largest industrial methane emitter reported to EPA's Greenhouse Gas Reporting Program (GHGRP) in 2021.⁸

Each year, more than 145 million tons of municipal solid waste (MSW) are sent to the roughly 1,200 open landfills across the United States for disposal.⁹ As the organic fraction of this waste – which includes food waste, yard waste, and paper – decomposes without oxygen in the landfill, it generates methane. Food waste is the largest MSW component landfilled, responsible for an estimated 58% of fugitive methane emissions from U.S. MSW landfills.¹⁰ Data reported voluntarily to EPA's Landfill Methane Outreach Program (LMOP) shows that 47% of reporting landfills (1,229 of 2,636) have a gas collection system in place to capture a portion of their methane emissions. Per LMOP, 487 landfills had energy projects as of July 2023, utilizing captured methane to generate electricity or upgrading it to renewable natural gas (RNG) for pipeline injection or transportation fuel.¹¹ Otherwise, collected methane is typically routed to a flare for destruction. Importantly, collection and control systems cannot capture all generated methane, as they are not installed in all areas of the landfill, experience downtime, and can malfunction. Large amounts of methane escape from landfills into the atmosphere, diffusely through the landfill surface and in more

³ "Control methane to slow global warming — fast," *Nature*, August 2021, <https://www.nature.com/articles/d41586-021-02287-y>.

⁴ Gabrielle B. Dreyfus et al., "Mitigating climate disruption in time: A self-consistent approach for avoiding both near-term and long-term global warming," *Proceedings of the National Academy of Sciences* 119, 22 (May 2022), <https://www.pnas.org/doi/full/10.1073/pnas.2123536119>.

⁵ *Global Methane Assessment: Benefits and Costs of Mitigating Methane Emissions*, United Nations Environment Programme and Climate and Clean Air Coalition, 2021, <https://www.ccacoalition.org/resources/global-methane-assessment-full-report>.

⁶ "Basic Information about Landfill Gas," U.S. Environmental Protection Agency, August 2023, <https://www.epa.gov/lmop/basic-information-about-landfill-gas>.

⁷ Preet Bains et al., *Trashing the Climate: Methane from Municipal Landfills*, Environmental Integrity Project, May 2023, <https://environmentalintegrity.org/reports/trashing-the-climate/>.

⁸ "Don't Waste Our Future," Industrious Labs, 2024, <https://dontwasteourfuture.org/>.

⁹ "National Overview: Facts and Figures on Materials, Wastes and Recycling," U.S. Environmental Protection Agency, November 2023, <https://www.epa.gov/facts-and-figures-about-materials-waste-and-recycling/national-overview-facts-and-figures-materials-landfilling>; "LMOP Landfill and Project Database," U.S. Environmental Protection Agency, August 2023, <https://www.epa.gov/lmop/lmop-landfill-and-project-database>.

¹⁰ Max Krause et al., *Quantifying Methane Emissions from Landfilled Food Waste*, U.S. Environmental Protection Agency Office of Research and Development, October 2023, https://www.epa.gov/system/files/documents/2023-10/food-waste-landfill-methane-10-8-23-final_508-compliant.pdf.

¹¹ "LMOP Landfill and Project Database," U.S. Environmental Protection Agency, August 2023, <https://www.epa.gov/lmop/lmop-landfill-and-project-database>.

concentrated hot spots, often due to cracks or gaps in the landfill cover, leaking gas wells, or the exposed working face. Landfill gas collection efficiency can vary widely by site, due in part to design and operational factors. While landfill emissions models often assume a default collection efficiency of 75%, studies show instances where collection efficiency can be much lower.¹²

Furthermore, recent airborne methane surveys suggest that landfill emissions may be higher and more persistent than previously expected.¹³ Since 2016, airborne surveys conducted by Carbon Mapper and partners have detected high-emitting methane plumes at more than 200 U.S. landfills across 29 states.¹⁴ In California, Carbon Mapper's flyovers found that a subset of landfills were the state's largest methane emitters (41 percent), with higher observed emission rates than the oil & gas or agriculture sectors.¹⁵ Detectable methane plumes at California landfills often reached 1,000 kg/hr, ten times what EPA considers to be a super-emitter in the oil & gas sector.¹⁶

A recent study under review in *Atmospheric Chemistry and Physics* uses observations from the TROPOMI satellite instrument to quantify methane emissions from 70 landfills reporting to EPA's GHGRP across the contiguous United States. The authors find a median 77% increase in observed emissions (13 Gg/a), compared to reported emissions (7.2 Gg/a). At the 38 facilities that recover gas, the authors find a mean recovery efficiency of 0.50 (0.33 – 0.54) that is much smaller than the GHGRP mean of 0.61 and the default assumption of 0.75.¹⁷ The authors attribute the discrepancy to two main factors: 1) over-estimated recovery efficiencies at facilities with gas collection systems and 2) under-accounting of site-specific operational changes across facilities.¹⁸

Landfill emissions also threaten nearby communities. Beyond the planet-heating methane, landfills release harmful co-pollutants that adversely impact the health and well-being of nearby communities. Landfill gas contains hazardous air pollutants (e.g., vinyl chloride, 1,1,1-trichloroethane, 2-butanone, organic mercury compounds), precursors to ozone and particulate matter (PM) (e.g., VOCs), and odor nuisance compounds (e.g., H₂S). These compounds have been

¹² James Hanson and Nazil Yesiliter, *Estimation and Comparison of Methane, Nitrous Oxide, and Trace Volatile Organic Compound Emissions and Gas Collection System Efficiencies in California Landfills Final Report*, Prepared for: The California Air Resources Board and The California Department of Resources Recycling and Recovery, March 25, 2020, <https://ww2.arb.ca.gov/resources/documents/landfill-gas-research>.

Nickolas J. Themelis and A.C. (Thanos) Bourtsalas, "Methane Generation and Capture of U.S. Landfills," *Journal of Environmental Science and Engineering A* 10 (2021): 199-206. <https://www.davipublisher.com/Public/uploads/Contribute/61ad830cee8a6.pdf>.

¹³ *National Strategy to Advance an Integrated U.S. Greenhouse Gas Measurement, Monitoring, and Information System*, The Greenhouse Gas Monitoring and Measurement Working Group & The White House, November 2023, <https://www.whitehouse.gov/wp-content/uploads/2023/11/NationalGHGMISStrategy-2023.pdf>.

¹⁴ "Carbon Mapper Data Portal," Carbon Mapper, January 2024, <https://carbonmapper.org/data/>.

¹⁵ Riley Duren et al., "California's methane super-emitters," *Nature* 575 (2019): 180-184, <https://pubmed.ncbi.nlm.nih.gov/31695210/>.

¹⁶ Jason Schroeder, "Landfill Methane Research Workshop: Methane Remote Sensing for Leak Identification and Mitigation," California Air Resources Board, December 5, 2022, <https://ww2.arb.ca.gov/sites/default/files/2022-12/Methane%20Remote%20Sensing.pdf>.

¹⁷ Hannah Nesser et al., "High-resolution U.S. methane emissions inferred from an inversion of 2019 TROPOMI satellite data: contributions from individual states, urban areas, and landfills," *EGUsphere* [preprint] (2023), <https://egusphere.copernicus.org/preprints/2023/egusphere-2023-946/>.

¹⁸ Docket No. EPA-HQ-OAR-2019-0424, "Revisions and Confidentiality Determinations for Data Elements Under the Greenhouse Gas Reporting Rule," Hannah Nesser, July 27, 2023, <https://www.regulations.gov/comment/EPA-HQ-OAR-2019-0424-0306>.

found to contribute to urban smog and impact human health and the environment.¹⁹ In addition, the leachate from landfills can contaminate nearby soil and groundwater. One study found that the typical emissions of ozone precursors from a single hypothetical landfill may result in persistent daytime additions to ozone of over 1 part per billion (ppb) by volume tens of kilometers downwind, and large leaks of landfill gas can enhance ozone pollution by over a tenth of a ppb. In Southeast Michigan, the combined influence of several landfills upwind of key monitoring sites may contribute significantly to observed exceedances of the U.S. ozone standard.²⁰ Studies have also shown that landfills can decrease neighboring residential property values.²¹ Landfills are often sited near vulnerable communities. Analysis using the EPA's Environmental Justice Screening and Mapping Tool shows that 54 percent of MSW landfills reporting to the GHGRP have communities located within one mile that exceed the national average for either percent low-income or percent people of color.²²

Across the country, journalists have documented the adverse impacts of landfills on nearby communities. Recent stories document the prevalence of cancer and kidney failure in the Snow Hill community near North Carolina's Sampson County landfill,²³ lung cancer clusters near New York's Seneca Meadows landfill,²⁴ and odor violations from California's Chiquita landfill that left some residents vomiting and with severe migraines.²⁵ A winner of U.S. EPA's 2023 EJ Video Challenge for Students, *Pollution to Prosperity: Tackling Landfill Impacts for a Thriving Future*, highlights the air quality, water, and health impacts of Virginia's first mega-landfill on the surrounding community in Charles City County, which has left some families boiling their tap water to avoid contaminants.²⁶ The film also proposes solutions, including water quality testing, air monitoring, community health surveys, and waste diversion.

THE SOLUTIONS

Solutions are available to better control emissions from landfilled waste *and* prevent future landfill methane generation. To maximize climate and community benefits, we must do both. Fortunately, there are a number of technically feasible, readily available strategies to reduce

¹⁹ *Understanding and Control of Municipal Solid Waste Landfill Air Emissions Request for Applications (RFA)*, U.S. Environmental Protection Agency, October 2022, <https://www.epa.gov/research-grants/understanding-and-control-municipal-solid-waste-landfill-air-emissions-request>.

²⁰ Eduardo P. Olaguer, "The Potential Ozone Impacts of Landfills," *Atmosphere* 12, 7 (2021): 877, <https://www.mdpi.com/2073-4433/12/7/877>.

²¹ Richard Ready, "Do Landfills Always Depress Nearby Property Values?," *Journal of Real Estate Research*, 32, 3 (2010): 321-340. <https://www.tandfonline.com/doi/abs/10.1080/10835547.2010.12091279>

²² Preet Bains et al., *Trashing the Climate: Methane from Municipal Landfills*, Environmental Integrity Project, May 2023, <https://environmentalintegrity.org/reports/trashing-the-climate/>.

²³ Cameron Oglesby, "A decades-long battle against North Carolina's largest landfill is ramping up," *Grist*, Jan 19, 2024, <https://grist.org/accountability/a-decades-long-battle-against-north-carolinas-largest-landfill-is-ramping-up/>

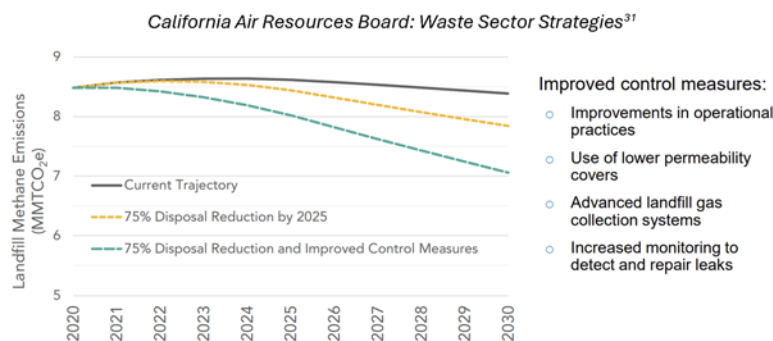
²⁴ Emma Misiaszek, "Activists rally against expansion of Seneca Meadows, NY's largest landfill," *CNYCentral*, Jan 23, 2024, <https://cnycentral.com/news/local/activists-rally-against-expansion-of-seneca-meadows-nys-largest-landfill>.

²⁵ "AQMD to address foul odor emitting from Chiquita Canyon Landfill," *KCAL News*, Sept 6, 2023, <https://www.cbsnews.com/losangeles/news/aqmd-to-address-foul-odor-emitting-from-chiquita-canyon-landfill/>

²⁶ Megan Salters, McKenna Dunbar, Sarah Murtaugh, "Pollution to Prosperity: Tackling Landfill Impacts for a Thriving Future," University of Richmond, February 2023, <https://www.youtube.com/watch?v=HHZQuTFHNSs>.

landfill emissions today, at modest cost.²⁷ Modernizing landfill operations – through comprehensive leak detection and repair, expanded gas collection system coverage, and enhanced cover practices – can cut methane immediately from waste-in-place, while protecting nearby communities from co-pollutants. At the same time, scaling up efforts that keep organic waste out of landfills – through strategies like edible food donation and composting – will avoid future landfill methane generation and ensure organic materials are put to their highest and best use in the circular economy.

The volume of methane-generating waste already sitting in U.S. landfills dwarfs the amount of new waste landfilled each year.²⁸ For example, California found that the total degradable carbon that is accumulated from waste deposited in previous years is over 20 times greater than the amount added.²⁹ And while methane production typically begins within the first year after the waste is landfilled, methane generation can continue for 10 to 50 or more years as the degradable waste decomposes over time.³⁰ That's why climate-leading states, including California, Maryland, and Washington, are pursuing efforts to reduce organic waste disposal *and* to strengthen waste-in-place control measures, accelerating overall emission reductions.



Waste-in-place controls are well understood and can be deployed quickly and at modest cost across a relatively small number of sources (i.e., there are 1,123 MSW landfills that reported to

²⁷ Heijlo Scharff et al., "The impact of landfill management approaches on methane emissions," *Waste Management & Research: The Journal for a Sustainable Circular Economy* (2023), <https://journals.sagepub.com/doi/10.1177/0734242X231200742>

²⁸ 3.14. Methodology for Estimating CH₄ Emissions from Landfills: Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2021 – Annex 3 Part B, U.S. Environmental Protection Agency, 2023, <https://www.epa.gov/system/files/documents/2023-04/US-GHG-Inventory-2023-Annex-3-Additional-Source-or-Sink-Categories-Part-B.pdf>

²⁹ 2022 Scoping Plan for Achieving Carbon Neutrality, California Air Resources Board, December 2022, <https://ww2.arb.ca.gov/sites/default/files/2023-04/2022-sp.pdf>

³⁰ Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2021 – Main Report, U.S. Environmental Protection Agency, 2023, <https://www.epa.gov/system/files/documents/2023-04/US-GHG-Inventory-2023-Main-Text.pdf>

³¹ "Preliminary Concepts for Potential Improvements to Landfill Methane Regulation," California Air Resources Board, Public Workshop, May 18, 2023, https://ww2.arb.ca.gov/sites/default/files/2023-05/LMR-workshop_05-18-2023.pdf

GHGRP in 2022).³² A recent paper, *The impact of landfill management approaches on methane emissions*, calculated the emission reduction potential of different management choices relative to business-as-usual (BAU) scenarios at North American (NA) landfills. For a typical NA landfill implementing few best practices, early gas collection and reducing the landfill cell size can reduce methane emissions by 27% vs. BAU. For a typical landfill implementing some best management practices, early and extended gas recovery can reduce methane emissions by 38% vs. BAU. For a typical landfill implementing nearly all best management practices, early sealing of the landfill could reduce methane emissions by 44% vs. BAU.³³ According to the paper, these approaches entail “basic, standardized, technology that can be deployed swiftly and at moderate cost” to reduce methane emissions today.³⁴ Below, we describe in more detail specific strategies that can better control emissions from landfilled organic waste.

- Earlier installation and expansion of wells to maximize gas collection system coverage:** According to EPA, 61% of methane generated by landfilled food waste is not captured by landfill gas collection systems and is released to the atmosphere as fugitive emissions. Because food waste decays relatively quickly, its emissions often occur before landfill gas collection systems are required to be installed or expanded.³⁵ However, it is technically feasible to install and expand the gas collection system within one year after waste is placed, rather than the more extended time frames currently allowed (up to 5 years). Analysis by the Environmental Integrity Project (EIP), based on Eastern Research Group (ERG)’s analysis for EPA’s 2019 technology review process for the Sec 112 Clean Air Act standards, found that earlier expansion of gas control systems (after 1 year) could reduce methane emissions by 400,000 tons per year at a cost-effectiveness of about \$140 per metric ton of methane reduced (or just ~\$2/ton CO₂e using the 20-year global warming potential).³⁶ This is well below the threshold of \$1,970 per ton of methane that EPA found to be reasonable for the oil and gas industry.³⁷ Using horizontal collectors during the disposal of waste can help capture gas as the lifts are being constructed. Optimizing wellhead spacing can also help ensure comprehensive coverage and reduce fugitive emissions.
- More robust wellhead tuning and maintenance to boost gas collection system performance:** More frequent wellfield monitoring and adjustments to system vacuum can help increase landfill gas recovery and limit system downtime. For example, automated tuning systems adjust the vacuum continuously, as temperature, pressure, and weather

³² “Number of reporters and emissions in the waste sector,” U.S. Environmental Protection Agency, 2023, <https://www.epa.gov/ghgreporting/ghgrp-waste>.

³³ Heijio Scharff et al., “The impact of landfill management approaches on methane emissions,” *Waste Management & Research: The Journal for a Sustainable Circular Economy* (2023), <https://journals.sagepub.com/doi/10.1177/0734242X231200742>.

³⁴ Ibid.

³⁵ Max Krause et al., *Quantifying Methane Emissions from Landfilled Food Waste*, U.S. Environmental Protection Agency Office of Research and Development, October 2023, https://www.epa.gov/system/files/documents/2023-10/food-waste-landfill-methane-10-8-23-final_508-compliant.pdf.

³⁶ “Petition for Rulemaking to Revise the New Source Performance Standards and Emission Guidelines for Municipal Solid Waste Landfills,” Environmental Integrity Project, June 2023, <https://environmentalintegrity.org/news/groups-petition-epa-for-stronger-controls-on-methane-from-landfills/>; Memorandum from E. Risch, Grp., Inc. on Clean Air Act Section 112 (d)(6) Tech. Rev. for Mun. Solid Waste Landfills to Allison Costa and Andy Sheppard, EPA, Off. of Air Quality Planning & Standards, at 29-30, 31-32, 36-41, 44-45 (June 25, 2019) <https://www.regulations.gov/document/EPA-HQ-OAR-2002-0047-0082>.

³⁷ Standards of Performance for New, Reconstructed, and Modified Sources and Emissions Guidelines for Existing Sources: Oil and Natural Gas Sector Climate Review, 87 Fed. Reg. at 74718.

conditions fluctuate, and can improve methane recovery and reduce fugitive emissions by 10-20% compared to baseline.³⁸ These systems can also provide operators with real-time information on potential issues related to the gas collection system, such as flooded wellheads or cover integrity issues, to inform timely repairs. Incorporating the gas collection system into the leachate system, or using gabion cubes along the bottom landfill liner, can also help enhance drainage, prevent flooding, and limit downtime.³⁹

- **Enhanced landfill cover practices to better control surface methane:** Increasing the thickness and compaction of daily and intermediate cover can allow for greater vacuum and lower surface methane emissions. Studies have shown that landfill methane emissions decrease when moving from areas of daily to intermediate to final cover; reducing lag times between these cover stages and minimizing the exposed surface area of the daily uncovered working face can help reduce fugitive emissions.⁴⁰ Applying a vegetative biocover as intermediate cover helps to enhance the microbial oxidation of methane escaping to the surface. A well-made biocover employing a large volume of aged compost can oxidize up to 35 or 40 percent of the methane in the gas passing through it.⁴¹
- **More comprehensive monitoring surveys to reduce fugitive methane:** The White House monitoring strategy acknowledges that walking surface emission monitoring (SEM) surveys “are not able to detect all anomalous emissions at a landfill that occur over a large footprint, some extending for hundreds of acres.”⁴² Maryland Department of Environment estimates that the more robust surface emission monitoring requirements in their recent rulemaking – which includes a tighter walking pattern – could reduce fugitive emissions by 10-40%.⁴³ Advanced methane detection technologies, such as drones, provide additional benefits relative to walking SEM approaches, including expanded coverage of the landfill surface area (including the active face, construction areas, and steep slopes), faster survey times, improved worker safety, and more objectivity and replicability. Using drones for SEM, which EPA approved in December 2022 as an alternative method, is cost-competitive with traditional manual surface emissions monitoring.⁴⁴ In addition to drone methods, continuous monitoring systems can be positioned throughout the landfill or around critical

³⁸ “Results,” LoCI Controls: Methane Capture & Emission Reduction, 2024, <https://locicontrols.com/results>.

³⁹ Eburn Ayandele et al., *Key Strategies for Mitigating Methane Emissions from Municipal Solid Waste*, RMI, 2022, <https://rmi.org/insight/mitigating-methane-emissions-from-municipal-solid-waste>

⁴⁰ James Hanson and Nazil Yesiller, *Estimation and Comparison of Methane, Nitrous Oxide, and Trace Volatile Organic Compound Emissions and Gas Collection System Efficiencies in California Landfills Final Report*, Prepared for: The California Air Resources Board and The California Department of Resources Recycling and Recovery, March 25, 2020, <https://ww2.arb.ca.gov/resources/documents/landfill-gas-research>; C. Douglas Goldsmith Jr. et al., “Methane emissions from 20 landfills across the United States using vertical radial plume mapping,” *Journal of the Air & Waste Management Association* 62, 2 (2012): 183-197, <https://www.tandfonline.com/doi/full/10.1080/10473289.2011.639480>

⁴¹ “Apply Biofilters or Biocovers,” U.S. Environmental Protection Agency, July 2023, <https://www.epa.gov/lmop/apply-biofilters-or-biocovers>.

⁴² National Strategy to Advance an Integrated U.S. Greenhouse Gas Measurement, Monitoring, and Information System, The Greenhouse Gas Monitoring and Measurement Working Group & The White House, November 2023, <https://www.whitehouse.gov/wp-content/uploads/2023/11/NationalGHGMMISStrategy-2023.pdf>.

⁴³ “Technical Support Document for COMAR 26.11.42 - Control of Methane Emissions from MSW Landfills,” Maryland Department of Environment, December 15, 2022, <https://mde.maryland.gov/programs/regulations/air/Documents/Technical%20Support%20Document%20-%20Control%20of%20Methane%20Emissions%20from%20MSW%20Landfills%20-%20Final%20w%20appendices.pdf>.

⁴⁴ “Webinar: Detecting Landfill Methane Emissions with Drones,” U.S. Environmental Protection Agency Landfill Methane Outreach Program (LMOP), September 28, 2023, <https://www.epa.gov/lmop/webinar-detecting-landfill-methane-emissions-drones>.

components to provide operators with real-time data to respond quickly to instances of elevated methane concentration and inform operational improvements. Environment and Climate Change Canada (ECCC)'s proposed regulatory framework for reducing Canada's landfill methane emissions incorporates both drone and continuous monitoring approaches, while providing flexibility for alternative monitoring methods with demonstrated performance equivalency.⁴⁵

- **Leveraging remote sensing to fix large leaks fast:** Remote sensing technologies, like aircraft and satellites, can alert operators to large methane releases to inform fast investigation and effective remediation on the ground. For example, environmental agencies in California and Pennsylvania worked with third-party aerial monitoring providers to survey for methane leaks and alerted landfill operators of large detected plumes. Operators took voluntary action to locate and mitigate the leaks. Overflights conducted by the Pennsylvania Department of Environmental Protection, in partnership with Carbon Mapper, achieved a 37% reduction in observed methane emissions from landfills.⁴⁶
- **High-efficiency flares to avoid methane slip during combustion:** Enclosed flares with high destruction efficiency (>99%) help avoid methane leakage during combustion. Analysis by EIP, based on ERG's report for EPA's 2019 NESHAP technology review, found that enclosed flares with a destruction efficiency of 99% could reduce methane emissions by 66,000 tons per year at a cost-effectiveness of about \$250-\$490 per ton of methane (or ~\$3-\$6 per ton CO₂e, GWP20).⁴⁷

Installing a gas collection system carries capital and operational costs (\$1.3 million for a 40-acre gas collection and control system, plus ~\$5,500 in annual O&M costs per acre), which can be offset in part through revenue from beneficial use projects.⁴⁸ Otherwise, many of the strategies to reduce emissions from landfilled waste do not involve purchasing equipment but rather improving existing practices around landfill cover, wellhead tuning, and methane monitoring to minimize fugitive emissions. A well-managed landfill can also generate savings for operators over time, by minimizing system downtime and avoiding major compliance or repair costs. EPA notes that much of the potential landfill methane abatement in the U.S. can be achieved at break-even prices and in some cases generate incremental revenue for operators through increased methane capture.⁴⁹

⁴⁵ Reducing Canada's landfill methane emissions: Proposed regulatory framework, Environment and Climate Change Canada (ECCC), 2023, <https://www.canada.ca/en/environment-climate-change/services/canadian-environmental-protection-act-registry/publications/reducing-landfill-methane-emissions.html>.

⁴⁶ "Methane Overflight Study Overview," Pennsylvania Department of Environmental Protection, Air Quality Technical Advisory Committee, March 9, 2023, <https://files.dep.state.pa.us/Air/AirQuality/AQPortalFiles/Advisory%20Committees/Air%20Quality%20Technical%20Advisory%20Committee/2023/3-9-23/AIRBORNE%20METHANE%20AQAC%20MEETING%20230309.pdf>.

⁴⁷ "Petition for Rulemaking to Revise the New Source Performance Standards and Emission Guidelines for Municipal Solid Waste Landfills," Environmental Integrity Project, June 2023, <https://environmentalintegrity.org/news/groups-petition-epa-for-stronger-controls-on-methane-from-landfills/>; Memorandum from E. Rsch. Grp., Inc. on Clean Air Act Section 112 (d)(6) Tech. Rev. for Mun. Solid Waste Landfills to Allison Costa and Andy Sheppard, EPA, Off. of Air Quality Planning & Standards, at 29-30, 31-32, 36-41, 44-45 (June 25, 2019) <https://www.regulations.gov/document/EPA-HQ-OAR-2002-0047-0082>.

⁴⁸ LFG Energy Project Development Handbook, U.S. Environmental Protection Agency Landfill Methane Outreach Program, January 2024, https://www.epa.gov/system/files/documents/2024-01/pdh_full.pdf.

⁴⁹ "Waste Overview, U.S. State-level Non-CO₂ Greenhouse Gas Mitigation Potential: 2025-2050," U.S. Environmental Protection Agency, 2019, <https://cfpub.epa.gov/ghgdata/nonco2/usreports/#page7>.

Reducing organic waste disposal at landfills prevents future methane generation and captures the value of materials. This approach includes efforts to reduce and redistribute surplus organics and recycle the remaining organic waste, while avoiding landfilling and incineration. Minimizing waste on farms, improving food inventory management, and donating excess edible food to shelters or converting it to animal feed all help to keep organics out of the waste stream. The remaining organic waste can then be separated and processed into compost, biogas, or other beneficial end products.



Sending organic waste to a composting facility or anaerobic digester avoids the generation of methane in landfills, while preventing organic waste from becoming waste in the first place avoids additional emissions across the supply chain. In a recent report, *From Field to Bin: The Environmental Impacts of U.S. Food Waste Management Pathways*, EPA compares the lifecycle greenhouse gas emissions of different food waste management pathways (kg CO₂e per metric ton of food waste). EPA found that source reduction had order-of-magnitude greater global warming potential benefits than any other pathway, by reducing the amount of additional food that must be produced. Landfills tend to have the highest global warming potential values, while food donation, upcycling, animal feed, AD, and composting can achieve substantial relative emissions reductions with beneficial or near neutral global warming potential.⁵¹

⁵⁰ "Waste Food Scale," U.S. Environmental Protection Agency, October 2023, <https://www.epa.gov/sustainable-management-food/wasted-food-scale>.

⁵¹ Shannon Kenny et al., *From Field to Bin: The Environmental Impacts of U.S. Food Waste Management Pathways*, U.S. Environmental Protection Agency Office of Research and Development, October 2023, <https://www.epa.gov/land-research/field-bin-environmental-impacts-us-food-waste-management-pathways>.

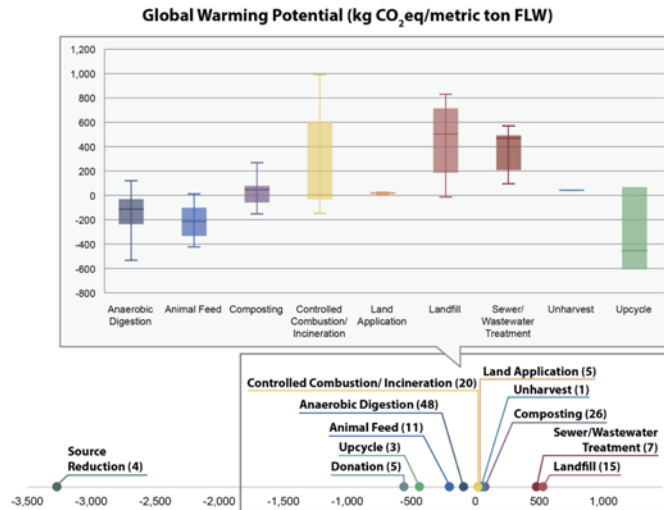
U.S. EPA Global Warming Potential of Waste Food Pathways⁵²

FIGURE 3-3. COMPARISON OF GLOBAL WARMING POTENTIAL OF WASTED FOOD PATHWAYS ACROSS LCA STUDIES

AD data assumes land application of digestate or biosolids. Sewer/WWT studies varied in assumptions about biosolids' destination. Carbon sequestration not consistently assumed for some pathways. See Table 3-4 for details. Donation excluded from boxplot because the range extends an order of magnitude below the next lowest value in the boxplot. See Appendix Table D-1 for data and sources.

Successful organics diversion programs typically require a combination of policy support (e.g., organics bans, pay-as-you-throw policies), behavioral change, investment in organics collection, processing, and recycling infrastructure (including favorable permitting), and healthy end markets for products and commodities made from diverted organics (e.g., compost procurement plans).

From an economic standpoint, preventing and reducing organic waste saves consumers money and avoids the costs associated with managing discards. Organics recycling projects, such as composting and anaerobic digestion, typically come with incremental capital costs to invest in new infrastructure, but the revenue from valorized end products (e.g., compost, biogas, digestate) can make projects economically viable and in some instances more favorable than landfilling over time – which can be passed on to consumers through lower rates.⁵³ Organics recycling and food recovery also bring significant benefits to communities and ecosystems, discussed further below.

⁵² Ibid.

⁵³ Alex Badgett and Anelia Milbrandt, "Food waste disposal and utilization in the United States: A spatial cost benefit analysis," *Journal of Cleaner Production* 314, 10 (2021), <https://www.sciencedirect.com/science/article/abs/pii/S0959652621022757>; Olivia Alves et al., "Your trash deserves better. These three cases show what's possible." RMI, No 17, 2023, <https://rmi.org/your-trash-deserves-better-these-three-cases-show-whats-possible/>.

STATE & LOCAL EXAMPLES: COSTS & BENEFITS

State policies and programs to reduce landfill methane emissions show compelling cost-benefits. Analyses of state rulemakings have found – for both stronger landfill emission controls and organics diversion mandates – that the cumulative economic, public health, and climate benefits generally exceed the implementation costs. There is growing momentum around state rulemakings to control landfill methane, as governments strive to address the climate crisis and meet their state-wide targets. Maryland, Oregon, and Washington have proposed or finalized strong landfill methane control rules in the past three years, and California, whose landfill methane regulation has been on the books since 2010, is now considering improvements to its nation-leading standard. The state rules make several improvements to landfill design, operational, monitoring, and reporting requirements to increase methane capture and reduce fugitive emissions.

- Oregon:**⁵⁴ In October 2021, the Oregon Environmental Quality Commission adopted new rules to regulate landfill gas emissions. In their staff report, the Department of Environmental Quality (DEQ) estimates that covered landfills could incur annual reporting and O&M expenses ranging from about \$8,000 to about \$400,000, with some landfills subject to a one-time investment of \$1-3 million to upgrade or install a landfill gas collection system. However, DEQ found that the rule would provide for future reduced costs to the general public from the reduction of greenhouse gas emissions and the impacts of climate change. Table 3 below provides an estimate of the reduced social cost of carbon, thanks to the lower thresholds and higher destruction efficiency required for landfill gas collection and control systems at four theoretical landfills. DEQ's report also underscores public health improvements due to the capture and destruction of more landfill gas, including toxic gases.

Table 3: Avoided social costs from gas collection system requirements

Size (acres)	Annual waste acceptance (ton/yr)	Control	Average annual methane destroyed 98% destruction (million ft ³)	Average annual methane destroyed 99% destruction (million ft ³)	Avoided social costs ²	
					Increased destruction ³	Lower GCCS threshold ⁴
20	75,000	Direct-use	2,084	2,106	NA	\$67M
50	150,000	RNG	4,168	4,211	NA	\$134M
100	800,000	Turbine	22,232	22,459	\$7M	NA
300	2,000,000	CHP Engine	55,580	56,147	\$18M	NA

1 Assume 10-year life span and 75% collection efficiency.

2 https://www.whitehouse.gov/wp-content/uploads/2021/02/TechnicalSupportDocument_SocialCostofCarbonMethaneNitrousOxide.pdf

3 Current federal regulations require 98% destruction while the proposed rules require 99% destruction.

4 The proposed rules will require some landfills to install GCCS that would not be required under federal rules. It is assumed the two largest landfills presented would be required to install a GCCS under federal rules while the two smaller landfills would not.

⁵⁴ "Staff Report for Oregon Environmental Quality Commission Meeting: Rulemaking, Action Item I - Landfill Methane Rules," State of Oregon Department of Environmental Quality, October 2021, https://www.oregon.gov/deq/EQCDocs/100121_I_LandfillMethane.pdf.

- **Maryland:**⁵⁵ Maryland's landfill rule (COMAR 26.11.42), finalized in June 2023, is projected to deliver an estimated 25-50% reduction in landfill gas emissions from covered landfills when fully implemented, according to estimates from the Maryland Department of Environment (MDE). MDE estimates that the 32 MSW landfills subject to the rule could incur annual expenses in the same range as Oregon's rule (~\$8,000-\$400,000) with some landfills subject to a one-time investment of \$1-3 million to upgrade or install a landfill gas collection system. MDE notes that for landfills with energy projects, the revenue generated from increased landfill gas capture could help offset costs associated with the proposed regulation and could also create jobs and local economic benefits. Furthermore, MDE concludes that the rule would be of benefit to the public and the environment as methane is reduced and minimized, helping to combat the adverse and costly impacts of climate change in Maryland. The total climate and social benefits of MDE's rule are estimated to be between \$22 million and \$45 million in 2030 (100-year GWP).
- **California:**⁵⁶ California finalized its nation-leading landfill methane regulation in 2010. The regulation requires owners and operators of certain uncontrolled municipal solid waste landfills to install gas collection and control systems, and for existing and newly installed gas and control systems to operate in an optimal manner. In its 2009 Initial Statement of Reasons (ISOR) for the proposed rulemaking, California Air Resources Board (CARB) estimated the rule to have a cost-effectiveness of about \$9 per metric ton of CO₂e reduced. CARB noted the regulations could create and expand businesses and jobs in landfill methane mitigation. CARB also noted that the regulation would provide benefits to both urban and rural communities in the state, helping to combat the adverse impacts of climate change and better control toxic co-pollutants in landfill gas and odors. In its annual report to the Joint Legislative Budget Committee on Assembly Bill 32, CARB estimated that its regulation reduced methane emissions by 1.8 MMT CO₂e in 2021.⁵⁷ In May 2023, CARB hosted a public workshop to present preliminary concepts for potential improvements to the Landfill Methane Regulation, leveraging the latest research and technological advances to increase effectiveness of methane emissions control measures.⁵⁸
- **Washington:**⁵⁹ In October 2023, Washington Department of Ecology released a preliminary analysis of its proposed rule (Chapter 173-408 WAC) to reduce landfill methane emissions. Across 26 landfills, Ecology estimates the rule will result in one-time costs of around \$10M and ongoing annual costs of \$846-\$871K. The total cost over the 20-year period is

⁵⁵ "Technical Support Document for COMAR 26.11.42 - Control of Methane Emissions from MSW Landfills," Maryland Department of Environment, December 15, 2022, <https://mde.maryland.gov/programs/regulations/air/Documents/Technical%20Support%20Document%20-%20Control%20of%20Methane%20Emissions%20from%20MSW%20Landfills%20-%20Final%20w%20appendices.pdf>.

⁵⁶ "Staff Report: Initial Statement of Reasons Proposed Regulation to Reduce Methane Emissions from Municipal Solid Waste Landfills," California Air Resources Board Stationary Source Division Emissions Assessment Branch, May 2009, <https://ww2.arb.ca.gov/sites/default/files/barcu/regact/2009/landfills09/isor.pdf>.

⁵⁷ Annual Report to the Joint Legislative Budget Committee on Assembly Bill 32 (Chapter 488, Statutes of 2006), California Air Resources Board, 2021, <https://ww2.arb.ca.gov/sites/default/files/2021-06/AB32-JLBC-2021-Report.pdf>.

⁵⁸ "Preliminary Concepts for Potential Improvements to Landfill Methane Regulation," California Air Resources Board, Public Workshop, May 18, 2023, https://ww2.arb.ca.gov/sites/default/files/2023-05/LMR-workshop_05-18-2023.pdf.

⁵⁹ "Preliminary Regulatory Analyses for Chapter 173-408 WAC, Landfill Methane Emissions," Washington Department of Ecology, October 2023, <https://apps.ecology.wa.gov/publications/documents/2302112.pdf>.

estimated at about \$26 million. Ecology notes that the benefits attributable to the proposed rule are greater than the costs and predominantly take the form of decreased methane emissions with additional benefits from the collection and destruction of odiferous or toxic compounds. Using the California rule as a proxy, Ecology estimates an estimated increase of roughly .02 MMT of methane controlled annually due to the proposed rule. With a social cost of methane of \$1,500 per ton, the estimated benefits attributable to the proposed rule are \$32.3 million annually with a net present value of nearly \$595 million over the 20-year planning frame of the proposed rule.

When it comes to keeping organics out of landfills, nine states have policies in place as of 2023 to limit organic waste disposal. Connecticut, Massachusetts, New York, Rhode Island, New Jersey, Maryland, Vermont, Washington, and California have all adopted state organic waste bans in the past decade.⁶⁰ While these rules require new investments in collection, processing, and recovery infrastructure, they also bring significant benefits: avoiding landfill methane generation, boosting food donation, creating green jobs, and stimulating local economic growth. We provide a few examples of the costs and benefits of organics diversion policies at the state level, with more information available in the Zero Food Waste Coalition's State Policy Toolkit.⁶¹

- **Massachusetts:**⁶² Massachusetts' commercial food waste disposal ban, in place since October 2014, has significantly increased food waste diversion from landfills, from a baseline of 100,000 tons to 360,000 tons in 2022. At the same time, food rescue of fresh and perishable foods has grown by more than 50%, the number of businesses separating food scraps from disposal has increased from 1,350 in 2014 to 3,100 in 2022, and Massachusetts' capacity to manage food waste has increased substantially. Furthermore, a study on the economic impact of Massachusetts' organic waste ban found that the policy created over 500 jobs and stimulated \$175 million in economic activity during its first two years.⁶³
- **Vermont:** Vermont's Universal Recycling Law, initially passed in 2012, encourages people to follow the Vermont Food Recovery Hierarchy, which prioritizes food waste reduction, food donation, feeding animals, and then composting and anaerobic digestion as the highest uses for food. In Status Reports, the Vermont Agency of Natural Resources highlights benefits of the law, including reducing greenhouse gas emissions, strengthening the local economy by building green businesses and jobs, feeding Vermonters through food donation, and boosting soil health with compost application.⁶⁴ Vermont saw food donation triple at the Vermont Foodbank after implementing its universal recycling law, along with

⁶⁰ *Achieving Zero Food Waste: A State Policy Toolkit*, Zero Food Waste Coalition, May 2023, <https://zerofoodwastecoalition.org/state-toolkit/>.

⁶¹ *Ibid.*

⁶² "Organics Action Plan," Massachusetts Department of Environmental Protection, November 2023, <https://www.mass.gov/doc/massachusetts-organics-action-plan-november-2023/download>.

⁶³ *Massachusetts Commercial Food Waste Ban Economic Impact Analysis*, ICF, December 2016, <https://www.mass.gov/doc/massachusetts-commercial-food-waste-ban-economic-impact-analysis/download>.

⁶⁴ *Vermont's Universal Recycling Law Status Report*, Vermont Agency of Natural Resources. Department of Environmental Conservation, January 2019, <https://dec.vermont.gov/sites/dec/files/awmp/SolidWaste/Documents/Universal-Recycling/2019.Universal.Recycling.Status.Report.pdf>.

significant growth in transfer stations, composting facilities, and food scrap haulers in the state.⁶⁵

- **California:**⁶⁶ California's SB 1383 aims to divert 75% of organic waste from landfills below 2014 levels by 2025. Jurisdictions must provide organics collection to residents and work with counties to build out organic waste recycling infrastructure, food recovery capacity, and establish procurement plans. CalRecycle has established an additional target that not less than 20% of currently disposed edible food is recovered for human consumption by 2025. Initial regulatory analysis found that the cumulative economic, public health, and climate benefits associated with recovering organic waste exceed the cost of the investments required. The successful implementation of the regulations will create thousands of green jobs, generate billions in economic activity and benefits, and protect Californians from immediate and long-term health and environmental impacts, also valued in the billions of dollars. These benefits cannot be achieved without substantial investments in new collection, processing, and recovery infrastructure.⁶⁷ While California failed to achieve its interim 2020 diversion target, giving jurisdictions more time to comply, organic waste processing capacity in California has increased by more than 400,000 tons in the past few years. So far, 75% of California Communities report they have residential organic waste collection in place and 242 million meals worth of unsold food have been sent to people in need. California now has 206 organic waste processing facilities and is building 20 more.⁶⁸

Furthermore, some local governments in states without organics policies are stepping up with organics diversion targets, collection services, and organics recycling plans. About 15 million U.S. households have access to food waste collection, and local governments are leveraging federal funds, such as the Solid Waste Infrastructure for Recycling (SWIFR) Program and the Composting and Food Waste Reduction (CFWR) Cooperative Agreements, to invest in organics diversion programs.⁶⁹

In addition to cutting planet-heating methane, addressing landfill emissions creates local benefits. Improving landfill methane capture also better controls for emissions of hazardous air pollutants, smog-forming compounds, and odors, while reducing explosion hazards. This all helps to improve **air quality, safety, public health, and quality of life** for communities near landfills. Expanding landfill methane monitoring and implementing best management practices can also create local jobs in methane mitigation, as well as economic benefits through productive use of

⁶⁵ Kevin Gaiss, "Vt. sees boom in food scrap haulers from last year's compost law," WCAX3, July 2021,

<https://www.wcax.com/2021/07/01/food-scrap-haulers-benefit-over-past-year/>; Angela Evancie, Myra Flynn, "How's Vermont doing with composting?," *Vermont Public*, January 6, 2022, <https://www.vermontpublic.org/podcast/brave-little-state/2022-01-06/how-s-vermont-doing-with-composting>

⁶⁶ "California's Short-Lived Climate Pollutant Reduction Strategy," CalRecycle, 2024, <https://calrecycle.ca.gov/organics/slcp/>.

⁶⁷ "Appendix A Cost Update: Initial Statement of Reasons (ISOR) for the Short-lived Climate Pollutant: Organic Waste Reduction regulations," CalRecycle, October 2019, <https://calrecycle.ca.gov/laws/rulemaking/archive/2020-2/slcp/>.

⁶⁸ "California's Climate Progress on SB 1383," CalRecycle, 2024, <https://calrecycle.ca.gov/organics/slcp/progress/>.

⁶⁹ Nora Goldstein, Paula Luu and Stephanie Motta, "BioCycle Nationwide Survey: Residential Food Waste Collection Access In The U.S.," *BioCycle*, September 2023, <https://www.biocycle.net/residential-food-waste-collection-access-in-u-s/>.

captured methane, which can in some cases displace more expensive fossil fuels. Strategies to prevent and divert organic waste from landfills can also help reduce landfill odors, minimize leachate generation and associated groundwater pollution, and prevent landfill expansion.

Reducing organic waste disposal in landfills has several other community benefits for **local food systems, ecosystems, climate resilience, and job creation**. Expanding surplus food donation can help to address local food insecurity, while composting can improve soil health and support local food production. Compost application has several additional benefits for local ecosystems and can boost local climate resilience; it sequesters carbon, prevents soil erosion, aids in reforestation and wetlands restoration, and assists in stormwater management and water conservation by better controlling and retaining runoff through soils. Finally, organics recycling can create jobs and workforce development opportunities in the circular economy at a higher rate per ton than landfills or incinerators. For example, one study found that for every \$10 million invested, composting sites can support 21.4 full-time jobs, while landfilling supports 8.4 and incineration supports 1.6.⁷⁰

Some landfill operators are taking voluntary steps to reduce their methane emissions, underscoring the feasibility of stronger controls. Large private landfill operators, such as Waste Management (WM), Republic Services, and GFL, have set targets to reduce their Scope 1 and 2 greenhouse gas emissions, most of which are attributable to landfill methane emissions. In their sustainability reports, these companies reference adoption of advanced technologies for fugitive emissions monitoring and other practices to increase methane capture. WM, for example, is investing in new technologies to monitor their emissions and improve the performance of their gas collection systems, with the goal of having a comprehensive landfill emissions measurement system in place by 2025.⁷¹ In addition, some cities with municipally operated landfills have included measures in their climate action plans to improve methane capture by implementing best management practices.⁷²

FEDERAL OPPORTUNITIES

Federal action is needed to reduce landfill methane emissions nationwide. Examples from states, local governments, and the private sector underscore that the solutions to address landfills are viable and cost-effective today. But federal standards and support are critical to help scale up these solutions, achieve major methane reductions, and protect communities across the country.

EPA regulates MSW landfills under the Clean Air Act and has broad authority to set design and work practice standards that achieve emissions reductions. The agency is statutorily required to revisit

⁷⁰ Brenda Platt, "Composting Makes Sense: Jobs through Composting & Compost Use," Institute for Local Self-Reliance, May 2013, <https://ilsr.org/composting-sense-tables/>. Clarissa Libertelli, Brenda Platt, Megan Matthews, *A Growing Movement: 2022 Community Composter Census*, Institute for Local Self-Reliance, Mar 2023, <https://ilsr.org/composting-2022-census/>.

⁷¹ 2023 Sustainability Report, Waste Management, 2023, https://sustainability.wm.com/downloads/WM_2023_SR.pdf.

⁷² "Example Government Climate Action Plans that Address Materials Management and Waste," U.S. Environmental Protection Agency, January 2024, <https://www.epa.gov/smm/example-government-climate-action-plans-address-materials-management-and-waste>.

its Section 111 standards for municipal solid waste landfills in August 2024, and should seize this opportunity to develop an ambitious framework that reflects the latest best practices in methane monitoring and control discussed above, while advancing organics diversion.⁷³ EPA can build from recent efforts to improve methane monitoring and control in its final Oil and Gas Methane Rule⁷⁴ and updates to the Greenhouse Gas Reporting Program.⁷⁵ EPA can also draw from state programs described above, Canada's recently proposed landfill methane regulatory framework,⁷⁶ and EPA's 2020 NESHAP rulemaking⁷⁷ for municipal solid waste landfills, which have already identified landfill methane mitigation measures that can achieve significant emissions reductions at relatively low cost.

New EPA standards would slash planet-warming methane, help achieve our domestic climate goals, and demonstrate leadership under the Global Methane Pledge that the U.S. helped launch in 2021. Robust landfill standards would also advance the waste sector targets set with Mexico and Canada at the North American Leaders' (NALS) summit, the 2030 U.S. food waste reduction goal, and help close the remaining gap on our economy-wide emission reduction targets under the Paris Agreement.

Stronger standards to reduce landfill methane emissions are particularly important in light of new incentives for renewable natural gas (RNG) in the Inflation Reduction Act. Incentivizing landfill energy production can put more sustainable waste management alternatives with lower lifecycle emissions, such as composting, at a relative disadvantage. EPA acknowledges in its RNG Operations Guide that "fugitive emissions of methane, depending upon their magnitude, can negate the climate and environmental benefits of RNG projects."⁷⁸ Therefore, any incentives for RNG should ensure best practices and monitoring requirements are in place at the landfill to minimize fugitive emissions and capture generated methane to the maximum extent practicable. Setting time bounds around incentives for landfill energy (e.g., limited to gas from waste already-in-place) can help limit the landfilling of organic waste and encourage diversion to lower-emitting disposal methods, like compost.

⁷³ "Petition for Rulemaking to Revise the New Source Performance Standards and Emission Guidelines for Municipal Solid Waste Landfills," Environmental Integrity Project, June 2023, <https://environmentalintegrity.org/news/groups-petition-epa-for-stronger-controls-on-methane-from-landfills/>

⁷⁴ "EPA's Final Rule for Oil and Natural Gas Operations Will Sharply Reduce Methane and Other Harmful Pollution," U.S. Environmental Protection Agency, December 2023, <https://www.epa.gov/controlling-air-pollution-oil-and-natural-gas-operations/epas-final-rule-oil-and-natural-gas>.

⁷⁵ "Rulemaking Notices for GHG Reporting," U.S. Environmental Protection Agency, September 2023, <https://www.epa.gov/ghgreporting/rulemaking-notices-ghg-reporting>.

⁷⁶ *Reducing Canada's landfill methane emissions: Proposed regulatory framework*, Environment and Climate Change Canada (ECCC), 2023, <https://www.canada.ca/en/environment-climate-change/services/canadian-environmental-protection-act-registry/publications/reducing-landfill-methane-emissions.html>.

⁷⁷ "Municipal Solid Waste Landfills: National Emission Standards for Hazardous Air Pollutants (NESHAP)," U.S. Environmental Protection Agency, 2024, <https://www.epa.gov/stationary-sources-air-pollution/municipal-solid-waste-landfills-national-emission-standards>.

⁷⁸ *Renewable Natural Gas: Facility Operation Best Practices to Create a More Climate-Friendly Project*, U.S. Environmental Protection Agency, 2022, https://www.epa.gov/system/files/documents/2022-11/RNG_Operations_Guide.pdf.

Beyond EPA standards, Congress can provide funds to catalyze landfill methane reductions, building on the success of the Bipartisan Infrastructure Law and the Inflation Reduction Act. Additional grant programs could help fund local waste prevention programs, food recovery and organics recycling infrastructure, and technologies to improve methane capture at municipal landfills. In particular, there are few federal incentives for composting, despite its methane reduction potential and substantial benefits for soil health, nutrient recycling, regenerative farming, and job creation. The Farm Bill presents an exciting opportunity to advance funding for food waste, composting, and organics recycling.⁷⁹

⁷⁹ *Opportunities to Reduce Food Waste in the 2023 Farm Bill*, Zero Food Waste Coalition, April 2022, <https://chfpi.org/wp-content/uploads/2022/04/2023-Farm-Bill-Food-Waste.pdf>.



Tom Frankiewicz
 U.S. Senate Committee on Environment & Public Works
Avoiding, Detecting, and Capturing Methane Emissions from Landfills
 February 28, 2024

Chairman Carper

1. The Environmental Protection Agency (EPA) is statutorily required to revisit the Clean Air Act section 111 standards for municipal solid waste landfills this year.
 - a. Please describe what you think are the best practices for landfill methane emissions reductions that EPA should consider incorporating into any new standards? Please include your recommendations, if any, about the extent to which satellite-based remote sensing should be included in such standards. I would also be interested to know the frequency with which methane detection surveys and monitoring should be conducted.

There are several common-sense updates EPA should incorporate into new section 111 standards for MSW landfills this year. A stronger rule should, among other changes, improve landfill gas collection system coverage and performance to increase methane capture, expand methane monitoring to quickly find and fix more leaks, require landfill cover practices that better mitigate surface emissions, and encourage organics diversion to avoid future methane generation. Below, we describe specific strategies that can better control emissions from landfilled organic waste. The [June 2023 petition for rulemaking](#) provides a more comprehensive list of recommendations to reduce landfill methane emissions.

- **Earlier installation and expansion of wells to maximize gas collection system coverage:** According to EPA, [61% of methane generated by landfilled food waste](#) is not captured by landfill gas collection systems and is released to the atmosphere as fugitive emissions. Because food waste decays relatively quickly, its emissions often occur before landfill gas collection systems are required to be installed or expanded. However, it is technically feasible to install and expand the gas collection system within one year after waste is placed, rather than the more extended time frames currently allowed (up to 5 years). [Eastern Research Group \(ERG\)'s analysis](#) for EPA's 2019 technology review process for the Sec 112 Clean Air Act standards, found that earlier expansion of gas control systems (after 2 years) could reduce methane emissions by 300,000 tons per year at a cost-effectiveness of about \$130 per metric ton of methane reduced (or just ~\$2/ton CO₂e using the 20-year global warming potential). This is well below the cost-effectiveness threshold that EPA found to be reasonable for the oil and gas industry. Using horizontal collectors during the disposal of waste can help capture gas as the lifts are being constructed, and installing the gas collection system as new waste is buried is already required under some state laws. Optimizing wellhead spacing can also help ensure comprehensive coverage and reduce fugitive emissions.
- **More robust wellhead tuning and maintenance to boost gas collection system performance:** More frequent wellfield monitoring and adjustments to system vacuum can help increase landfill gas recovery and limit system downtime. For example,

automated tuning systems adjust the vacuum continuously, as temperature, pressure, and weather conditions fluctuate, and can improve methane recovery and reduce fugitive emissions by [10-20% compared to baseline](#). These systems can also provide operators with real-time information on potential issues related to the gas collection system, such as flooded wellheads or cover integrity issues, to inform timely repairs. Incorporating the gas collection system into the leachate system, or using gabion cubes along the bottom landfill liner, can also help enhance drainage, prevent flooding, and limit downtime.

- **Enhanced landfill cover practices to better control surface methane:** Increasing the thickness and compaction of daily and intermediate cover can allow for greater vacuum and lower surface methane emissions. [Studies](#) have shown that landfill methane emissions decrease when moving from areas of daily to intermediate to final cover; reducing lag times between these cover stages and minimizing the exposed surface area of the daily uncovered working face can help reduce fugitive emissions. Applying a vegetative biocover as intermediate cover helps to enhance the microbial oxidation of methane escaping to the surface. A well-made biocover employing a large volume of aged compost can [oxidize up to 35 or 40 percent of the methane](#) in the gas passing through it.
- **More comprehensive monitoring surveys to reduce fugitive methane:** The [White House monitoring strategy](#) acknowledges that walking surface emission monitoring (SEM) surveys “are not able to detect all anomalous emissions at a landfill that occur over a large footprint, some extending for hundreds of acres.” Maryland Department of Environment estimates that the more robust surface emission monitoring requirements in their recent rulemaking – which includes a tighter walking pattern – could reduce fugitive emissions by [10-40%](#). Advanced methane detection technologies, such as drones, provide further benefits relative to walking SEM approaches, including expanded coverage of the landfill surface area (including the active face, construction areas, and steep slopes), faster survey times, improved worker safety, and more objectivity and replicability. EPA approved a specific tethered drone as an optional SEM alternative method ([OTM-51](#)), which is cost-competitive with traditional manual SEM. In addition to drone methods, continuous monitoring systems can be positioned throughout the landfill to provide operators with real-time data to respond quickly to instances of elevated methane concentration and inform operational improvements. Environment and Climate Change Canada (ECCC)’s [proposed regulatory framework](#) for reducing Canada’s landfill methane emissions incorporates both drone and continuous monitoring approaches, while providing flexibility for alternative monitoring methods with demonstrated performance equivalency.
- **Leveraging remote sensing to fix large leaks fast:** Remote sensing technologies, like aircraft and satellites, can alert operators to large methane releases to inform fast investigation and effective remediation on the ground. For example, state environmental agencies in [California](#) and [Pennsylvania](#) worked with third-party aerial monitoring providers to survey for methane leaks and alerted landfill operators of large detected plumes. Operators took voluntary action to locate and mitigate the leaks. The overflights conducted by the Pennsylvania Department of Environmental Protection, in partnership with Carbon Mapper, achieved a [37% reduction in observed methane emissions](#) from landfills. Moreover, EPA finalized a super emitter program in the oil and gas sector Sec 111 rules and could utilize developed program parameters in the MSW landfills sector.

- **High-efficiency flares to avoid methane slip during combustion:** Enclosed flares with high destruction efficiency (>99%) help avoid methane leakage during combustion. [Analysis by the Environmental Integrity Project](#), based on ERG's report for EPA's 2019 NESHAP technology review, found that enclosed flares with a destruction efficiency of 99% could reduce methane emissions by 66,000 tons per year at a cost-effectiveness of about \$250-\$490 per ton of methane (or ~\$3-\$6 per ton CO₂e, GWP20). Several states, including California, Maryland and Oregon already require 99% destruction efficiency.

A recent paper, [The impact of landfill management approaches on methane emissions](#), calculated the emission reduction potential of different management choices relative to business-as-usual (BAU) scenarios at North American (NA) landfills. For a typical NA landfill implementing few best practices, early gas collection and reducing the landfill cell size can reduce methane emissions by 27% vs. BAU. For a typical landfill implementing some best management practices, early and extended gas recovery can reduce methane emissions by 38% vs. BAU. For a typical landfill implementing nearly all best management practices, early sealing of the landfill could reduce methane emissions by 44% vs. BAU. According to the paper, these approaches entail "basic, standardized, technology that can be deployed swiftly and at moderate cost" to reduce methane emissions today.

On monitoring surveys and remote sensing: Under current section 111 standards, MSW landfill operators are required to conduct quarterly surface emission monitoring (SEM). Every calendar quarter, a technician walks the landfill with a handheld gas analyzer (e.g., flame ionization detector) around the perimeter and in a serpentine walking pattern with 30-meter spacing to measure surface methane concentrations. Technicians must also monitor at each cover penetration and areas where visual observations indicate potential gas (e.g., distressed vegetation and cracks in cover). If the detected concentration exceeds 500 ppm, the landfill operator must take corrective action to address the exceedance within 10 days. This framework has several limitations, including its incomplete coverage (hazardous areas, construction areas, steep slopes, and the active working face are exempt from monitoring), infrequency (quarterly), and subjectivity (dependent on operator, process, and regulatory interpretation). Furthermore, traditional SEM surveys are physically demanding with many miles of walking and are potentially dangerous for technicians due to terrain, weather conditions, and exposure risks. Due to these limitations, traditional SEM surveys miss methane leaks that could be mitigated. For example, aircraft and drone surveys have detected significant emissions coming from the landfill's [active working face](#), an area currently excluded from SEM due to safety concerns, and EPA enforcement reports show concerning disparities between the number of exceedances found by EPA inspectors compared with recent SEM surveys by the operator or contractors.

Advanced monitoring technologies – from satellites to aircraft to drones to fixed sensors – can significantly improve upon the current SEM framework. These technologies have the ability to cover the entire landfill surface area, increase the frequency of data collection, improve worker safety, and provide more objective data that is less susceptible to human error or interpretation. In a rule update, EPA should incorporate these advanced monitoring technologies – building on the recent update to the section 111 standards in the oil and gas sector – and account for their expanded temporal and spatial coverage. Methane-detecting drones, for example, can efficiently survey the entire landfill surface to identify areas for leak repair or other operational

improvements, and some operators are conducting voluntary drone surveys on a *monthly* basis. Continuous sensor systems, positioned around the landfill, can alert operators of leaks in real-time, accelerating response times. And, aircraft and satellite remote sensing surveys can alert operators and the public to large leaks. As Dr. Tia Scarpelli noted in her testimony, through aerial surveys conducted since 2016, Carbon Mapper has identified large methane emission sources at [over 200 of 300 surveyed sites](#). Current and planned satellite constellations have the capability to scan large areas and identify high-emissions events at frequent cadences, such as days to weeks. EPA finalized a Super Emitter Program for the oil and gas sector and should replicate relevant program parameters for MSW landfills to ensure prompt responses to large leaks that may otherwise go unchecked during the long intervals between SEM.

b. What lessons can EPA apply from state efforts to reduce organic waste disposal and to strengthen landfill control measures?

A number of states have either implemented policies or are considering measures that go beyond the requirements in EPA's section 111 standards to better control methane emissions from buried waste. Maryland, Oregon, California, and soon Washington have implemented comprehensive updates to their state air emissions regulations. The state rules make a number of improvements to landfill design, operational, monitoring, and reporting requirements to increase methane capture and reduce fugitive emissions. The Maryland Department of Environment estimates their rule, once fully implemented, will achieve a [25-50% reduction](#) in emissions from covered landfills. In addition, several states have taken surgical action to improve landfill regulations beyond federal standards to set a precedent for the EPA to follow. In Michigan, landfills are required to monitor for water build-up in wells and conduct monitoring for methane exceedances within just 180 days of waste being placed. New York requires intermediate cover to be placed within 30 calendar days, and horizontal gas lines must be installed in putrescible waste as it is buried. New Jersey requires gas component leak detection and high-efficiency of flares. And other states are poised to act: Colorado and New York have publicly stated their intent to update state landfill regulations to better detect and control methane leaks. California is also considering additional updates to its standard, with [CARB stating last May](#) that, "With more than 10 years of experience implementing the Landfill Methane Regulation, CARB has identified opportunities for improvement in consideration of new technologies, lessons learned, and the State's ambitious methane emissions reduction goals."

When it comes to keeping organics out of landfills, nine states have policies in place as of 2023 to limit organic waste disposal. Connecticut, Massachusetts, New York, Rhode Island, New Jersey, Maryland, Vermont, Washington, and California have all adopted state organic waste bans in the past decade. These state efforts help to avoid landfill methane generation, boost food donation, create green jobs, and stimulate local economic growth.

State action to reduce landfill methane emissions shows [compelling cost-benefits](#) and provides a model for EPA to advance more comprehensive gas collection, cover practices, monitoring, and organics diversion. Examples from states across the country underscore that the solutions to address landfill emissions are viable and cost-effective today, but federal standards and support will be critical to help scale up these solutions, achieve significant methane reductions, and protect all communities across the country equitably.

c. Could EPA's standards be updated to include any waste diversion strategies? Why or Why not? If yes, what needs to be taken into account if waste diversion strategies are considered and included?

We strongly encourage EPA to incentivize organics waste diversion strategies through a section 111 update. Waste prevention programs, food rescue, and composting all help to avoid future landfill methane generation and bring substantial benefits to local food systems, ecosystems, and economies. One approach, outlined in the [June 2023 petition for rulemaking](#), is for EPA to expressly identify organics diversion as an alternative compliance method, so long as equivalent or greater methane reductions are demonstrated, and establish rules for state, local, and tribal agencies to consider and approve landfill operator plans to divert organic waste rather than landfilling it.

EPA should also explore other methods under a section 111 rule to keep organic waste out of the landfill, potentially by requiring on-site separation and processing of organic waste. Sorting or extrusion technologies can extract the organic fraction of MSW for separate processing at an on-site composting facility or digester. EPA's 2022 report, [Downstream Management of Organic Waste in the United States: Strategies for Methane Mitigation](#), highlights examples of composting facilities and digesters co-located at landfills, and there are several technologies that can extract organics from incoming MSW – though precautions would need to be taken to protect against contamination and ensure safe end uses.

In addition, EPA has other authorities and funding resources beyond section 111 to advance organics diversion.

2. EPA recently announced grants for landfill methane monitoring research. What additional research is needed to validate new methods to detect releases of methane and other pollutants from landfills?

EPA should take an active role in method development and validation for advanced monitoring technologies. While EPA's new [research grants](#) will help develop methods to *quantify* landfill emissions and assess best management practices, which can inform future improvements to inventories and regulatory standards, we cannot wait for the results of these multi-year research studies to start deploying readily available technologies for *leak detection and repair*, especially when current SEM methods are falling short. Many of these technologies have already been tested in controlled release studies (e.g., at [CSU's METEC](#)), but EPA plays an important role in evaluating these technologies and developing standard operating procedures for landfill applications in a regulatory context. In December 2022, EPA approved a drone-based alternative to SEM (OTM-51/ALT-150). The agency's measurement technology group (OAQPS) and environmental measurement and modeling group (ORD) should accelerate efforts to validate and incorporate other commercially available monitoring approaches (e.g., laser-based drones, continuous monitoring systems, and other ground-based and aerial methods) as an alternative under current landfill standards, which can serve as a glidepath for formal incorporation in the next section 111 rule update.

a. What barriers exist to deploying advanced monitoring technologies at scale?

Landfill operators are recognizing the value of advanced monitoring technologies, and several are deploying these approaches voluntarily for research purposes and/or to inform operations. EPA should move quickly to certify these technologies, building on OTM-51, and develop standardized operating procedures to accelerate deployment under the current CAA standards. But ultimately, the expanded capabilities of these advanced methods warrant formal inclusion in the updated section 111 standards, so that all landfills are using the most robust, objective, real-time data available to reduce their fugitive methane emissions. Advanced methods are cost-competitive with traditional walking surveys, and a regulatory framework should encourage adoption of the most comprehensive monitoring approaches with timely follow-up to address any detected methane leaks and robust reporting to share emissions data with the public.

b. What other funding mechanisms exist at EPA to support the use of advanced monitoring technologies for landfills?

The Inflation Reduction Act (IRA) provides [\\$20 million for methane emissions monitoring](#), a portion of which EPA intends to use to procure a set of methane measurement equipment that can be loaned to states, local governments, and Tribes. Landfills could leverage this equipment for methane monitoring at their sites. In addition, EPA programs such as the Greenhouse Gas Reduction Fund, Climate Pollution Reduction Grants, and Community Change Grants can be leveraged for methane monitoring, mitigation, and reporting at municipal and Tribal landfills. Furthermore, the IRA funds from the [Methane Emissions Reduction Program](#) (\$1.55B) can be used to support methane monitoring, and while focused on the oil and gas sector, third-party remote sensing campaigns on a national scale could simultaneously provide data to inform methane mitigation at landfills.

3. The EPA's October 2023 report entitled, Quantifying Methane Emissions from Landfilled Food Waste, found that wasted food causes 58% of methane emissions from municipal solid waste landfills.

a. Please describe further actions from Congress that would help divert food waste from entering landfills in the first place?

Congress should look to EPA's recently updated [Wasted Food Scale](#) to prioritize efforts to prevent food loss and waste and advance organics recycling. Expanding funding for food waste prevention, recovery, and composting programs at the state and local level – such as through the [Solid Waste Infrastructure for Recycling \(SWIFR\)](#) and [Composting and Food Waste Reduction \(CFWR\)](#) grant programs – can help prevent food waste from entering landfills in the first place, while bringing tangible benefits to local communities.

In addition, while energy projects that use waste feedstocks currently benefit from federal investment and production tax credits, there are no such incentives for composting facilities, despite their methane reduction efficiency and substantial benefits for soil health, nutrient recycling, regenerative farming, and job creation. The [Farm Bill](#) presents an exciting opportunity to advance funding for composting and food waste reduction.

Other critical actions include implementing national standards for food date labeling ([Food Date Labeling Act](#)), national standards for compostable products to minimize contamination, educational and behavioral change campaigns to educate and activate consumers, and compost procurement policies (e.g., Congress can direct agencies to procure compost from diverted organics for application in gardens, parks, and roadways).

We also applaud bipartisan efforts from the EPW committee to expand composting in America (e.g., [Recycling and Composting Accountability Act](#)) as well as bicameral legislation to curb food waste (e.g., [COMPOST Act and Zero Food Waste Act](#)).

Senator Boozman:

- 1. Based on EPA's newest reports, food waste is a major source of methane from landfills and, in 2018, 24% of material sent to landfills was food. We also know food waste happens across the country, both in rural and urban areas, and solutions should be tailored to meet local needs. How can improvements be made to increase composting and recycling in rural communities to keep food waste out of landfills?**

Expanding access to food waste recovery and recycling infrastructure is critical to keep methane-generating waste out of our nation's landfills. In rural communities, creating food scrap drop-off locations and supporting [on-farm or community composting](#) infrastructure can deliver local environmental, economic, and social benefits – boosting [soil health, conserving water, and providing plant nutrition](#).

The federal government can support local programs by expanding grants and incentives for food waste recovery and composting collection and processing infrastructure, such as through the [Solid Waste Infrastructure for Recycling \(SWIFR\)](#) and [Composting and Food Waste Reduction \(CFWR\)](#) grant programs. The [Farm Bill](#) also presents an exciting opportunity to advance funding for composting and food waste reduction. In rural communities, recognizing [compost \(or soil carbon amendment\) as a conservation practice](#) can help farmers, ranchers and forest stewards apply for financial assistance.

We applaud recent bipartisan efforts from the EPW committee to expand composting in America, including through the [Recycling and Composting Accountability Act](#). At the same time, support for methane abatement at municipal landfills will help better control harmful emissions and co-pollutants from previously landfilled organic waste.

Senator CAPITO. Thank you.
Ms. Scarpelli.

**STATEMENT OF TIA SCARPELLI, PH.D., RESEARCH SCIENTIST
AND WASTE SECTOR LEAD, CARBON MAPPER**

Ms. SCARPELLI. Good morning, Chairman Carper, Ranking Member Capito, and members of the committee. Thank you for the opportunity to speak before you today.

My name is Dr. Tia Scarpelli, and I am a Research Scientist and the Waste Sector Lead at Carbon Mapper. Carbon Mapper is a non-profit organization with a mission to deliver actionable and transparent methane and CO₂ emissions data that can be used to inform and accelerate emissions mitigation.

Our work to use remote sensing to detect and quantify localized methane emissions is grounded in over a decade of methane research conducted by National Aeronautics and Space Administration (NASA) Jet Propulsion Laboratory (JPL), as well as published in science-based literature.

I have three messages that I would like to express today. No. 1, that landfills are a major source of methane emissions; No. 2, monitoring technologies show persistent large emissions at landfills related to specific processes and facility infrastructure; and No. 3, advanced monitoring is a critical tool in our current toolbox to guide mitigation and verify emissions reductions.

Landfills are an important contributor to U.S. methane emissions. Through aerial surveys conducted since 2016, we have surveyed 300 of over 1,200 open landfills. It identified large methane emissions sources at over 200 sites. Over a third of these landfills have been observed emitting more than 1,000 kilograms of methane per hour, with high methane concentrations sometimes extending kilometers in length away from the landfill. Per year, the emissions from this handful of landfills account for one-quarter of the U.S.'s waste sector methane emissions in 2021.

Many of these large methane emissions come from two main sources. One is the landfill's surface, and the other is landfill gas infrastructure. Both can be mitigated using available technologies. These large methane sources often persist for days, months, and even years.

For both of these categories, advanced monitoring technologies are readily available to help operators more efficiently monitor methane while also supporting more cost effective emissions management. There is an opportunity for data-driven methane mitigation at landfills.

Remote sensing is an advanced monitoring technique that generates high resolution images of methane gas. In many cases, we are able to precisely determine where the source is located on the landfill. We have identified some of the highest emitting sources at U.S. landfills, enabling prioritization for mitigation.

Studies have also shown discrepancies between observed and reported emissions. This indicates that many of these large, persistent landfill emissions are not included or are misrepresented in traditional emissions accounting methods. Given the dynamic nature of landfills, a routine and comprehensive monitoring system is critical for assessing emissions and verifying mitigation. At the

Sunshine Canyon Landfill in California, for example, airborne monitoring showed large emissions from surface cover.

In collaboration with the operator and local agencies, our observations informed improvements to cover material and the gas capture system, and followup monitoring verified that emissions were reduced. There is no single monitoring technology that can see all of the methane at the granularity that is needed at landfills. We need a portfolio of solutions that includes ground-based, aerial, and satellite technologies.

Currently, walking surveys are done quarterly at landfills using handheld methane detectors. These traditional surveys only cover a portion of the landfill and do not cover dangerous areas, like the landfill workforce. This is the area where new waste is added, which means that large emissions sources may be missed during the survey.

Emerging technologies are already being deployed at landfills, including the use of drones for leak detection and the use of airborne and satellite remote sensing to identify high emitters. With more wide-scale adoption across U.S. landfills, these technologies can enable significant methane reductions.

Increased monitoring in itself is not enough. There is an additional need for voluntary action by operators or regulations to address methane leaks once they are identified.

In closing, I offer these key takeaways: No. 1, remote sensing technologies are making methane emissions visible and can help the waste sector identify large emissions sources, improve emissions estimate and support cost effective emissions management to minimize methane loss in the first place. No. 2, landfills are complex systems. They need comprehensive monitoring the leverages all the tools in our 21st century toolbox while giving operators flexibility to choose cost-effective methods that maximize mitigation potential or return on investment.

I want to thank the committee for their work and the opportunity to share this research with you today. I look forward to your questions.

[The prepared statement of Ms. Scarpelli follows:]

**Testimony of Dr. Tia Scarpelli,
Research Scientist and Waste Lead, Carbon Mapper**

Oral Statement

Good morning Chairman Carper, Ranking Member Capito, and Members of the Committee. Thank you for the opportunity to speak before you today.

My name is Dr. Tia Scarpelli, and I'm Research Scientist and the Waste Sector Lead at Carbon Mapper. Carbon Mapper is a non-profit organization with a mission to deliver actionable and transparent methane and CO₂ emissions data that can be used to inform and accelerate emissions mitigation. Our work to use remote sensing to detect and quantify localized methane emissions is grounded in over a decade of methane research conducted through NASA's Jet Propulsion Laboratory as well as published in the science-based literature.

I have three messages I'd like to express today:

1. Landfills are a major source of methane emissions in the United States
2. Monitoring technologies show persistent large emissions at landfills related to specific processes and facility infrastructure
3. Advanced monitoring is a critical tool in our current toolbox to guide mitigation and verify emissions reductions

Landfills are an important contributor to US methane emissions. Through aerial surveys conducted since 2016, we have surveyed 300 of over 1200 open landfills and identified large methane emission sources at over 200 sites. Over a third of these landfills have been observed emitting more than 1000 kilograms of methane per hour with high methane concentrations sometimes extending kilometers in length away from the landfill. Per year, the emissions from this handful of landfills account for one quarter of the US reported waste sector methane emissions in 2021.

Many of these large methane emissions come from two main sources - one is the landfill surface and the other is the landfill gas infrastructure, which can be mitigated using available technologies. These large methane sources often persist for days, months, and even years. For both of these categories, advanced monitoring technologies are readily available to help operators more efficiently monitor methane while also supporting more cost-effective emission management.

There is an opportunity for data-driven methane mitigation at landfills. Remote sensing is an advanced monitoring technique that generates high resolution images of methane gas - in many cases we're able to precisely determine where methane is being emitted from at the landfill. We have identified some of the highest emitting sources at US landfills, enabling prioritization for mitigation. Studies have also shown discrepancies between observed and reported emissions. This indicates that many of these large persistent landfill emissions are not included - or are misrepresented - in traditional emissions accounting methods.

Given the dynamic nature of landfills, a routine and comprehensive monitoring system is critical for assessing emissions and verifying mitigation. At the Sunshine Canyon Landfill in California for example, airborne monitoring showed large emissions from surface cover. In collaboration with the operator and local agencies, our observations informed improvements to cover material and the gas capture system, and follow-up monitoring verified reduced emissions.

There is no single monitoring technology that can “see” all of the methane at the granularity that’s needed at landfills. We need a portfolio of solutions that includes ground-based, aerial, and satellite technologies. Currently, walking surveys are done quarterly at landfills with handheld methane detectors. These traditional surveys only cover a portion of the landfill and do not cover dangerous areas like the landfill work face - the area where new waste is added - which means that large emission sources may be missed during the survey.

Emerging technologies are already being deployed at landfills, including the use of drones for leak detection and the use of airborne and satellite remote sensing for identification of high-emitters. With more wide-scale adoption across US landfills these technologies can enable significant methane reductions. Increased monitoring in itself is not enough, there is an additional need for voluntary action by operators or regulations to address methane leaks once identified.

In closing, I offer these key takeaways:

1. Remote sensing technologies are making invisible methane emissions visible - and can help the waste sector identify large emission sources, improve emission estimates, and support cost-effective emissions management to minimize methane loss in the first place.
2. Landfills are complex systems and they need comprehensive monitoring that leverages all of the tools in our 21st century toolbox while giving operators flexibility to choose cost effective methods that maximize mitigation potential or return on investment.

I want to thank the committee for their work and the opportunity to share this research with you today. I look forward to your questions.

WRITTEN TESTIMONY

1. Introduction

Methane is a potent greenhouse gas with nearly 90 times the heat-trapping power of CO₂ over a 20 year time frame. Because methane is a short-lived climate pollutant, action to mitigate methane emissions can have near term benefits for the climate and in many cases there are existing technologies that can reduce emissions today. The waste sector accounted for 18.5% of 2021 US methane emissions with most emissions related to municipal solid waste landfills (U.S. EPA, 2023).

The decomposition of organic material deposited at landfills generates methane and if not collected or destroyed this methane can be released to the atmosphere. There are operational practices and design measures, including installation of a gas capture system, that can be implemented at a landfill today. These systems increase landfill gas capture so that it can be sent to a destruction device like a flare or collected for beneficial use. Methane can escape from the landfill as a diffuse area emission or as a more concentrated emission, also referred to as a point source emission. Point source emissions may be related to methane leakage from infrastructure, like a flare stack or gas well, or leakage from a specific region of the landfill like the landfill work face where waste is actively deposited.

Advanced monitoring technologies exist that can detect and quantify these large methane point source emissions, including airborne and satellite remote sensing. Many remote sensing technologies use an imaging spectrometer, which can detect a methane emission rate as low as 5-10 kg/hr as it is released from the point source. As shown in Figure 1, the high-resolution data from these technologies allows us to identify the likely locations on the landfill surface from which the methane is emitted. Airborne and satellite observing systems can monitor potential point sources distributed across regional to global scales, including the detection of large methane point sources in the oil/gas, coal, livestock, and waste sectors.

My testimony focuses on the use of remote sensing for detection and quantification of methane point sources. Methane research using this technology goes back over a decade at NASA's Jet Propulsion Laboratory. Carbon Mapper uses imaging spectrometers on aircraft, including NASA's Next Generation Airborne Visible/Infrared Imaging Spectrometer (AVIRIS-NG) and Arizona State University's Global Airborne Observatory (GAO), and from space, including the NASA EMIT instrument on the international space station. To date, these technologies have participated in many scientific studies that mapped methane sources in the US, including onshore and offshore oil and gas sources (Cusworth et al., 2021; Ayasse et al., 2022), various sources in major oil and gas basins (Cusworth et al., 2022), and multiple economic sectors in the state of California (Duren et al., 2019). The methods underpinning detection and quantification of emissions from the AVIRIS-NG and GAO aircrafts have been validated by numerous controlled release tests (Ayasse et al., 2023; Thorpe et al., 2016) to establish minimum detection capabilities for these observing platforms.

Use of this technology has shown that—when armed with data and insights on methane point sources—people can take action to mitigate these emissions. It was these research findings and

the support of philanthropic donors that motivated the formation of a public-private partnership with Carbon Mapper, JPL, Planet, the state of California, RMI, Arizona State University and the University of Arizona to launch satellites starting this year (using the same imaging spectrometer used successfully with airborne studies) to routinely detect, pinpoint, and quantify high emission methane and CO₂ sources globally.

2. Summary of Research Findings

Landfill methane emissions and sources

Through aerial surveys conducted since 2016, Carbon Mapper has surveyed over 300 of roughly 1200 open landfills in the US and identified large methane emission sources at over 200 of these sites. This handful of US landfills emit approximately 39 MMT CO₂e per year which translates to one quarter of the US reported waste sector emissions in 2021 and one third of reported emissions for landfills¹. Emissions at landfills have been observed at over 1000 kilograms of methane per hour with high methane concentrations sometimes extending kilometers in length away from the landfill. Figure 1 shows example images of methane plumes at landfills in the United States².

The California Methane Survey was one of the early studies to use remote sensing to map methane point sources and demonstrate their prevalence across economic sectors, including landfills. The survey was a multi-year study started in 2016 that used an advanced NASA imaging spectrometer onboard aircraft to map large methane point sources across California (Duren et al., 2019). The initial survey took place in 2016 and 2017, covering 60% of California's methane emitting infrastructure, including over 270 landfills (both open and closed). The survey found that a subset of California landfills (32 facilities) were the largest observed emission sources. These landfills accounted for 41% of the total observed methane point source emissions with construction activities, gaps in landfill cover, and leaking gas wells identified as sources of emissions at the landfills (Duren et al., 2019).

An additional study using the California Methane Survey observations found that methane point sources could also be related to the landfill work face (Cusworth et al., 2020). The work face is where new waste is placed at the landfill and an earthen material cover is placed over the new waste daily, primarily to reduce odors and vectors (e.g., rodents). This region of the landfill can be difficult to monitor with traditional methods (SEMs walking surveys EPA Method 21) due to operator traffic, unstable waste, and the potential for the work face to shift location day-to-day. Methane emissions related to the landfill work face were not seen extensively during the California Methane Survey, but Carbon Mapper flights in other regions have shown large emissions from the work face at many landfills. Figure 2 shows example images of methane plumes from the landfill work face.

¹ Determined using the EPA reported 146 MMT CO₂e for 2021 **waste sector** methane emissions and 123 MMT CO₂e for methane emissions specific to **landfills** (U.S. EPA, 2023). Carbon Mapper observed emissions are averaged by landfill across 2016-2023 and then summed across US landfills to get 160,000 kilograms of methane per hour and converted to CO₂e using the EPA GHG Equivalency Calculator.

² A methane plume is an enhancement of methane (i.e., region of higher concentration compared to the background methane concentration) in the atmosphere, originating from a methane emission source.

Similar to the California Methane Survey results, aerial monitoring using independent methods³ has shown emission rates of 90–3275 kilograms of methane per hour for medium to large landfills with gas capture systems in California (Hanson et al., 2020). Ground-based measurements³ in the same study found that areas of the landfill with daily cover (daily cover is placed over the work face at the end of the working day) had the highest methane fluxes while areas with final cover had the lowest methane fluxes (Hanson et al., 2020). A study of 20 US landfills also found that emissions were highest from the work face with and without daily cover compared to the parts of the landfill under intermediate and final cover (Goldsmith et al., 2012).

In addition to California, Carbon Mapper and partners at JPL, the University of Arizona and Arizona State University have observed over 300 landfills in 29 states with airborne remote sensing from 2016–2023⁴. Large methane emissions were detected at a majority of these landfills with emissions persisting over multiple revisits and in some cases across multiple years. This makes landfills distinctly different from oil and gas methane sources, which tend to be more intermittent and shorter-lived. Because of this, there is potentially a large climate benefit to mitigating these persistent landfill sources given that they account for a large fraction of waste sector emissions (Cusworth et al., *in review*).

Entities ranging from national/state governments to major US companies, have made commitments to reduce methane emissions. Methane emission reduction targets typically rely on models and inventories to estimate baseline emissions and make projections of potential emissions reductions. Remote sensing observations show that waste sector methane emissions in the US national inventory (Nesser et al., 2023) and facility reported emissions in the Greenhouse Gas Reporting Program (GHGRP; Cusworth et al., *in review*; Nesser et al., 2023) may underestimate methane emissions for a subset of US landfills. Carbon Mapper data also shows a subset of US landfills that over-report emissions compared to the GHGRP. Studies have attributed the disagreement between the GHGRP and observations to an overestimation of gas recovery efficiencies (Nesser et al., 2023) and abnormal operations like construction or well drilling (Nesser et al., 2023; Cusworth et al., *in review*). Carbon Mapper surveys also show evidence of work face emissions for a majority of landfills that report lower emissions compared to observations, indicating that GHGRP methodologies may not adequately account for this source.

Remote sensing data as a tool for mitigation

Aerial and satellite remote sensing data has been used to notify operators of large emission events. In many cases, operators have taken voluntary action to investigate and address methane leaks once notified. Two examples are outlined below where aerial remote sensing data was used to notify operators of large emissions in partnership with state agencies.

Airborne remote sensing observations were collected in California in 2020 and 2021 in partnership with the California Air Resources Board (CARB). During these flights, CARB was quickly notified of methane plumes so that notifications could be shared with facility operators leading to voluntary follow-up investigation of emissions. CARB reported that the observations

³ The aerial monitoring was done using a mass balance measurement approach where methane is measured directly upwind and downwind of the landfill while the ground-based measurements were done using flux chambers (Hanson et al., 2020).

⁴ Data can be found at <https://data.carbonmapper.org>.

directly supported mitigation in just under half of the incidents where notifications were shared (CARB, 2023). Over 50 incidents (unique methane plume detections) were sent to operators at landfills. Follow-up measurements were done by operators for just under half of the methane plume detections, and operators commonly identified construction activity on the landfill surface, malfunctioning gas wells, and cracks in surface cover as sources of emissions (CARB, 2023). The highest observed emissions were associated with construction events and the practice of taking wells offline near the work face where new waste was being deposited (CARB, 2023).

Similar airborne observations were collected in Pennsylvania in partnership with the Pennsylvania Department of Environmental Protection. During the flights, 10 discrete methane sources were detected at landfills and shared with operators. For a majority of these detected sources, follow-up investigation was done by operators to verify the source and voluntary mitigation action was taken (Pennsylvania DEP, 2022). Landfill 2 in Figure 2 shows an example of a methane plume from this airborne study coming from the work face. Methane sources identified by operators included the erosion of temporary liners and malfunctioning wells in the work face area, and both sources were reported mitigated by operators through installation of gas surface collectors and well repair (Pennsylvania DEP, 2022).

3. Best practices and methane monitoring

Landfill best practices

We have used remote sensing observations to investigate the large methane emission sources at landfills, including the landfill work face, cracks or gaps in cover, venting flare stacks, and leaks from the gas capture system (e.g., flooded or down wells). There are existing best practices that can address these sources. For example, the use of biocovers can prevent large emissions through gaps or cracks in cover, and early gas capture system expansion and minimization of the work face area can reduce methane emissions related to the placement of new waste at landfills. In addition to methane monitoring, continuous monitoring of analytics, like pressure and temperature, at gas capture wells and flare stacks can be used to identify component malfunction leading to early mitigation of methane leaks from these infrastructure.

In some cases, remote sensing has been used to verify that best practices lead to emissions reductions. This is done by observing the site before and after mitigation steps are taken to verify a change in emissions. For example, large methane emissions were observed at the Sunshine Canyon Landfill in California during the California Methane Survey. The source of emissions was identified as the intermediate cover slopes of the landfill and the Sunshine Canyon Landfill Local Enforcement Agency was notified. It was found that non-standard practices of not removing daily cover before new waste placement had led to reduced methane flow to the gas capture system and resulted in increased pressure buildup and methane leakage. Mitigation efforts were undertaken including installing additional landfill gas collection pipes, new horizontal and vertical wells, and new surface cover (Cusworth et al., 2020). Methane observed at the landfill decreased after these mitigation steps were taken, and an added benefit was a drop in the number of odor complaints from the surrounding community.

Large emissions have been observed at landfills with gas capture systems in place. Improved operational practices and methane monitoring can help reduce emissions, but preventing the

organic waste from entering the landfill is also key. By diverting organic waste from the landfill, we reduce the potential methane generation and the potential for large methane leaks. Previous studies have shown methane point source emissions at compost piles and solid waste digesters (Cusworth et al., 2020; Duren et al., 2019), so it is important to follow best practices at these waste diversion sites and continue to use methane monitoring.

Role of advanced monitoring

In addition to best practices at landfills, methane monitoring is key for reducing emissions. Monitoring can be used to identify and quantify methane emission sources at the landfill. Advanced monitoring technologies include various forms of sensors and platforms that can be combined in different ways. Sensors may measure methane directly from the atmosphere or indirectly in the form of passive or active remote sensing (Ayandele et al., 2022). Sensors used for continuous monitoring are stationary and can be placed across the landfill surface or around the landfill boundary. Sensors that measure methane directly or use passive or active remote sensing can be placed on mobile platforms including drones, vehicles, aircraft, or satellites.

Typically, monitoring instruments are either designed to (1) pinpoint the location of leaks or (2) provide an estimate of the methane emissions for the facility. For **leak detection**, the goal is to identify the location of high methane concentrations across the landfill. An ideal monitoring system for leak detection would identify these hotspots with high spatial accuracy and be cost-competitive with existing monitoring methods. For methane **emissions quantification**, the goal is to provide an emission rate for the facility to identify any unknown large emission events that could indicate abnormal operations. An ideal monitoring system would observe the entire landfill and provide some indication of where the large emission source is located at the site (to guide follow-up investigation). Methane monitoring technologies that perform these tasks already exist and are being used at landfills, including the use of drones for leak detection and the use of airborne and satellite remote sensing for identification of high-emitters.

Current leak detection at landfills consists of quarterly walking surface emission monitoring (SEM). The limitations of a walking SEM include the subjective nature of identifying potential leak points and the potential for large emissions in dangerous areas like side slopes or the work face. Existing advanced monitoring technologies can be used for on-site leak detection to identify emission hotspots across the surface of the landfill. Drone monitoring for example can provide more complete coverage of the landfill surface, including the landfill work face which has been identified as a potentially large emission source that is missed by traditional SEM. Drone monitoring is already performed at landfills, and there is an existing drone-based alternative test method for Method 21 (traditional walking SEM).

Airborne and satellite remote sensing technologies are designed to survey a broad geographic area to quickly identify any landfills with abnormally large emissions. Carbon Mapper airborne data has been used in this framework to detect large emission events. For example, operators were notified of large emission events in California through partnership with CARB (CARB, 2023) and a similar notification process was followed in Pennsylvania (Pennsylvania DEP, 2022). For both studies, landfill operators reported performing follow-up verification of the methane leak and identified the emission source, and in some cases, operators were able to mitigate the emissions.

4. Recommended Next Steps

There are unique opportunities for mitigation of large methane point sources at landfills. In the oil and gas sector, there have been advances in the use of monitoring technologies for quick detection and mitigation of methane emission events. We have observed large methane point sources at landfills similar to the oil and gas sector, and notification of large emission events have been used to notify operators of anomalous activity, leading to follow-up investigation and emissions mitigation. In order to advance methane mitigation at landfills, the following recommendations should be considered:

1. *Review of landfill best practices*: Studies have shown that the landfill gas capture system, side slopes under intermediate cover, and the work face can be large sources of methane at US landfills. Required best practices at large landfills should be updated to include engineering features and operational practices that reduce emissions from these sources.
2. *Development of a comprehensive monitoring strategy*: Monitoring and managing methane leaks at landfills is possible with a portfolio of monitoring technologies, including ground-based, aerial, and satellite technologies. A comprehensive strategy must address both leak detection across the landfill surface and the identification of high-emitting facilities. For example, drone monitoring may be used for quarterly surveys that prioritize leak detection while outside of those quarterly surveys airborne and satellite remote sensing would identify large, anomalous emitters, allowing industry to prioritize large leaks for mitigation. The identification of high-emitters using remote sensing is already being done for the oil and gas sector through the Super-emitter Response Program, so there is a ready opportunity to have these same instruments also identify high-emitting landfills, providing landfill operators with more tools to enable mitigation.
3. *Review of reporting frameworks*: The emissions quantification capabilities of airborne and satellite remote sensing instruments can be used to assess existing reporting methods. Reconciling the reported and observed emissions will be key for tracking progress toward national and sub-national emission reduction targets.

In closing, there is a major opportunity to address methane emissions in the US by mitigating large methane sources at landfills. To do this, landfill best practices must be updated and a comprehensive tiered monitoring strategy must be developed based on the current understanding of the activities and infrastructure leading to methane emissions at landfills.

Thank you for the opportunity to testify and I look forward to your questions.

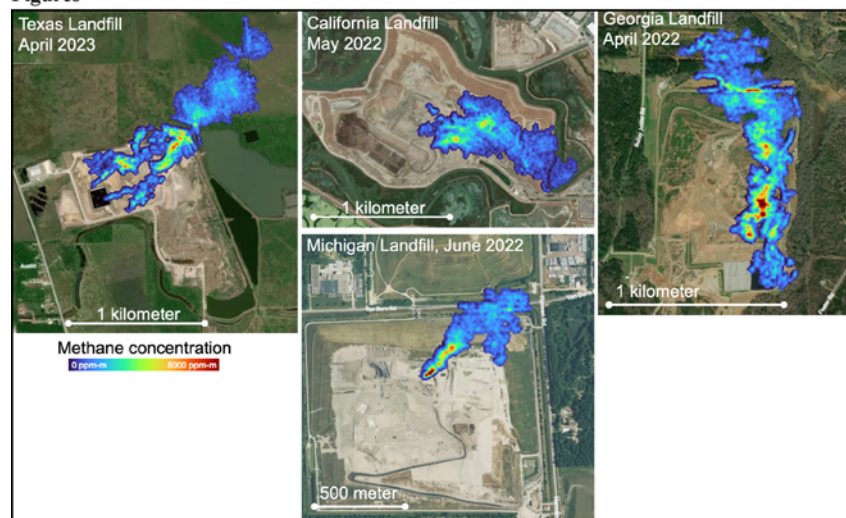
Figures

Figure 1. Examples of methane plumes at US landfills observed by Carbon Mapper (<https://data.carbonmapper.org/>). All methane plumes shown here have emission rates greater than 1000 kilograms of methane per hour.

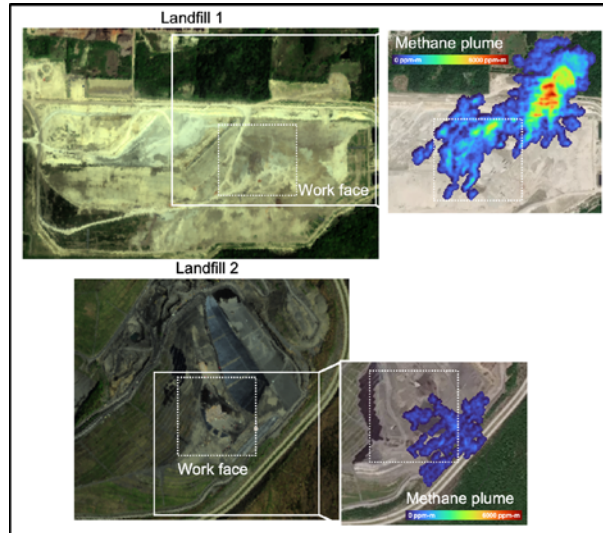


Figure 2. Landfill methane plumes originating from the work face. The images show the landfill surface at the time of the observation with the work face outlined in the white dotted line. Inset images show the methane plumes observed.

References

- Ayandele, E., Huffman, K., Jungclaus, M., Tseng, E., Duren, R., Cusworth, D., and Fisher, B.: Key Strategies for Mitigating Methane Emissions from Municipal Solid Waste, RMI, <https://rmi.org/insight/mitigating-methane-emissions-from-municipal-solid-waste/>, 2022.
- Ayasse, A. K., Thorpe, A. K., Cusworth, D. H., Kort, E. A., Negron, A. G., Heckler, J., Asner, G., & Duren, R. M.: Methane remote sensing and emission quantification of offshore shallow water oil and gas platforms in the Gulf of Mexico. *Environmental Research Letters*. <https://doi.org/10.1088/1748-9326/ac8566>, 2022.
- Ayasse, A. K., Cusworth, D., O'Neill, K., Fisk, J., Thorpe, A. K., and Duren, R.: Performance and sensitivity of column-wise and pixel-wise methane retrievals for imaging spectrometers, *Atmos. Meas. Tech.*, 16, 6065–6074, <https://doi.org/10.5194/amt-16-6065-2023>, 2023.
- CARB, Summary Report of the 2020 and 2021 Airborne Methane Plume Mapping Studies, California Air Resources Board, <https://ww2.arb.ca.gov/resources/documents/summary-report-2020-and-2021-airborne-methane-plume-mapping-studies>, 2023.
- Cusworth, D.H., Duren, R.M., Thorpe, A.K., Tseng, E., Thompson, D., Guha, A., Newman, S., Foster, K.T. and Miller, C.E.: Using remote sensing to detect, validate, and quantify methane

- emissions from California solid waste operations. *Environmental Research Letters*, 15(5), p.054012, <https://iopscience.iop.org/article/10.1088/1748-9326/ab7b99>, 2020.
- Cusworth, D.H., *et al.*: Intermittent methane emissions in the Permian basin *Environ. Sci. Technol. Lett.*, <https://doi.org/10.1021/acs.estlett.1c00173>, 8 567–73, 2021.
- Cusworth, D.H., *et al.*: Strong methane point sources contribute a disproportionate fraction of total emissions across multiple basins in the United States *Proc. Natl Acad. Sci.* 119 e2202338119, <https://doi.org/10.1073/pnas.2202338119>, 2022.
- Cusworth, D.H., Duren, R.M., Ayasse, A.K., Jiorle, R., Howell, K., Aubrey, A., Green, R.O., Eastwood, M.L., Chapman, J.W., Thorpe, A.K., Heckler, J., Asner, G.P., Smith, M.L., Thoma, E., Krause, M.J., Heins, D., Thornehoe, S.: Quantifying methane emissions from United States landfills, *in review*.
- Duren, R.M., Thorpe, A.K., Foster, K.T., Rafiq, T., Hopkins, F.M., Yadav, V., Bue, B.D., Thompson, D.R., Conley, S., Colombi, N.K. and Frankenberg, C.: California's methane super-emitters. *Nature*, 575(7781), pp.180-184, <https://doi.org/10.1038/s41586-019-1720-3>, 2019.
- Goldsmith, C.D. Jr, Chanton, J., Abichou, T., Swan, N., Green, R., Hater, G.: Methane emissions from 20 landfills across the United States using vertical radial plume mapping, *Journal of the Air & Waste Management Association*, 62(2):183–197, <https://doi.org/10.1080/10473289.2011.639480>, 2012
- Hanson, J.L., *et al.*: Estimation and comparison of methane, nitrous oxide, and trace volatile organic compound emissions and gas collection system efficiencies in California landfills, Report prepared for The California Air Resources Board and The California Department of Resources Recycling and Recovery, https://ww2.arb.ca.gov/sites/default/files/2020-12/CalPoly_LFG_Study_03-30-20.pdf, 2020.
- Nesser, H., Jacob, D. J., Maasackers, J. D., Lorente, A., Chen, Z., Lu, X., Shen, L., Qu, Z., Sulprizio, M. P., Winter, M., Ma, S., Bloom, A. A., Worden, J. R., Stavins, R. N., and Randles, C. A.: High-resolution U.S. methane emissions inferred from an inversion of 2019 TROPOMI satellite data: contributions from individual states, urban areas, and landfills, *EGUsphere* [preprint], <https://doi.org/10.5194/egusphere-2023-946>, 2023.
- Pennsylvania DEP, Pennsylvania Methane Overflight Study Final Report, Pennsylvania Department of Environmental Protection, Bureau of Air Quality, <https://files.dep.state.pa.us/Air/AirQuality/AQPortalFiles/Advisory%20Committees/Air%20Quality%20Technical%20Advisory%20Committee/2023/3-9-23/AIRBORNE%20METHANE%20AQTAC%20MEETING%20230309.pdf>, 2022.

Thorpe, A.K., *et al.*: Mapping methane concentrations from a controlled release experiment using the next generation airborne visible/infrared imaging spectrometer (AVIRIS-NG), *Remote Sens. Environ.*, 179, 104–115, <https://doi.org/10.1016/j.rse.2016.03.032>, 2016.

U.S. EPA's Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2021, <https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks>, 2023.

Senate Committee on Environment and Public Works
Hearing Entitled “Avoiding, Detecting, and Capturing Methane Emissions from Landfills”
January 31, 2024
Questions for the Record for Dr. Scarpelli

Chairman Carper

1. **Please provide specific examples on how aerial monitoring can provide technical assistance to landfill operators in order to reduce and detect methane leaks.**
 - You can’t manage what you don’t measure, however, measuring - and managing - methane at landfills can be a challenge due to their dynamic nature. Remote sensing provides a unique opportunity to fill critical monitoring gaps at landfills by helping identify large emission sources, improve emission estimates, and support cost-effective emissions management to minimize methane loss in the first place.
 - Regular monitoring using remote sensing can provide a quick indication of when and where large methane leaks are occurring and guide follow-up mitigation action. This includes providing (1) a list of individual landfills that have large emissions to prioritize for mitigation (the same list of large emitters may not match the large emitters predicted by models), (2) an approximate location of any emission source (down to an emission rate of 5-10 kg/h) on the landfill surface to guide follow-up by the operator, and (3) an indication of the persistence of the each emission source (is the source still emitting as the site is re-visited). This has been tested in practice with CARB and Pennsylvania DEP where a number of landfills across the state were observed, the locations of detected emission sources were shared with operators, and, in some cases, the operator voluntarily verified the source on the ground and took mitigation action.
 - After mitigation action, aerial surveys can verify that emissions are reduced, and regular monitoring ensures that changes made to the landfill do not lead to new emission sources. At the Sunshine Canyon landfill, aerial monitoring identified large emissions from surface cover. This information, including the detected emissions and location of the emission source, was shared with the operator and local agencies. The operator made changes to the cover material and the gas capture system, and aerial monitoring was used to verify that the changes made did lead to emissions reductions.
 - By identifying the processes and infrastructure responsible for large emissions, the observations can guide best practices, preventing future methane leaks. Remote sensing technologies, including aerial and satellite monitoring, provide an efficient and rapid way to inform identification and remediation of large emission events on the ground. These technologies have identified and attributed large, localized emissions at landfills to the work face, gas destruction devices, gaps or cracks in surface cover, malfunctioning gas wells, and construction activities.

2. What information or recommendations do you have regarding the ways in which aerial monitoring can or should be combined with other systems and platforms in order to maximize the effectiveness and efficiency of landfill monitoring?

Airborne and satellite remote sensing instruments are ideal for surveying multiple facilities across a region (e.g., aircraft typically survey across a state for a single campaign whereas a satellite can observe sites across the country and globally). Carbon Mapper uses instrument technology (imaging spectrometer) designed to detect and quantify large, localized sources with fine spatial accuracy (i.e. a localized site at the scale of meters). These types of instruments are traditionally deployed on aircraft or satellites, providing a wide field of view that can effectively identify large emission sources across the entire landfill surface or from neighboring facilities like a renewable natural gas facility. The data produced by these instruments includes the location of the emission source at high spatial resolution, an image of the methane plume that is being emitted by the source into the atmosphere, and an emission rate. The location of the source can have an uncertainty of 50-100 meters for landfills.

These instruments are ideal for identifying the facilities that have large emission events and the region within the facility where the emission source is located. This information can be used to prioritize the landfills and the sources within those landfills with the highest and most persistent emissions. For the operator to take mitigation action, the operator should be rapidly notified of any large emission sources and provided with the approximate location. Operators may choose to do follow-up investigation on-site using other advanced monitoring technologies with finer-scale spatial resolution like drone-mounted remote sensing instruments to further localize the source.

Because imaging spectrometers are designed to see large, localized sources, other types of advanced monitoring can be used to look for smaller and more diffuse sources across the landfill surface. The choice of technology will vary depending on whether the goal is to *quantify* these more diffuse emissions or *identify and repair* the methane leak. If the survey of diffuse sources finds anomalously high methane concentrations at the landfill, this can be followed-up with satellite remote sensing observations to verify if a large methane emission is occurring and repeat monitoring can verify if this large event persists after corrective action is taken.

3. **EPA recently announced grants for landfill methane monitoring research. What additional research is needed to validate new methods to detect releases of methane and other pollutants from landfills?**
 1. **What barriers exist to deploying advanced monitoring technologies at scale?**
 2. **What other funding mechanisms exist at EPA to support the use of advanced monitoring technologies for landfills?**

Monitoring and managing methane leaks at landfills is possible using monitoring technologies that exist today. There are two related but distinct needs for landfill methane monitoring: one is to support ongoing operational management on the ground through leak detection and the other is annual-scale quantification to support emissions accounting. Advanced methane measurement technologies including remote sensing satellites and aircraft as well as low-altitude drones have demonstrated the ability to detect and precisely locate sources of high methane emissions within landfills. Pilot studies across the US – including those that benefit from site-level feedback from operators – are demonstrating that many advanced monitoring technologies are ready for prime-time today in terms of guiding mitigation action through the detection of large emission events and the rapid notification of these events to operators. In addition to rapid notification of high emission events to operators for expedited attention, monitoring systems should publish methane data on a regular basis to improve situational awareness and inform communities and local, state and federal policy-makers.

There is an urgent need and opportunity to begin operational deployment now of such systems at scale for active municipal solid waste landfills across the US. Operational scale-up of such systems should provide routine (ideally weekly or better) monitoring of all active landfills participating in EPA's Greenhouse Gas Reporting Program (GHGRP) with notification to operators of high emission events within several days of detection followed by public release of methane data following completion of quality control review. Satellite remote sensing is well suited to routine monitoring across the US of GHGRP landfills, though a constellation of satellites is needed to achieve high cadence revisits of each landfill (weekly or better). The primary barriers to operational scale-up of such systems are financing and data transparency - complicated by the highly fragmented nature of landfill management in the US. Congress can help remove these barriers by appropriate federal funding in the form of EPA competitive grants for methane data delivery services to landfill operators, local and state regulators, and communities that meet specified requirements for precision, visualization, timeliness, and transparency.

Meanwhile, continued landfill methane monitoring research - such as that funded by EPA's research division¹ - can help reduce uncertainty in quantitative emission estimates. Additional

¹<https://www.epa.gov/research-grants/understanding-and-control-municipal-solid-waste-landfill-air-emissions-grants>

recommendations regarding the operational leak detection and annual quantification needs are detailed below.

Additional research needs:

- The current standard for annual emissions accounting (e.g., GHGRP) is to use models and standard emission factors to generate facility-scale emission inventories. Research shows that those traditional bottom-up approaches often fail to account for real-world conditions at the landfill including leaks and features that aren't included in the models. This is an area where advanced measurement technologies can supplement the models and facility data to improve annual accounting. This system of systems approach to accounting is being actively matured and validated on multiple fronts today by some major landfill management companies as well as multiple research teams, including several funded by the EPA.
- There are other pollutants that are co-emitted with methane from landfills. We can observe methane emitted from landfills from space, and we can use these observations to infer population exposure to other co-emitted pollutants if we know the emission ratio of these pollutants compared to methane. Research teams, including those funded by the EPA, are actively investigating the ratios of these pollutants to methane and how these ratios vary with other factors (e.g., waste composition and age, etc.) and how methane monitoring can be used to investigate community health concerns.

Scaling up advanced monitoring:

- For operational methane management at landfills: Deployment of advanced monitoring at scale across US landfills for leak detection is limited by the availability of timely, accessible, and transparent data. While philanthropists and science agencies have supported years of critical research studies for technology development, there is an urgent need going forward for public funding that can support timely and trusted methane monitoring from advanced measurement technologies ranging from satellites and aircraft to drones and surface sensors. A federal program is needed that offers competitive grants for operational methane monitoring, providing much needed technical support for landfill operators and municipalities across the US. There is an opportunity to leverage IRA funds from the [Methane Emissions Reduction Program](#) (\$1.55B) to support methane monitoring. While focused on the oil and gas sector, third-party remote sensing campaigns on a national scale could simultaneously provide data to inform methane mitigation at landfills.
- For emissions accounting at landfills: A portfolio of advanced monitoring technologies is needed to see all the emissions at a landfill. A major barrier to scaling up the use of these technologies for emissions accounting at landfills is the lack of a comprehensive strategy for reconciling these multi-scale observations and existing models. This strategy should address how the various technologies, including ground-based, aerial, and satellite

technologies, can inform a baseline facility emission estimate and how the observations can inform model improvements, including the magnitude of emissions and the nature of the emission sources (i.e., the relative contribution of the different sources at the landfill to overall emissions). To develop this strategy for improving emissions accounting, there is a need to assess the emissions data provided by a portfolio of monitoring technologies at landfills. Much of this data will already be collected by scaling up operational monitoring, as noted above, and by making this data public, the observations can serve an additional need to inform improvements in emissions accounting.

Senator Boozman:

1. **Based on EPA's newest reports, food waste is a major course of methane from landfills and, in 2018, 24% of material sent to landfills was food. We also know food waste happens across the country, both in rural and urban areas, and solutions should be tailored to meet local needs. How can improvements be made to increase composting and recycling in rural communities to keep food waste out of landfills?**

Remote sensing observations of methane at US landfills show that the landfill work face - where new waste is placed at the landfill - can be a source of large methane emissions. Improved operational practices, guided by routine methane monitoring, can help reduce emissions from the work face, but preventing the organic waste from entering the landfill is also key. By diverting organic waste from the landfill, we reduce the potential for methane generation and large methane leaks at the landfill. Previous studies have also shown that large methane sources can occur at compost piles and solid waste digesters. It will be important for waste diversion facilities to follow best practices that avoid large methane emissions to ensure that waste diversion practices have the intended impact of reducing methane emissions from waste. Scaling up methane monitoring across the waste sector, including at large waste diversion facilities, can help to ensure those operations are functioning as intended and verify that best practices (e.g., aeration of compost piles) are avoiding the generation of these large methane emissions.

Senator CAPITO. Thank you, and I apologize; I left the Doctor part out of your first name of your address, so I apologize for that.
 Ms. SCARPELLI. No problem.
 Senator CAPITO. Ms. Germain.

STATEMENT OF ANNE GERMAIN, P.E., BCEE, CHIEF OPERATING OFFICER AND SENIOR VICE PRESIDENT OF REGULATORY AFFAIRS, NATIONAL WASTE AND RECYCLING ASSOCIATION

Ms. GERMAIN. Thank you. Chairman Carper, Ranking Member Capito, members of the committee, thank you for allowing me to testify today on opportunities to avoid, detect, and reduce landfill methane emissions.

My name is Anne Germain, and I serve as the Chief Operating Officer and Senior Vice President of Regulatory Affairs at the National Waste and Recycling Association. We are a trade association representing the private sector waste and recycling industry.

Landfills protect the environment by responsibly managing society's waste. Our sector is subject to extensive Federal, State, and local requirements, including stringent design, operating, monitoring, closure, and post-closure standards established under the Resource Conservation and Recovery Act (RCRA) as well as landfill gas collection and control requirements under the Clean Air Act.

Besides these regulatory obligations, we have made significant advancements in landfill gas capture and control systems that meet or exceed our regulatory requirements. We also closely monitor emissions from our landfills and engage in corrective actions swiftly and efficiently. We are actively deploying infrastructure that transforms yesterday's waste into renewable energy, which can power communities, fuel vehicles, and support progress in offsetting the impacts of climate change.

Recently, a narrative has emerged that air emissions from landfills have increased. Based on data from the EPA, however, municipal solid waste landfills air emissions have declined by nearly 45 percent between 1990 and 2021. All the while, landfill waste volumes have increased by about five percent over that same period. We are proud of this progress, and we are not aware of any other industry that has achieved even remotely comparable improvements.

However, we are committed to reducing climate impacts even further, consistent with the goals of the Global Methane Pledge and the Administration's commitment to reduce methane emissions from the waste sector by at least 15 percent by 2030. Achieving these goals necessitates the development of more accurate measurement and measurement methods to quantify emissions.

Our members are actively assessing how various aerial and ground-based methane emission measurement methods developed for other sectors can be applied to landfills. Translating direct measurements to quantification of landfill methane is challenging because landfill emissions fluctuate frequently, sometimes even daily. It is influenced by the age and quantity of waste that is in place, the waste composition, the cover type, and location, landfill gas operations, waste placement activities, and even the weather.

These dynamic conditions impact modelling assumptions and drive emissions estimates.

Aerial emissions monitoring is gaining attention and encompasses a variety of technologies, including satellite imagery, aerial flights, and drones. Aerial emissions monitoring, however, has a limitation, as it is not continuous and only captures moments in time when emissions may be temporarily higher or lower than normal.

One area where aerial monitoring and on-ground sampling can be used for immediate benefit is in identifying the location and concentration of any emissions. This enables site operators to take immediate action to investigate and correct suspected leaks. Further work will be necessary before these technologies, however, can be used to calculate landfill methane emissions accurately. We would all benefit from additional funding to support the acceleration and progress around emissions monitoring, calculations, and reporting.

The oil and gas industry and agriculture industries have benefited from substantially greater levels of funding for their methane emissions reductions research and development in comparison to the solid waste sector, and we recommend that Congress recognize this disparity as EPA moves forward with rulemaking on landfills.

We also wish to highlight certain policies that, if addressed, could incentivize landfills to capture greater amounts of landfill methane beyond mandated requirements. Of immediate consequence is the Department of the Treasury's proposed rule on the expanded investment tax credit for qualified biogas property under the Inflation Reduction Act.

Our sector worked hard to advocate for this tax credit and has relied on its availability in planning multibillion-dollar investments in biogas processing infrastructure. We were surprised by Treasury's recent proposal to virtually eliminate landfill biogas processing facilities from credit eligibility, which would, in turn, disincentivize methane abatement solutions within our sector.

We therefore ask your support in requesting that Treasury reverse course and return to Congress' initial goal of driving economy-wide investments consistent with the Administration's climate objectives.

The landfill sector is also facing other threats to its plan to invest in technology and detect and capture landfill emissions. For example, although landfills are incentivized to capture methane emissions through EPA's Renewable Fuel Standard Program, the agency has received a petition to revisit the annual standards that it recently finalized. Granting the petition would disrupt the long-term stability needed for continued investment in landfill gas collection and renewable energy programs.

Overcoming challenges such as this are among the most significant regulatory opportunities available to EPA to incentivize landfill operators to make capital investments in beneficial use infrastructure and capture greater levels of methane emissions, thereby supporting broader climate solutions and public policy objectives.

We acknowledge that action to address climate crisis is necessary, and we look forward to working with Congress, the Administration, and other stakeholders in evaluating meaningful policy

solutions to capture greater amounts of methane that result from our industry's provision of necessary and vital public services.

I appreciate the opportunity to appear before this committee, and I look forward to any questions.

[The prepared statement of Ms. Germain follows:]

Written Testimony
of
Anne Germain, PE, BCEE
Chief Operating Officer & SVP of Regulatory Affairs
National Waste & Recycling Association
Before the U.S. Senate Committee on Environment and Public Works

Chairman Carper, Ranking Member Capito, and Members of the Environment and Public Works Committee, thank you for allowing me to testify today on opportunities to avoid, detect, and reduce landfill methane emissions. My name is Anne Germain, and I serve as Chief Operating Officer & Senior Vice President of Regulatory Affairs at the National Waste & Recycling Association, a not-for-profit trade association representing the private-sector waste and recycling industry.

Landfills protect the environment by responsibly managing society's waste. Our sector is subject to extensive federal, state, and local environmental requirements, including stringent design, operation, monitoring, and closure and post-closure standards established under RCRA as well as landfill gas collection and control requirements under the Clean Air Act. Beyond regulatory obligations, our sector has made significant advancements in landfill gas capture and clean energy production. We have invested heavily in surface cover, landfill capping, and landfill gas collection systems that meet or exceed regulatory requirements. Moreover, we closely monitor emissions from our landfills and engage in corrective actions swiftly and efficiently. We also are actively deploying infrastructure that transforms yesterday's waste into renewable energy, which can power communities, fuel vehicles, and support progress in offsetting the impacts of climate change.

Recently, a narrative has emerged that air emissions from landfills have increased. **Based on data from the EPA, however, municipal solid waste landfill air emissions have declined by nearly 45 percent between 1990 and 2021, all while landfilled waste volumes increased 5 percent during the same time period. We are proud of this progress and are not aware of any other industry which has achieved even remotely comparable improvements.** We are committed to reducing climate impacts even further, consistent with the goals of the Global Methane Pledge and the Administration's commitment to reduce methane emissions from the waste sector by at least 15 percent by 2030. Achieving these goals necessitates the development of more accurate measurement methods to quantify these emissions.

Our members are actively assessing how various aerial and ground-based methane emissions measurement methods developed for other sectors may be applicable for landfill applications. Translating direct measurement to quantification of landfill methane is challenging because landfill emissions fluctuate frequently—even daily—as influenced by the age and quantity of waste in place, waste composition, cover type and location, landfill gas operations, waste placement activities, and weather. These dynamic conditions greatly impact modeling assumptions that drive emission estimates.

Aerial emissions monitoring is gaining attention and encompasses a variety of technologies, including satellite imagery and aerial flights from manned aircraft and drones. Aerial emissions monitoring has limitations, however, as it is not continuous and only captures individual moments in

time when emissions could be temporarily higher or lower than normal. One area where both aerial monitoring and on-the-ground sampling can be used for immediate benefit is in identifying the location and concentration of site emissions. This enables landfill operators to take immediate action to investigate and repair suspected leaks. Further work will be necessary before these technologies will be able to calculate landfill methane emissions accurately, however, and we would benefit from additional funding from Congress to accelerate progress around emissions monitoring, calculation, and reporting. The oil and gas and agriculture sectors have benefited from substantially greater levels of funding for methane emissions reduction research and development in comparison to the solid waste sector, and we recommend that Congress recognize this disparity as EPA moves forward with its rulemaking effort.

We also wish to highlight certain policies that, if addressed, would incentivize landfills to capture greater amounts of landfill methane beyond levels mandated by regulatory requirements. Of immediate consequence is the Department of Treasury's proposed rule on the expanded investment tax credit for "qualified biogas property," as enacted under the Inflation Reduction Act. Our sector worked hard to advocate for this tax credit and has relied on the availability of it in planning multi-billion-dollar investments in biogas processing infrastructure. Consequently, we were surprised by Treasury's recent proposal to virtually eliminate landfill biogas processing facilities from credit eligibility and, in turn, disincentivize methane abatement solutions within our sector. We therefore ask for your support in requesting that Treasury reverse course and return to Congress's goal of driving economy-wide investments consistent with the Administration's climate objectives.

The landfill sector also is facing other threats to its plans to invest in technology to detect and capture landfill emissions. For example, although landfills are incentivized to capture methane emissions through EPA's implementation of the Renewable Fuel Standard program, the agency has received a petition to revisit the annual standards that it recently finalized. Granting the petition would disrupt the long-term stability needed for continued investment in landfill gas collection and renewable energy production. Overcoming challenges such as this are among the most significant regulatory opportunities available to EPA to incentivize landfill operators to make capital investments in beneficial use infrastructure and capture greater levels of methane emissions, thereby supporting broader climate solutions and public policy objectives.

Our sector acknowledges that action to address the climate crisis is more necessary than ever, and we look forward to working with Congress, the Administration, and other stakeholders in the evaluation of meaningful policy solutions to capture greater amounts of methane that results from our industry's provision of necessary and vital public services. I appreciate the opportunity to appear before this Committee and look forward to answering any questions you may have.



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February 3, 2024

Via Electronic Transmission: www.regulations.gov

Ms. Carolyn Hoskinson, Director
Office of Resource Conservation and Recovery
U.S. Environmental Protection Agency (28221T)
1200 Pennsylvania Ave., NW
Washington, DC 20460

Re: Draft National Strategy for Reducing Food Loss and Waste and Recycling Organics; EPA-HQ-OLEM-2022-0415

Dear Ms. Hoskinson:

The National Waste & Recycling Association (NWRRA) is pleased to submit the following comments for the Environmental Protection Agency's (EPA) Draft National Strategy for Reducing Food Loss and Waste and Recycling Organics. The NWRRA is a not-for-profit trade association representing private solid waste and recycling collection, processing, and management companies. NWRRA member companies manage around 38 million tons of yard waste and food waste each year through various beneficial use programs and disposal options.

NWRRA does not have a preferred technology solution for managing organic wastes: we look for the best available approach based on customer needs, the nature and quantity of the organics, environmental and economic sustainability goals, and markets factors. While this approach has led NWRRA member companies to acquire or invest in a range of strategies, companies, and technologies, we remain open and flexible to adjusting as conditions change.

Objective 3: Increase the recycling rate for all organic waste

A. Support the development of additional organics recycling infrastructure through grants and other assistance for all communities, especially those that are underserved.

NWRRA recommends that EPA consider the need for further funding for private sector organics recycling infrastructure upgrades as part of the agency's Strategic Actions. The vast majority of food waste in the United States are processed by private entities. Grant funding is often not easily accessible to these entities. Of the six grant opportunities highlighted in this Strategic Action, none are available to the private sector. We thus encourage EPA to

support funding streams available to the private sector for equipment upgrades and existing facilities, as well as for the development of new organics recycling facilities. This will allow for greater opportunities for cost-effective and timely improvements to the collection and sorting of organic materials.

E. Address contamination in the organic waste recycling stream.

EPA has identified addressing contamination in the organic waste recycling stream as one of its goals under Objective 3. NWRA members support reducing contamination. The expansion of food and yard waste collection programs in the past decade has led to the development and promotion of an increased number of biodegradable and compostable products. Unfortunately, there is considerable confusion in the marketplace resulting from indiscriminate use of the terms degradable, biodegradable, and compostable, and the labelling of products as biobased, biodegradable and oxo-biodegradable. The fact that all products certified as compostable per the governing ASTM standard often do not break down at industrial composting facilities further adds to the level of confusion. As such, NWRA advocates that part of this effort should include developing labeling standards for compostable packaging and ensuring that food contact packaging is compostable.

To reduce contamination in the organic waste recycling stream, some states are pursuing stricter mandates on the labeling of compostable products. These laws impose stricter requirements on which products or packaging that can be labeled as “compostable.” Currently, the FTC Green Guides provide some guidance on how products and packaging can make a compostable claim, but state compostable product labeling laws typically have more stringent requirements than what is required in the FTC Green Guides. NWRA recommends that EPA support proper labeling of compostable products by recognizing the labeling issues and compiling a list of state laws and regulations that provide alternatives to the standards contemplated in the Green Guides.

Of course, EPA should also encourage the FTC to adopt stricter requirements on the use of the term “compostable.” NWRA recommends that EPA encourage FTC to establish guidelines limiting the use of the term “compostable” to food contact products, food packaging, and other single-use or food-soiled items that are used to facilitate food waste collection and processing. Products such as food waste collection bags and bin liners along with food packaging and service ware that does not need to be separated from food scraps as part of the recycling program, are intended to assist with convenience and mitigate the “yuk factor” that is associated with food waste diversion/collection. Many consumers do not want to directly handle organic food waste and the ability to use compostable bags and bin liners increases the likelihood these consumers will participate in a food waste diversion program. Doing so provides options for people, institutional and commercial food service providers to streamline source separation and collection in some applications. To that end, claims of compostability should be limited to products that are designed to touch, contain, or carry a food product, scraps, or other organic materials, such as yard trimmings, that can be collected for organics recycling and are accepted by organics recyclers.

To the extent that the EPA is considering policies that are expected to increase the quantity of compostable packaging and products beyond de minimis amounts, it is important that EPA consider the capital investment required to adapt to this change in feedstock. Composting and anaerobic digestion sites are currently meant to operate with the vast

majority of material being organic matter such as food and yard waste, and existing sites may need to restrict compostable packaging or make significant investments in new equipment or operating practices in order to ensure that the facilities can operate as designed. Our industry's goal is to divert and process organic wastes. Food-related packaging and products that assist with organic waste diversion should be the focus of policy programs and incentives. The amounts accepted should also be limited to the bare minimum required to assist with delivering the materials to our facilities. Many biodegradable and compostable products that are unrelated to food waste diversion create confusion regarding source separation and could instead be included in paper and other commodity recycling programs. It is also critical to restrict items unrelated to food service (e.g., phone cases, mailer pouches, shoes) currently labeled "compostable" but which do not facilitate diversion or degradation of food waste.

ASTM standards (e.g., D6400 and D6868) should be part of the definition of compostable. However, the current lab testing criteria by itself is insufficient. Our members' experience is that lab testing timeframes often do not correlate to full-scale composting times or conditions. Compost manufacturers strongly advocate for field testing that directly demonstrates a compostable material will break down in a representative commercial facility as an additional requirement to make compostable claims. The mesh bag method used by the Compostable Field-Testing Program (CFTP) or the similar methodology developed and used by the Compost Manufacturer's Alliance prior to allowing the use of the "Composter Approved" trademark are examples of appropriate field test protocols that could be incorporated into an ASTM standard or similar standardized field test prior to allowing compostable claims.

Items that do not break down in a timely manner are either collected for disposal or contaminate end products. Conventional plastics and those making a compostable claim are considered foreign matter in compost products in most jurisdictions and may cause products to fail compost quality tests. Therefore, it is recommended that "compostable" become a term restricted in its use with a definition that should include both lab and field-testing criteria prior to allowing compostable claims.

Further the restrictions on emerging contaminants, particularly the 100 ppm total fluorine limit and the requirement to state there is no intentional addition of per- and polyfluoroalkyl substances is not adequate to protect compost and soil quality. Requirements to avoid fluorinated compounds exceeding acceptable limits in compost must lie with the manufacturers of packaging and compostable products, and the burden must not be placed on organics recycling facilities who are passive receivers, do not add these compounds, and have no feasible method of reducing their concentration through processing.

Objective 4: Support policies that incentivize and encourage food loss and waste prevention and organics recycling

Food waste diversion mandates should account for existing organics processing infrastructure. Specifically, any such mandates should only apply to generators that are located a reasonable distance to the nearest organics recycling facility. Organic materials differ greatly from trash and recycling in that they are heavy and wet drastically increasing the "wear-and-tear" on collection vehicles and transporting over long distances is

EPA Food Waste Strategy
February 2, 2024
Page 4 of 4

impractical. Additionally, bans should account for the nearest facility's capacity to accept the generators' food waste. In the event such facilities do not exist, mandates should provide for waivers until such facilities are operational.

Our members are involved in managing food waste from collection to processing and disposal. We appreciate the opportunity to comment on this draft. If you have any questions about our recommendations, please do not hesitate to contact me at agermain@wasterecycling.org.

Very truly yours,

A handwritten signature in cursive script, appearing to read "Anne M. Germain".

Anne M. Germain
COO & SVP Regulatory Affairs

Senate Committee on Environment and Public Works
Hearing Entitled "Avoiding, Detecting, and Capturing Methane Emissions from Landfills"
January 31, 2024
Questions for the Record for Ms. Anne Germain

Chairman Carper:

1. Please describe any priority actions from the Environmental Protection Agency's National Draft Strategy for Reducing Food Loss and Waste and Organics Recycling that you believe would support more robust organics recycling and composting in the U.S.

NWRA has provided comments to EPA on their organics strategy which are attached.

Any alternative end of life management for food waste depends on adequate infrastructure being in place. In addition, food waste diversion should be addressed first with large generators and subsequently addressing mid-sized to small generators as infrastructure capacity allows. Because large generators will likely be commercial entities, they are also serviced by private sector collection services and often, private sector processing facilities. To incentivize additional infrastructure, therefore, we encourage support for private sector infrastructure development. Further, we support more research into any challenges associated with managing food waste from collection to processing.

For existing composting facilities, contamination is an ongoing problem and accepting food waste increases contamination significantly. But the issue with food waste contamination is not related to food itself, but instead related to packaging that arrives with food waste. A significant amount of this packaging claims to be "compostable." While some of packaging is truly compostable, other "compostable" packaging does not breakdown adequately. These products often look-alike making it hard to determine which ones are which. Composters trying to process large quantities of material often end up treating all questionable products as contamination. For example, in California, 20 out of 24 composters that responded to a survey stated that plastic-containing material including plastic-lined fiber products claiming to be recyclable are treated as contamination. Composters are attempting to make a marketable product that will adversely be affected due to quality considerations, potential loss of certification and the problem with look-alikes between truly compostable and non-compostable packaging. Our recommendation was for EPA to recommend to the FTC that it adopt stricter requirements on the term "compostable."

In addition, we encouraged limiting the term, "compostable," to food-contact packaging. Soiled food-contact packaging can impact its desirability in the recycling bin. However, non-food-contact packaging and products are less likely to become soiled. Rather than potentially contaminating the compost system, manufacturers of non-food-contact packaging and products should use recyclable packaging. The EPA should ensure that FTC is aware of the practicalities of recycling and encourage appropriately labeling for consumer awareness.

2. What additional research do you believe needs to be undertaken in order to further improve the performance of methane detection systems for landfills, and to reduce the cost of landfill methane monitoring?

As stated in my prepared remarks, NWRA believes EPA should support research into translating emissions captured from aerial and fixed technologies into site emissions taking into account limitations associated with landfill dynamics.

In addition, we think EPA should conduct field research on degradation of materials over time in various weather and site conditions to improve the accuracy of their models.

3. How will data collection, like the studies included in the Recycling and Composting Accountability Act, help increase recycling and composting rates, which can help avoid methane emissions that come from landfills?

The studies in the RCAA will assist in improving diversion from landfills which will reduce the total tonnage entering landfills. Fewer tons entering the landfill will ultimately mean less landfill gas is generated.

While these studies focus on diversion and are necessary for the recycling industry, we still recommend that landfill-specific studies be undertaken to assist the industry in reducing its emissions further than the 45% it already has reduced.

4. Please describe in detail the costs to upgrade landfill methane capture infrastructure, identifying specific areas in need of funding to advance sustainable waste management.

According to EPA's LFG energy project development handbook,¹ a typical project would cost approximately \$1.3M to construct and about \$220k to operate annually. Beneficial utilization of the landfill gas, however, can be significantly more expensive – ranging from \$3-16M.

NWRA recommends that in order to promote landfill gas utilization, the IRS should expand their proposed definition of "qualified biogas property," to allow equipment that concentrates the gas to pipeline quality to be considered functionally interdependent. This would accelerate the development of beneficial landfill gas projects.

Senator Boozman:

1. Based on EPA's newest reports, food waste is a major source of methane from landfills and, in 2018, 24% of material sent to landfills was food. We also know food waste happens across the country, both in rural and urban areas, and solutions should be tailored to meet local needs. How can improvements be made to increase composting and recycling in rural communities to keep food waste out of landfills?

¹ EPA, LFG Energy Project Development Handbook, January 2024.
https://www.epa.gov/system/files/documents/2024-01/pdh_full.pdf

Unlike recycling that requires end markets that may be far from the point of generation, food waste composting and anaerobic digesters can be place anywhere. Rural areas may benefit by proximity to agriculture where anaerobic digesters can serve both food waste and agriculture waste generating needed fuel for pipeline, natural gas vehicles or conversion to electricity. Similarly, compost can be a local process that can easily be implemented in a rural area. Agricultural extension services often are well equipped to provide technical support for compost operations. However, diversion efforts will require the development of additional infrastructure to support acceptance of food waste. While technically this is possible in both urban and rural settings, practically speaking, the costs may be unsupportable in more rural areas. That being said, support should be provided to encourage infrastructure development.

Senator CAPITO. Thank you. Thanks to all three of you. In the absence of our Chairman, I will take my license and begin to ask the questions.

Ms. Germain, I addressed in my opening statement some of the concerns from small municipal landfills. Just give me a lay of the land here, what is the percentage, if you looked at the whole numbers of landfills, what numbers of those are municipal, percentagewise, approximately?

Ms. GERMAIN. It is about 50/50.

Senator CAPITO. 50/50.

Ms. GERMAIN. Tom said that there are about 1,200 landfills in the Country. About half of them are publicly owned, and about half of them are privately owned. If you look at the volume of material going into the landfills, however, it switches; about two-thirds of the waste goes to privately owned landfills, and about a third goes to publicly owned landfills. That shows you, basically, that the publicly owned landfills are significantly smaller than privately owned.

Senator CAPITO. Okay, so let us get into what kind of, and we have heard a lot about some of the development of technologies of capturing, not just capturing, but also measuring and monitoring. What kind of challenges would that bring to a small municipal landfill? Are they already doing it if they are complying with the EPA regulations, which I am sure they would want to do?

Ms. GERMAIN. Right. The New Source Performance Standards (NSPS) does have size limitations, so landfills below a certain size threshold are not subject to the new source performance standards, so many of the smaller landfills may not be subject to those rules at all. Changing the rules to focus on extending it to smaller landfills would, of course, subject them to control and capture requirements that they might not currently be doing.

Senator CAPITO. Okay.

Tom, let me ask you a question, back to my first question. Percentagewise, kind of the lay of the land, then if you looked at total emissions going out from what you said, 1,200 landfills, are more of them going out from the private, are the emissions equivalent, do you see what I am trying to ask? Are the emissions more at the small and municipals, or because maybe they have not made the provisions? Can you clarify that a little bit?

Mr. FRANKIEWICZ. Yes. On that exact percentage, I would have to get back to you.

Senator CAPITO. It does not have to be exact.

Mr. FRANKIEWICZ. No, I can not speak to which percent has higher emissions. I can, just following up on, in terms of the types of technology for controls, things like gas collection, improved cover, best practices for operations and maintenance, the types of things that are required between gas collection and monitoring for the NSPS are generally tried and true technologies. Those technologies for controlling emissions at a site are not new technology and are deployed both at municipal and private landfills.

Senator CAPITO. Right. I mean, they are obviously all at a cost, and I think that is in a lot of different ways.

Is there an economic, Anne, I will go back to you, is there an economic incentive in capturing and selling methane, and what are some of the regulatory obstacles to that?

Ms. GERMAIN. It is very much dependent on the type of facility. Right now, the Section 48 tax credits that I referred to in the Renewable Fuel Standard (RFS) do provide some incentives for capturing outside of the regulation, and then basically utilizing.

Depending on the landfill's location, they might be able to utilize the gas in some way, but many of them do not have any access to be able to create some energy from the gas, so they would have to make it pipeline quality. Currently, the way the Section 48 tax credit regulations are written by Treasury, they would disqualify gas upgrading equipment necessary to make it pipeline quality.

Senator CAPITO. Yes. Okay, Senator Ricketts?

Senator RICKETTS. Thank you, Madam Chair. First of all, I would like to ask for unanimous consent to enter a letter from the American Biogas Council, which outlines their concerns and implications with the Inflation Reduction Act's Section 48, just referenced here, expansion to include biogas as an eligible technology and the exclusion of cleaning and conditioning equipment.

Senator CAPITO. Without objection, so ordered.

[The referenced information follows:]



January 31, 2024

The Honorable Tom Carper
Chair, Environment and Public Works
United States Senate
513 Hart Senate Office Building
Washington D.C. 20510

The Honorable Shelley Moore Capito
Ranking Member, Environment and Public Works
United States Senate
172 Russell Senate Office Building
Washington D.C. 20510

Dear Chairman Carper and Ranking Member Capito,

On behalf of over 400 companies in all parts of the biogas supply chain, the American Biogas Council commends Chairman Carper and the Committee for convening this hearing, *Avoiding, Detecting, and Capturing Methane Emissions from Landfills*. The American Biogas Council represents the voice of the U.S. biogas industry, dedicated to maximizing carbon reduction and economic growth using biogas systems. Our members are leading the way to a better future by maximizing all the positive environmental and economic impacts biogas systems offer when they recycle organic material into renewable energy and soil products. As such, we are concerned the Department of Treasury's Notice of Proposed Rulemaking (NPRM) for Section 48 of the Internal Revenue Code threatens to undermine the expanded federal support for biogas and methane emission reduction included in the Inflation Reduction Act (IRA).

As part of the IRA, the Section 48 Energy Credit (26 U.S. Code § 48) was expanded to include Qualified Biogas Property as an eligible technology solution for the investment tax credit (ITC). This expansion can offer significant potential to reduce methane emissions by providing an ITC to turn raw biogas captured from landfills, as well as animal and crop waste at farms, feed lots, and food processing facilities, into a useful fuel for U.S. homes and industry. The expanded credit targets biogas that is sold or otherwise used productively and excludes disposing of the raw biogas by burning it. The ITC not only moves landfill gas to new markets, but it also incentivizes the diversion of organic materials, like food waste, from landfills. In this way, the expanded tax credit both manages methane from existing sites and supports new recycling systems.

The IRA specifically instructs "cleaning and conditioning" equipment to be included as eligible under the new investment tax credit. Including this gas upgrading equipment is vital since all raw biogas created from an anaerobic digester or collected from a landfill, without cleaning and conditioning, **cannot** be used in commerce in any way; it cannot be stored, transported, dispensed, or deployed as a fossil natural gas substitute. The only use for raw biogas that is not cleaned and conditioned is on-site combustion.

Released in November 2023, the Department of Treasury's NPRM for the expanded tax credit inexplicably excluded this essential "cleaning and conditioning" equipment from the definition of property that qualifies for the ITC. This exclusion clearly contradicts the explicit language of amended Section 48, contradicts the direct intent of the Congressional authors, and will severely limit the provision's potential to stimulate the rapid expansion of this important clean, renewable fuel.

Cleaning and conditioning equipment is typically the most expensive part of turning raw landfill gas or raw biogas into a useful, pipeline quality product. Without the support of this tax credit, many projects turning waste biogas into a valuable renewable fuel will be economically prohibitive, especially those at



smaller farms and landfills. This narrow interpretation will undermine many planned biogas projects where cleaned and conditioned biomethane would be used as a fuel for heavy duty trucks, provide process heat to a manufacturer, serve as a feedstock for hydrogen, or heat homes and businesses – the very end uses enabled and intended by Congress.

If finalized as proposed, we are concerned about impacts throughout the biogas supply chain including but not limited to:

- Projects that will not move forward due to the agency's interpretation of the guidance;
- Beneficial uses of biomethane that are now uneconomical;
- Impacts on small agriculture projects;
- Impacts to jobs in rural communities; and/or
- Climate impacts of biomethane (avoided methane emissions)

As the Committee considers ways to avoid, detect, and capture methane emissions from landfills, we ask you to consider the environmental impacts at farms and landfills where, without the inclusion of this key cleaning equipment, these entities will be forced to flare potent greenhouse gases into the atmosphere. The currently proposed restrictive interpretation of the scope of the Section 48 ITC would cause many projects to be lost, undermining and setting back this Committee's efforts to reduce methane emissions from landfills and other sources to help address climate change.

The American Biogas Council looks forward to working with Chairman Carper, Ranking Member Capito, the Committee, Congress, and the Administration to ensure farmers and landfill operators can continue to reduce methane emissions and participate in the valuable renewable fuels market. We welcome the opportunity to participate in an open dialogue to further discuss how Congress can act on this important issue.

Copied to:

Senator Benjamin L. Cardin
 Senator Bernard Sanders
 Senator Sheldon Whitehouse
 Senator Jeff Merkley
 Senator Edward Markey
 Senator Debbie Stabenow
 Senator Mark Kelly
 Senator Alex Padilla
 Senator John Fetterman

Senator Kevin Cramer
 Senator Cynthia Lummis
 Senator Markwayne Mullin
 Senator Pete Ricketts
 Senator John Boozman
 Senator Roger F. Wicker
 Senator Dan Sullivan
 Senator Lindsey Graham

Sincerely,

[The American Biogas Council](http://www.americanbiogas.org)

Senator RICKETTS. Nebraska has tremendous examples of utilizing methane from landfills to generate renewable energy. For over 20 years, the Elk City Station in Douglas County has utilized methane from the local landfill. That is about a six megawatt project.

In 2014, the city of Lincoln and Lincoln Electric System had partnered on a landfill gas to energy project to harness the methane gas produced in the city of Lincoln's Bluff Road Landfill, and that is about a 4.8 megawatt project. The city of Lincoln utilizes about 80 megawatts annually, and so this is a great way to diversify their energy generation.

But landfills are not the only opportunity. Our livestock producers are increasingly working toward capturing methane from their facilities to use for energy generation. The Federal Government needs to continue to support voluntary emissions reductions technologies to make sense for communities and producers and not penalize our critical utilities.

Now, we talked about, you mentioned Section 48, Ms. Germain. Section 48 of the IRS code now provides for an investment tax credit to turn raw biogas captured from landfills and, of high importance to my State, created from animal and crop waste at farms and feedlots and food processing facilities into useful fuel. In fact, Nebraska has three times as many cattle as it does people, so this is kind of a big deal for us. We are the Beef State.

This new provision targets biogas that is sold or otherwise use productively and excludes disposing of the raw biogas by burning it. The new language also adds that cleaning and conditioning equipment is covered by the new investment tax credit.

This addition is vital, since raw biogas created from a farm or a feedlot, anaerobic digester, or collected from a landfill without cleaning and conditioning, as already pointed out, cannot be used in commercial fuel, put in a pipeline, or stored. It essentially must be burned onsite, and, of course, that is the very outcome the new provision is trying to avoid.

Foolishly, the Department of the Treasury last month issued proposed rules for biogas investment tax credits that inexplicably exclude the cleaning and conditioning equipment necessary to upgrade raw biogas so that it can be stored, transported, and used as renewable fuel. Treasury is proposing to deny this tax credit to biogas cleaning and conditioning equipment needed to take the raw biogas and turn it into pipeline quality bio methane.

This equipment is typically the most expensive part of turning raw landfill gas or raw biogas created from farm digesters into useful, renewable product envisioned by the amendments to Section 48. Without this support, many projects to transform waste biogas into valuable renewable fuel would be uneconomical, especially at those small and rural landfills.

I would also point out the Administration is constantly doing things that are counter to the goal of reducing the impact to the environment. For example, since you mentioned the Renewable Fuels Standard, they have set Renewable Volume Obligations (RVO), for example, for biodiesel and renewable diesel below the industry's ability to actually produce that, what we are currently producing right now, thus creating havoc in that marketplace.

Also, flex fuel vehicles, which burn higher percentages of ethanol, reduce the impact on the environment. They do not get the same tax credits as EVs and so forth, so we are constantly seeing that.

Anyway, Ms. Germain, do you agree that without incentives for biogas cleanup equipment, many landfills will have an economic challenge in investing into the necessary and expensive equipment needed to process raw landfill gas into a commercial renewable gas?

Ms. GERMAIN. Yes. We definitely agree with that. That is one of the reasons why we submitted a letter to Treasury about changing the definition of qualified biogas property.

Senator RICKETTS. Great. In other words, the Administration's strained interpretation of the new biogas provisions will, in fact, strand this valuable fuel because it cannot be moved offsite and to homes, business, and industry that would welcome and pay a premium for renewable, natural gas or advanced electrical technologies.

Ms. Germain, do you agree that, to ensure these waste streams can contribute to the Nation's energy needs, anaerobic digesters must be coupled with biogas upgrading equipment to turn raw biogas into a useful commercial fuel?

Ms. GERMAIN. The viability of anaerobic digesters are dependent on being able to utilize credits. That will incentivize those facilities to be able to be developed. We need the infrastructure if we are going to be looking at increased biogas production from anaerobic digesters.

Senator RICKETTS. Since the Administration is denying the investment tax credit to the key equipment to allow digester systems to create a useful and lucrative energy product, do you agree that the Administration's position will result in fewer digesters being built and, therefore, more organic material ending up in landfills?

Ms. GERMAIN. Yes.

Senator RICKETTS. Great. Thank you, Madam Chairman.

Senator CAPITO. Thank you.

Mr. Chairman.

Senator CARPER.

[Presiding.] Thanks. Thank you for chairing. How is it going? We all serve on different committees. Sometimes we are needed to be in two or three places at once. Thanks for bearing with me, and thank you, Senator Capito.

I am going to ask a question of Dr. Scarpelli. This deals with uncovering landfill emissions. One of the reasons we know the scale of methane emissions from landfills is thanks to the extensive work that is done by researchers using NASA technology to detect and to quantify these emissions.

For example, Dr. Scarpelli, your organization conducted, I am told, aerial surveys looking for methane sources in California and found that certain landfills were the largest observed emissions sources. Please describe for us how Carbon Mapper adapted this new technology for the purposes of detecting emissions, and talk with us, share with us some of the results of your studies that your organization and others have produced.

Ms. SCARPELLI. Thank you for the question, Senator. Thank you for the comments about the history of the technology. Carbon Map-

per, the technology we use, was originally developed at NASA Jet Propulsion Laboratory. We still interact with NASA Jet Propulsion Laboratory in a couple of different ways. As you mentioned, the aerial technology that we use includes the Airborne Visible Infrared Imaging Spectrometer—Next Generation (AVIRIS NG), which is an aircraft that was designed—

Senator CARPER. Say that again, the what?

Ms. SCARPELLI. It is AVIRIS NG. It is the name of the aircraft. It is a NASA JPL aircraft. That is what we fly.

Senator CARPER. JPL?

Ms. SCARPELLI. Jet Propulsion Laboratory. That is one of the aircraft that we fly. It has what we call an imaging spectrometer, that is the instrument on board, and that is also on the NASA Earth Surface Mineral Dust Source Investigation (EMIT) instrument on the International Space Station, it is also an imaging spectrometer. That is the technology that we use.

When we go and fly on an aerial campaign, we work with the stakeholders as well, so that is where we are trying to extend, not just to develop the technology for research purposes, but also engage with the people that can use the data on the ground.

Then, we are also part of a broader coalition of partners that includes NASA Jet Propulsion Laboratory and our commercial partner, Planet Labs and other partners. This is part of a broader coalition to launch satellites.

These satellites are actually developed, originally a new generation of these imaging spectrometers. The idea there is that eventually, we would have a satellite constellation that could do biweekly to daily revisits of sites globally across the world. Then, Carbon Mapper's goal is to get that data into the hands of people on the ground who can use it. We have had positive experiences, including in the State of California, where we have worked with stakeholders to get the information to the operators so they can take voluntary action to mitigate emissions.

Senator CARPER. I want you to go back on what you just said, and compress it into one paragraph, and just dumb it down. Just make it as clear as you can, please. Go ahead. Sometimes, I say, how would you explain this to your grandmother, or your grandfather? Go ahead.

Ms. SCARPELLI. Okay. The phrase we like to use is that you can not manage what you do not measure, for methane.

Senator CARPER. Yes, I have used that a few times, yes. That is a good one.

Ms. SCARPELLI. Yes. It is very accurate, I think, and it applies to landfills, as our goal is mitigation. At landfills, you can use it for beneficial use, as well. Anything that we can provide with these technologies to increase gas capture and to reduce leaks is what our goal is.

Really, the key there is these technologies can provide technical assistance to operators. We just want to provide and get that into jurisdictions that maybe can not afford an aerial campaign on their own, so satellites, because they have this routine monitoring, provide that opportunity.

Senator CARPER. Let me followup with that. How do you validate the results of the satellite and the aerial surveys? In other words,

how do we know whether the results accurately quantify the observed methane emissions?

Ms. SCARPELLI. We have participated with the technology in various what we call controlled release experiments. These are validation studies where you release a known amount of methane, and then different technologies can observe that release. Then you try to, you estimate it using your own processing steps. Then, you compare it to the known amount of methane that is being released and see if you can produce back that—

Senator CARPER. When you say “you,” who is “you”?

Ms. SCARPELLI. Carbon Mapper would participate with an aircraft instrument, or you can also have different technologies all participate at the same time. Some of these are in the private sector. Some of these are academic institutions. The idea there is that we do not know the known release, and so we have seen that, in these experiments, we are able to reproduce the known release rates of methane.

Senator CARPER. Thank you.

Senator Markey, welcome. Good to see you.

Senator MARKEY. Thank you, Mr. Chairman.

In Massachusetts, we have a rule that any business or organization that generates more than half a ton of food waste a week can not put all that food in the garbage. The ban has not only reduced greenhouse gas emissions, but also saved space by keeping millions of pounds of food out of landfills. Thousands of Massachusetts businesses have begun donating unused food to shelters and to food banks across the State. Our State’s food waste rule accomplished this win-win scenario while also creating over 500 jobs and generating \$175 million in economic benefits during its first two years.

Mr. Frankiewicz, can you elaborate on the community and economic benefits that organic waste prevention and organics recycling programs have had across the Country?

Mr. FRANKIEWICZ. Thank you, Senator Markey. Excellent question. We really look at organics diversion and landfill gas control as being a two-pronged approach. I know sometimes it might seem odd to talk about these two different things at one time, but you are basically working upstream and downstream to reduce landfill gas emissions.

When it comes to organics diversion and food loss, food waste prevention, there are really, I think, several significant benefits. Of course, you have the climate benefit, which is global. Generally speaking, for every 6,000 tons of methane, there is 6,000 tons of methane that is avoided for every one million tons of food waste that is diverted.

Senator MARKEY. Is Massachusetts’ program a model?

Mr. FRANKIEWICZ. It is definitely a great example of a State—

Senator CARPER. That is a leading question. Strike that one from the record.

Senator MARKEY. Your Honor, I am going to bring that up on appeal.

[Laughter.]

Mr. FRANKIEWICZ. It is a great example of a State taking proactive action that both has global benefits with methane reductions, but most of those benefits are actually experienced locally.

On average, Americans spend \$1,300 a year for groceries that is just wasted. By avoiding that food loss, food waste, Americans are saving money on their monthly grocery bills.

Senator MARKEY. Yes, absolutely. That is great. By the way, Delaware is the First State, but not in everything, Okay? Massachusetts can be first in something, maybe.

[Laughter.]

Senator MARKEY. Mr. Frankiewicz, what role can the EPA play in scaling up similar organic waste prevention and recycling programs nationwide? What is the recommendation to the EPA that you have?

Mr. FRANKIEWICZ. As you know, or as you may know, EPA has done a lot of great work researching both the methane impacts from food loss, food waste, but also the community benefits. They currently have a strategy out right now that is out for comment, but EPA has shown great guidance in terms of researching best practices for this. This is something that is often implemented at the local level, at the community level, at the State level, there is a lot that can be done in terms of grant support and also technical capacity.

There are grants out right now, the Society for Worldwide Interbank Financial Telecommunication (SWIFR) grants that are supporting communities and implementing programs, but there is still a lot that can be done in terms of developing best practices and capacity building and technical assistance, because money is part of it.

Senator MARKEY. We will work with the EPA on that.

Mr. FRANKIEWICZ. Yes.

Senator MARKEY. That sounds like a great recommendation.

Landfill operators in Massachusetts, like New Bedford's Landfill Gas-to-Energy Project, are showing that gas collection and monitoring systems are a cost effective way to reduce greenhouse gas emissions. LoCI Controls, a startup founded by two MIT alumni in Cambridge, has developed low cost lunchbox sized sensors that have reduced landfill emissions by four million tons of carbon dioxide equivalent in just a few years. These Massachusetts projects and technologies prove it is feasible to do better than the status quo.

Mr. Frankiewicz, again, what are some of the simple strategies that all landfill operators could use to reduce their methane emissions today?

Mr. FRANKIEWICZ. Senator Markey, I am glad you brought this up.

When you talk about the costs of different technologies, not only are many of these technologies tried and true, having gas collection operation practices for soil cover, improving working face, having a smaller, tighter working face, but when it comes to gas collection and the relationship to energy projects, that is what you call a win-win solution.

Because generally, using this improved technology for automated well-tuning, where currently it is typically done manually, you generally see recovery improvements of 10 to 20 percent. That increased recovery of methane is increased revenue for an energy

project and often pays for the cost of that collection system in about a year.

Senator MARKEY. It would also reduce odors, as well.

Mr. FRANKIEWICZ. Yes, that is something I think that, we talk about odors, we talk about methane, we talk about toxics. Landfill gas is a stew of different carbon dioxide and water, hydrogen sulfide, a smog-forming compounds. When you reduce methane, you are reducing all of those other things, as well.

Senator MARKEY. Thank you. Thank you, Mr. Frankiewicz, and thank you, Mr. Chairman.

Senator CARPER. Thanks for those questions.

Senator Cardin, welcome. Good to see you.

Senator CARDIN. Thank you.

Before Senator Markey leaves, let me just quote from Maryland Code Environmental Article 9, Section 1724.1, our Maryland law: any person or business or cafeteria that produces more than two tons of food residual in a given week must ensure organic waste is separate and diverted from landfills.

I just want you to know, Maryland is very much in the forefront here. Senator Carper joined me in a visit to the organic recycling facilities that we have in the State of Maryland that operate efficiently in reducing energy and producing safe fertilizer materials from organic waste.

So I just wanted to underscore the point that Senator Markey has made. Landfills produce a lot of methane emissions, and we can do a better job of keeping things out of landfills, so thank you for your leadership on that issue in Massachusetts. We want you to know that Maryland and Massachusetts have more in common than just the first letter of our names.

Let me also just point out the fact, which is pretty obvious, and that is, in my State of Maryland, landfills represent 40 percent of our methane emissions. That is a large amount.

The other issue here, Mr. Chairman, that I think is very important, and I want to compliment our Chairman and Ranking Member, we have done a lot on methane emissions reductions. Thank you for what you have done, and the leadership on this committee was very instrumental in the Bipartisan Infrastructure Package and the other bills that we have been able to pass, including the Inflation Reduction Act, that have dealt with methane reductions. I think we have a proud record in this committee.

But this is also a matter of environmental justice. I know where landfills are located. These are traditionally underserved communities. They pay a heavier price because of the location of the landfill. Anything we can do to mitigate the damages caused by landfills or reduce the amount of material that needs to go into landfills helps communities that have traditionally been underserved.

In my State, we have taken major steps. We have a strong regulatory system in regard to landfills. We do covering issues. We do a lot to mitigate the impact of landfills.

I guess my question is, to the panel, we see States are doing good things. Is there a way that we can have stronger Federal policies that partner with the States, giving them the incentives they need in order to take more aggressive action to prevent the negative impacts of landfills as it relates not only to methane emissions, but

to the other concerns that are raised? Why do not we just go right down the line?

Mr. FRANKIEWICZ. Sure. Senator Cardin, I want to commend Maryland on their efforts to lead, both on one thing, with Maryland and Washington State both, they have taken this dual-pronged approach of increasing stringency of landfill gas regulations while encouraging organics diversion, and that is really the best way to do these things.

You mentioned landfills as an environmental justice issue. I think that is an important point. More than half of landfills are located within a mile of disadvantaged communities. I think that is also a reason, while some States have shown leadership in moving forward on these programs, not all have, and that is where you really need strong Federal standards, both for increased landfill gas control. As I mentioned, when you reduce landfill gas emissions, you are also reducing toxins, smog-forming pollution, and odor.

Also, there is more that the Federal Government could do to support organics diversion and treatment. That is really where you see some of the greatest community benefits, as well, both in terms of avoided food loss and waste that impacts people's budgets, but also composting and composting facilities, generally speaking, create six jobs for every two and one job that is created for landfilling and incineration, respectively.

Senator CARDIN. Dr. Scarpelli.

Ms. SCARPELLI. Thank you for the question, Senator. We have heard here today that reducing methane emissions can help with community benefits, both in terms of odor and community health, because there is often the pollutants co-emitted with the methane. Speaking from a monitoring perspective, we have seen that these monitoring technologies can help find leaks and mitigate them quicker.

In terms of Federal programs, I think the key here is we need to scale up the use of these technologies. Having public funded grants that are competitive for the technologies to be scaled up, and providing jurisdictions with access to those technologies and that technical assistance in jurisdictions where they would not necessarily be able to get that on their own. I think that, from a monitoring perspective, would really be key.

Senator CARDIN. I have a very generous Chairman. I am sure he would give me an extra few minutes, Ms. Germain, if you would like to make a response.

Senator CARPER. The Senator's time has expired. Not really. Go ahead.

[Laughter.]

Ms. GERMAIN. Sure. One of the things to recognize when we are looking at some of these food waste diversions is to understand that we currently, the infrastructure that is in place for composting and anaerobic digestion facilities, there is just not enough of them to be able to take all the potentially diverted materials. We need to focus on what we can do to improve that infrastructure, and also to focus on the quality of the materials.

One of the things some of our members own and operate are anaerobic digestion and composting facilities, and just like you are

probably already aware with recycling, we are dealing with a lot of contamination in our composting and our anaerobic digestion facilities. We want to make a viable product that can be utilized as a soil amendment. In order to do that, we need to ensure that we have high quality material that is not contaminated with material that does not belong in there.

We know that a lot of manufacturers are trying to take food contact packaging and claim that it compostable, but yet, a lot of this so-called compostable packaging really does not compost in our systems. It requires extra steps and a lot of effort to try and remove it and make a clean-looking product.

We are recommending to EPA as part of our comments to their organic strategy that they really require not just lab standards, but field testing of any packaging that claims compostability, and that there should be some standardization on labeling before people can claim that their products and packaging can be composted.

Senator CARDIN. Thank you very much. Thank you, Mr. Chairman.

Senator CARPER. Thank you, Senator Cardin. Thanks for your faithful attendance here and for helping to lead a good fight.

I see a couple of other Senators, I think, are on their way trying to get here from other assignments. One of them is Senator Merkley. Before he gets here, I am going to ask another question or two, and when he shows up, we will recognize him.

With that, Mr. Frankiewicz, I know you have talked about the interplay between efforts at the State and the Federal levels to reduce methane emissions from landfills. You mentioned in your testimony that EPA is required to revisit the Clean Air Act's Section 111 standards for municipal solid waste landfills in August of this year. Is it August of this year? I think it is. That is a question. Yes, take my word for it; it is August of this year.

Mr. FRANKIEWICZ. I believe it is August, but I might have to get back to you on that.

Senator CARPER. There you go.

Let me ask a couple of questions that I think followup on your conversation with Senator Markey. Would you please expand on how both organic waste diversion and EPA's methane emission regulations work together to reduce the methane emissions associated with landfills?

Mr. FRANKIEWICZ. Yes, sure. Thank you, Senator Carper. That is an excellent question.

As I mentioned earlier, I think Dr. Scarpelli and I have both mentioned this two-pronged approach, and that is because the methane comes from the organic matter that decomposes in the landfill. Once it is there, the way to control it is with gas collection systems, systems of wells and blowers that suck up the landfill gas and typically burn it then in a flare. The best way to control landfill gas emissions, ultimately, is to keep those organics out of the landfill. Once they are in there, they can decompose, creating methane for up to 50 years.

It is not really a matter of doing one or the other. You really have to do both. That is why States that have kind of taken a two-pronged approach is a really practical way to do this, but implementation has been uneven. Really the best way to have a com-

prehensive approach is for EPA to take on both revisiting its landfill gas standards, the Section 111 standards that you mentioned, this summer, but also really leaning into organics diversion in parallel.

Senator CARPER. Okay. We have been joined not by Senator Merkley, but by Senator Whitehouse. We are happy to turn it over to you. I have asked questions and Senator Capito has asked her questions, and if you are ready, Senator Whitehouse, you are recognized. Glad you are here.

Senator WHITEHOUSE. Thank you very kindly. I crossed Senator Merkley; he was in my Budget hearing. Everybody has a lot going on today, but I am grateful for this hearing, and I appreciate the witnesses being here.

Dr. Scarpelli, let me ask you particularly about the methane tracking and spotting technology that is out there now that we have satellites that can detect methane leaks and geolocate with great precision the sources of those leaks. Is there anything about a landfill that makes it harder to detect by satellite than say, a gas pipeline leak?

Ms. SCARPELLI. Thank you for the question, Senator. Landfills are complex engineered systems, and so one of the main differences in terms of detecting leaks is that it is a large area and there are many potential points that leaks could be coming from, whereas in an oil and gas well, there is specific infrastructure that are the leak points.

So that is why it is really key to have comprehensive monitoring. You want to be able to see across the facility and also there are gas facilities that are maybe capturing the gas and sending it to pipeline. You can have leaks across different surfaces of the landfill, the actual wells collecting it on the landfill. There are all of these potential sources across a large area, so it is really important to map that whole area for potential leaks.

Senator WHITEHOUSE. You can at least identify that the leak is happening, and then turn to more ground-based detectors to figure out which kind of a leak it is if you are looking at a leaking landfill?

Ms. SCARPELLI. Yes, and that is why I think it is key to have a combination of technologies. Some are better at that really high accuracy, where is the leak coming from, versus the remote sensing technology, the key there is that we are seeing the large sources, and so in terms of prioritizing, we want to get the biggest ones first to get the most return on our investment and mitigation, and so it really helps prioritize and lets us get those big ones first, and then we will move on to the smaller leaks.

Senator WHITEHOUSE. Yes. Do you know what the current status is with the EPA folks about having regular and reliable access to satellite methane leak data?

Ms. SCARPELLI. I can not speak to EPA regulations. I know there has been, there are these fundings to looking into these different technologies, and the way that we can best combine them to get the most comprehensive view of the sites. We have seen that these technologies work, that we can identify leaks, and it helps operators mitigate. That has been our experience.

Senator WHITEHOUSE. Yes. Well, here is what I think is happening, and that is that EPA has systematically undercounted methane leaks for a very long time. Environmental Defense Fund (EDF) has done a far better job of tracking methane leakage, a private organization, and EDF thinks that its numbers are actually low, because there are some technical issues with trying to do really complete tracking. With the advent of better satellite methane leak imaging, that can all be resolved.

But EPA having done this poorly for a very, very long time, it is my understanding, it has no direct contractual relationship with any satellite-providing entity so that it can deploy its efforts when a large methane leak appears, which is, to me, a little bit like the fire department not tracking where smoke is pouring out of buildings and going to respond to the problem.

I just do not know why that has not happened yet. It seems like it is an incredibly obvious thing, when the technology is out there to access the technology. I understand that NASA has acquired a good deal of technology, and that some entities make it available for free, but maybe not for free and immediately at the same time. Obviously, if you are dealing with a leak, immediately is a pretty good value to be able to provide.

We are hoping that the methane leak task force that has been set up will get access to that technology before too long so that we can treat a methane leak properly, not just score that it happened months later or react after it has been spilling for weeks and weeks. To have on-time information that causes environmental protection officials, or even local lawyers, or the mayor, I do not care whom, to know that there is a methane leak going on in real time, and in real time, respond and try to get it shut down.

It just seems unbelievably sloppy to not have that system in place. We are counting on that methane task force to cure those disabilities, those self-imposed disabilities that have been bedeviling EPA.

Thank you, Chairman.

Senator CARPER. Thank you. Thanks for your vigilance and continued involvement in this issue. I know it comes from the heart.

Senator WHITEHOUSE. It is their vigilance that is where the issue is.

Senator CARPER. Yes.

Mr. FRANKIEWICZ. Senator Carper, may I add to that? Is that possible?

Senator CARPER. Go ahead.

Mr. FRANKIEWICZ. Thank you.

Senator Whitehouse, thank you for raising that point. There has been a lot of discussion on technology, and the satellites are pretty amazing. The technology does not make the data available, and that is something that is really up for both State, local, and Federal Government to do.

Carbon Mapper is one of the few organizations that makes all their data available. For years now, companies have been availing themselves of private satellite data to better inform their operations, but there is no obligation to make that data available.

So that is one thing that we would really like to see, both at a State and Federal level, that in addition to this advanced moni-

toring, making sure that it is available in a timely way, because emissions transparency is just as important as the technology.

Senator WHITEHOUSE. Just to be clear, I am told that the Federal Government is now in procurement mode with regards to acquiring access to real time leak detection services. January 2024, now in procurement mode with respect to acquiring access to these services. That kind of speaks for itself.

Senator CARPER. We have been joined by Senator Padilla. Senator Padilla, good to see you. How are you? Welcome.

Senator PADILLA. Thank you. Thank you, Mr. Chair.

Something that, if I have spoken on it in committee before, it has been a while, Mr. Chairman, but I am not sure if you knew that when I grew up, we lived not too far from a landfill.

Senator CARPER. Where was that?

Senator PADILLA. In the city of Los Angeles, the northeast corner of the San Fernando Valley, the once-upon-a-time infamous Lopez Canyon Landfill, to be precise, owned and operated by the city of Los Angeles.

I share that to establish that when I say that living near a landfill is beyond just an annoyance, I speak from real world experience. It is in many ways a threat to our health, public health, individual health.

It also prompted, Mr. Chairman, my environmental activism, because my mom, along with a group of neighbors and community leaders, would bring kids out to protest for the closure of the landfill. This was back when I was in high school. We bore the brunt of what landfills mean in all of the communities in which they are located. Too often, it is soil contamination, water impacts, diesel trucks driving through your neighborhoods emitting toxic exhaust, and on and on and on.

In California, this is where I want to talk about equity for a second, people of color are more than twice as likely to live within a mile of a landfill compared to the rest of the population.

Mr. Frankiewicz, can you discuss the health impacts of landfill emissions on nearby communities?

Mr. FRANKIEWICZ. Thank you for raising that really important point, because as important as the climate challenge is, the impacts of air pollution are felt on a daily basis. I mentioned earlier that landfill gases are a mix of a number of gases, so it is methane, water, carbon dioxide. It is also a long list of hazardous air pollutants, and also smog-forming ozone pollution. Those are immediately felt by the local community.

When we talk about controlling methane or even enhanced methane recovery, what we are really talking about is reducing the amount of air pollution that is affecting local communities. One thing I will add to that, some of the strategies to improve gas collection, like automated well tuning, better cover, leak detection, these are things that have a direct impact on safety as well.

One of the things that can be caused by improperly controlled landfill gas collection systems is intrusion of oxygen, and that is one thing that causes landfill fires. When you operate better, recover more gas and operate a better landfill gas collection system, you are reducing pollution and drastically improving safety.

Senator PADILLA. We know, as far as we have come in the last generation or two, liners to protect soil, groundwater, and gas collection systems, to your own point, we still have a lot more work to do. Just yesterday, the Los Angeles Times reported “rivers of odorous waste” erupting like a geyser from the Chiquita Canyon Landfill in Southern California. Carcinogens like benzene were eight times higher than the State’s health limit, but these results were not shared with the public for weeks.

To your point, Mr. Frankiewicz, how can EPA provide closer to real time information on air quality to the public to protect public health?

Mr. FRANKIEWICZ. I think this, again, comes down to emissions transparency, because the technology on its own does not put the information in the hands of people for action. There are actions that EPA could take, both in terms of grants and also provide funding. This would likely be within Congress’ power to provide funding for both the satellites but also making that data available.

There is some lag time for processing that data, but I think of EPA’s Air Now portal, because there has been a system of air monitors around the Country for years, but it was not until Air Now and the Air Quality Index that information became accessible to citizens. I think something of that nature would really empower local citizens.

Senator PADILLA. Great. I want to connect some dots between monitoring, mapping, and remote sensing. I am pleased to see a witness today with the Carbon Mapper Project, which partners with the Jet Propulsion Laboratory (JPL), based in California, a facility that I am particularly proud of. Their satellite will build off of JPL’s EMIT instrument, which was launched in 2022 and is currently operating on the International Space Station.

Although EMIT, Mr. Chairman, was designed to measure dust, it is proven to also detect methane from landfills around the world at high spatial resolution.

Dr. Scarpelli, can you elaborate on how Carbon Mapper’s project builds on JPL technology for methane detection from space?

Ms. SCARPELLI. Thank you for that question, Senator.

As you mentioned, these technologies are building off of each other. The NASA JPL has an airborne instrument as well, and they have the NASA EMIT instrument that you mentioned that is on the International Space Station.

Our satellites will be the next generation. They have different capabilities, so the idea here is that we are seeing high emission sources, and we are getting the information into the hands of the operators on the ground who can take action to mitigate. We can provide the location of those sources, and so the operators know where to look on the ground.

These are seeing, if we can see it, that means it is pretty big. Seeing it from space as well, that means it is pretty large. This ranges from 10 kilograms of methane per hour to hundreds to thousands of kilograms of methane per hour. As you mentioned, these can impact community health.

We see methane plumes from the landfills that overlap surrounding communities. Being able to take that technology and get

it into the hands of operators to achieve quick mitigation will really benefit the local communities.

Senator PADILLA. Thank you very much. My time is up. Thank you, Mr. Chairman.

Senator CARPER. Thanks so much for joining us.

My colleague knows that my wife and I have a son who lives out in California, lives out in the Bay Area. Every now and then, when we are on a recess, I go out to California and visit technology companies to find folks that are doing things that are relevant to our jurisdiction as a committee.

A year or two ago, or three years ago, I visited a company which was taking cow manure and food waste and anaerobic digesters and creating, if you will, a fuel for buses and trucks and all. If you fly into the San Francisco airport, you will notice, I think they do a better job on separating not just trash, stuff that is not recyclable, with recyclables, and with the food waste. They do a great job. You go throughout the SFO airport, and they have these three containers all throughout the airport facility. They do a good job.

California has, as my colleague knows, a lot of cows, and they produce a lot of cow manure. In Delaware, we have some cows, but we really have a lot of chickens. For every person in Delaware, I think there are close to 300 chickens. We are sort of using the model that you have pioneered in California in DelMarVa, which includes Delaware and Maryland, Senator Cardin, have been using the same technology, a different source of fuel, not cows, but chickens, and it works pretty darn well.

I like to say, one of the greatest compliments we can pay is copying what others are doing and hopefully making it at least as good, maybe better. We will see, but thank you very much.

Senator PADILLA. Thank you, Mr. Chair.

Senator CARPER. Senator Merkley is on his way. He is going to join us.

While he is on his way, I am going to ask a couple more questions. The first one is to go back with Dr. Scarpelli and touch on something we talked about a little bit earlier, and then, Ms. Germain, I have a question or two for you.

Dr. Scarpelli, how can deploying comprehensive monitoring provide benefits for both landfill operators and the local communities?

Ms. SCARPELLI. Thank you for the question, Senator. I think I will split that into operators, then communities. Speaking to local communities, we have mentioned that these large methane sources can have co-emitted pollutants along with them, so by addressing the methane sources quickly, we are also reducing that co-emission of the pollutant.

In addition, we have seen in examples, like for the Sunshine Canyon Landfill in California, for example, where by mitigating the methane, we also see a reduction in the number of odor complaints from the surrounding community at the landfill.

Then speaking to benefits to operators, the key here is we want to capture more methane. If they have beneficial use at the site, this means more return on investment for the operator.

We see it as technical assistance that the operators can take advantage of to go out and find the leak and fix it as quickly as possible, because landfills are complex, so knowing where to look on

the landfill, where the leak is, it is not an easy task. Sometimes mitigation, it is engineering design, and so verifying that once you have made a change, the emissions actually were reduced, is also incredibly important and useful to the operator.

Senator CARPER. Thank you.

Ms. Germain, I will probably ask Mr. Frankiewicz to join you in answering this question, but I want to lead off with you, if we could.

In addition to methane, landfill gas contains, as we have heard here today, hazardous air pollutants, odors, and other dangerous gases. They impact air quality, they impact health, and they impact our quality of life for neighboring communities, many of which are already vulnerable anyway.

Ms. Germain, your organization is a national leader in landfill management policy and has a unique perspective in the community impacts related to this pollution. I oftentimes, and my colleagues would bear this out, but I oftentimes use the phrase, find out what works and do more of that. What we are trying to do is a little bit of that as we address this problem, this challenge, but I think it is an opportunity.

Would you share an example or two of government or maybe corporate policies that are helping to reduce methane emissions from landfills through gas capture or organics diversion?

Ms. GERMAIN. Sure. One of the things that we have seen a lot of are, our members have made sustainability commitments. They have made them publicly, and so from a corporate initiative, looking at some of those corporate policies where they have made the sustainability commitments that encompasses methane reductions.

So we collectively have been looking at a lot of the technologies that have been discussed already, not just satellite, but also aerial, drone, ground based. In fact, recently, collectively, we worked to, as an industry, to do a controlled release and tested out 14 different technologies.

So there is a tremendous number of different technologies out there. Which one is the right one, which one is best, are they all good? We are not sure. We have not had the opportunity to really explore that. EPA has not had the funding to be able to conduct some of this research, so the industry collectively conducted some of this research back in November. We just got the results in earlier this year, and we anticipate presenting it at a conference at the end of February. This will give us additional information on which of the technologies will be most useful so that we can utilize that going forward in our efforts to use best practices in reducing our methane emission from our sites.

Senator CARPER. Good. I do not know if either of our other witnesses would like to add to that or add their thoughts on that last question, but the question I was asking Ms. Germain was to share an example or two of corporate policies that are helping to reduce methane emissions from landfills through gas capture or organics diversion. Would either of you want to add to that?

Ms. SCARPELLI. I would like to add something to that. I just want to reiterate the importance of doing these controlled release experiments. This really does help technologies both determine and improve their own methodologies and validate the technology.

One of the important things is that I know it is not easy to do a controlled release. We are seeing these very large emission sources from some landfills. Being able to release an accurate amount of methane that reflects that, so that the technologies can really be tested on those large releases is really important.

Senator CARPER. Yes, ma'am. Ms. Germain, go ahead.

Ms. GERMAIN. Yes. As we, and thanks, Tia, for saying that, because we think it is really important to continue on with these controlled release studies.

We did have to conduct this controlled release study in Canada because the length of time for us to be able to get authorization to do it in the U.S., due to the length of time for us to get the permitting, was going to be very time consuming. We also have received interest from the Canadian government to help support ongoing research in this area, and we would certainly appreciate some of those similar efforts in the U.S.

Senator CARPER. Good. Let me come back to Mr. Frankiewicz, if I could, but would you, Mr. Frankiewicz, please provide for us some examples of the additional benefits that promote the health and well-being of nearby communities with the kind of technology we are talking about here today?

Mr. FRANKIEWICZ. Thank you, Senator, I am happy to. There are really a multitude of benefits.

When you are talking about landfill gas control, as I have mentioned a couple times now, you are controlling gases across the board, and so there is immediate air quality benefits. Also something that is not mentioned often, but is a significant issue, is odor. Not all landfills cause odors. A well-managed gas system certainly prevents it, but odor is probably the No. 1 issue that local communities will complain of. Things that you do to improve gas collection, reduce leaks, have bio-covers, all reduce odors and hazardous air pollutants that impact communities.

I will give the example of Wake County in North Carolina. They were under an enforcement action for odor problems, and the way that they remedied it was through a combination of monitoring, finding and fixing leaks, and improving cover, intermediate cover and daily cover for their site. It had an immediate impact.

Then, also, the other part of this two-pronged approach we keep talking about, when it comes to organics diversion, and not just diversion, but avoiding food loss and food waste, that is a food security issue. There are plenty of families that are food insecure, yet at the same time, we are throwing away food each year. Things to reduce food loss, food waste, getting that food into food banks improves food security.

Last, we all talk about the benefits of composting. I think there is pretty strong support for that, but one of the things that I think is not mentioned often enough, one of the key reasons for composting organic waste is that you are able to actually recover those nutrients that are in soil. All those nutrients that go into growing food, when that organic waste goes into a landfill, it is locked there. When you actually compost the food waste, that compost and those nutrients go back to the farms.

So people always talk about, without farms, there is no food. Well, without healthy soil, there is no farms, and so it is really important to close that loop.

Senator CARPER. One of my friends likes to say that composting is the gift that keeps on giving, and there is actually a lot of truth to that.

I have maybe one more question for Ms. Germain and for Mr. Frankiewicz. My colleagues hear me say some things over and over again that I think bear repeating. I have often said that recycling is a win-win solution. That is because diverting waste is not only good for our environment; it is also good for the economy; it is good for job creation. I am always looking for win-wins.

There is so much that we are doing to protect our environment, to address climate change, that actually does create a lot of jobs. Jeff, welcome.

Would each of you just take a moment while Senator Merkley is settling in, would each of you, Ms. Germain and Mr. Frankiewicz, share some more information, with us, if you will, on how organics waste diversion can increase employment rates and contribute to economic growth? Do you want to lead us off on that?

Ms. GERMAIN. With respect to organics, obviously, as Tom already said, there are a lot of benefits to organics composting or anaerobic digestion. You have soil amendment. With anaerobic digestion, you have the opportunity to gain energy from that.

The issue right now is that we do not have adequate infrastructure, so we would need to ensure that we buildup the infrastructure. We definitely, I will go back to, I know I am repeating myself, but I will go back to the labeling issue, where we really need to focus on ensuring that the product that we create is usable as an end product.

So we really need to focus on the contamination issues related to that, because everybody wants to be able to claim that their packaging is compostable, and it is just not the case with a lot of it. We really need to be thoughtful and mindful as we move forward with diverting materials.

As far as the comment about reducing our food waste, certainly, I agree. We want to ensure that the hierarchy that EPA has established, we want to feed hungry people, we want to feed hungry animals first, but recognize that a lot of our food waste, if it is a banana peel, that is not going to be feeding anybody. We are going to want to end up managing that in a different way, and so that is going to end up in the waste system.

Senator CARPER. I might add, my colleagues, Senator Capito and our colleague from Arkansas as well, Senator Boozman, are very much involved in the Recycling Caucus, leading it. One of the things we have done here, I believe in leadership by example, and one of the things we have done here on Capitol Hill, in our office, and I hope in every Senate office and hopefully in every House office, right in our offices is the opportunity for our employees to recycle plastics, metal, aluminum metal, whatever, glass. We have composting capability, as well.

We are a pretty faithful, pretty good at it. I am very proud. We can always do better, but I am proud.

Mr. Frankiewicz, I want to come back to you with the same question, and then I am going to kick it over to Senator Merkley. Again, what are some specific jobs associated with organics recycling and waste diversion? And then Senator Merkley.

Mr. FRANKIEWICZ. Ms. Germain talked about the importance of moving up the waste hierarchy. One of the things you see in moving up the waste hierarchy is, the farther up you go, the more jobs that are created. Roughly speaking, for every \$10 million invested in waste management, there are 21.4 full time jobs created in composting, while landfilling supports 8.4 to incineration's 1.6. Certainly, money invested in waste management creates jobs, but the farther up you go up the waste hierarchy, the more jobs that are created.

Senator CARPER. Good.

Senator Merkley, welcome. Good to see you again, twice in one day. We showed up for work together, and here we are, together again.

Senator MERKLEY. Thank you very much, Mr. Chairman.

Thank you all for bringing your expertise to the hearing today. I wanted to understand a little bit more about the monitoring of methane emissions. Mr. Frankiewicz, the traditional monitoring approach is, whether it is modeling based on assumptions or ground-based monitoring, and I think that is primarily done through an infrared technology, but perhaps you can clarify. Are those adequate to inform our approaches to methane emissions?

Mr. FRANKIEWICZ. I am sorry, I did not quite hear the last part.

Senator MERKLEY. Are the traditional approaches, either just modeling based on preexisting assumptions, or kind of ground-based monitoring sufficient to understand really the amount of methane that is emerging from different settings?

Mr. FRANKIEWICZ. They are not adequate, and we see two ways that technology can improve those estimates. Generally speaking, the kind of landscape of the technology that you have, some of it overlaps, but generally speaking, you have technology that is maybe more focused on emissions quantification and others that are better at detection.

When it comes to quantification, the observations that are done through a network of satellites can both ground truth and improve the modeling methodology. It is not in a place to replace it, but it could certainly improve the measurements that are used for both modeling and inventory purposes.

When it comes to detection, the current methodology is highly subjective. There are technologies that are drone-assisted, but still operated by people that drastically improve the chances of detecting and fixing those leaks.

Senator MERKLEY. As we have brought these technologies to bear, satellite monitoring, drone monitoring, have we found that our original estimates of methane were on target, or were they significantly lower than what we are discovering?

Mr. FRANKIEWICZ. They found that they are significantly lower, and in fact, EPA came out with a report recently on its Greenhouse Gas Reporting Program that generally found that the inventory underreported based on current modeling-based methodology.

Senator MERKLEY. Let me turn specifically to landfills. Do we spot super emitters like landfills better in terms of using satellite or drone technology? Is it helping us understand the large scope of the problem?

Mr. FRANKIEWICZ. They are, and I will certainly defer to Dr. Scarpelli on this specific technology. One of the things that EMIT and other technology has shown is that you can detect these from space. When it comes to pinpointing those leaks, that is where it is helpful to use kind of a matrix approach to pinpoint these leaks, but you absolutely can see these super plumes from space.

Senator MERKLEY. Dr. Scarpelli, do you want to amplify on that?

Ms. SCARPELLI. Yes, I agree with Mr. Frankiewicz's comments. We can use these technologies to see these large emissions sources. One of the benefits of remote sensing, and we have seen this in practice working with State governments, is that you get a view across the facility. You do not necessarily need to know where the leak is coming from to see it, because we are seeing all the full facility, and we can quickly survey multiple sites.

These satellites are circling the Earth, so it can see across the U.S. It is not just one drone at one facility, and so having a combination of these different scaled technologies is really important for identifying those high emitters.

Senator MERKLEY. I have heard that the EPA has kind of dragged its feet on contracting for satellite based methane contracting. What is that all about?

Ms. SCARPELLI. I can not speak to EPA's contracting. I would say there is a need to have Federal support to help scale up these technologies and provide access to the data quickly. The feedback we have gotten from operators is that it is really important to get the data quickly and have the data be transparent so that they can quickly fix leaks. That is one of the roles that the Federal Government can play.

Senator MERKLEY. Mr. Chairman, this is something that perhaps we can followup on, because if we have this high value satellite technology that EPA has been funded to contract for but has not contracted for, then maybe we can help accelerate that process to try to help tackle this challenge.

Once we identify the particularly significant sites, and I was surprised to come to understand how significant landfills are, do we have, really, the affordable technologies to be able to capture that methane out of landfills? Do we have the funding to tackle that challenge? It is going to take more Federal help?

Ms. SCARPELLI. I can speak to the monitoring perspective on that. We do have monitoring technologies that can help find these leaks, and these are being deployed at landfills. Really, the key here is we just need to scale up the use of these technologies. I defer to others in terms of the availability of actual design changes that can be made to achieve the mitigation.

Mr. FRANKIEWICZ. Yes, the control technology is proven. It is gas collection, soil cover, finding and fixing leaks, these are things that landfills have been doing for a long time. With advanced monitoring and doing it in tandem, they are actually able to design these systems better and operate them better.

Ms. GERMAIN. I just wanted to clarify that as we talk about finding the leaks, and certainly, that is one of the things we are really interested in deploying these technologies for, is to be able to find the leaks and repair them as quickly as possible, the subtext seems to be that all the landfills have leaks. A lot of the measurements have been non-detects, so most landfills have no detectable leaks, and I do not know that is coming across during this conversation. As some of these flyovers and detections are occurring, most of the landfills do not have any leaks, but the landfills that do can have significant leaks that, if they are told about quickly, can be immediately repaired.

Senator MERKLEY. I know I have run over my time, so you can interrupt me, Mr. Chairman. My impression has been that when you have landfills that have been filled with gravel or soil, it is one thing, but when you have garbage and other things that are decomposing, it is quite another that is the place where you have landfills with really high methane emissions.

Why do some landfills have, as you pointed out, little methane, but are significant emitters?

Ms. GERMAIN. It is usually a function of the collection system, so even the municipal solid waste landfills that take all the organic matter, they have those landfills that have shown to have no leaks.

Senator MERKLEY. It is attributed to the effectiveness of the technology?

Ms. GERMAIN. Right, and so, as we have been talking about, if you can go rapidly, fix the leak, correct it, then it can be confirmed on the next flyover. They can confirm that there is no more leak from that facility.

Senator MERKLEY. Doctor?

Ms. SCARPELLI. It is true that we do, speaking to how many emitters we see, we have surveyed about 300 landfills in the U.S., and we have seen 200 of those landfills have high emissions. It is not necessarily that the biggest ones are the ones with the biggest emissions, and the emissions do vary by site.

We find that the landfill workforce is a major source of emissions, and then the landfill gas capture system is also, and this can be if the wells are flooded, they potentially would have methane leak out of those wells.

We have seen it with the flare stacks. If the flare is down for a period of time, you can have methane leaking out of that. We have seen these varied emissions sources across the landfill. We have had examples, as well, where we have identified the methane leak from surface cover, for example, and then the operator has gone in, made adjustments to the cover, we have flown it again, and we have seen the leaks have actually been reduced. We have used the technology to verify that.

Senator MERKLEY. Well, that is very effective.

To the degree that there is organic matter in the landfill, do we see cities going, we will reduce the methane leak by having separate organic digesters to essentially produce methane and maybe put it into the fossil gas system, or in other words, keep it out of the landfill to begin with?

Mr. FRANKIEWICZ. Keeping it out of the landfill is definitely the right approach. That will, in the long term, reduce overall methane

emissions from landfills, but because you mentioned the waste in place, right, that decomposes for upwards of 50 years. Unfortunately, you do have to do both at the same time.

Just to put a finer point on Dr. Scarpelli's point about detecting leaks from space, I think some of these large super emitters, you can see from space, and for sure, that should be an area of focus. That should not be the rule of thumb, right, only control what you see from space, and that is where near aerial observations and drone based observations are important, because then you could look at, and we advocate for lowering the detection threshold from 500 ppm to something closer to 200 ppm. Just because you can not see it from space does not mean you might not have a large, diffuse area of source emissions across the cover. That is where things like using bio-covers and autotuning of wells to better control your gas can reduce those leaks that you may not see.

Senator MERKLEY. Thank you all very much, again. Thank you, Mr. Chairman.

Senator CARPER. Thanks very much for joining us, Senator Merkley, and for your consistent and excellent leadership.

We have a vote underway. I need to run and vote before time runs out.

Before that, I am going to telegraph my pitch. In baseball, you want to pitch in a way that we can see how the pitcher holds the ball before he releases the ball to the plate, figure out if they are going to throw a spitball or a screwball, a hanging curveball, you can tell by the way they telegraph their pitch. I am going to telegraph my pitch.

I am going to telegraph and say that I am going to tell a quick story, and then I am going to come back to each of you and ask you to take maybe a minute and just tell us where you think there is really important common ground that we have heard here in this hearing. It has been an excellent hearing, and we are grateful for that, but just be thinking about that. Now, I will tell you a story.

I have been a naval flight officer in the Vietnam War and spent half my time in Southeast Asia with my squadron and half of our time flying out of Moffett Field Naval Air Station, which is right on Route 101, across from Mountain View, California, about halfway between San Jose and San Francisco. I mentioned earlier some of the things that I have learned by going back to that part of the world and about, among other things, anaerobic digestion. The first time I ever learned about it was back out there to see one of our sons.

When I left California and moved to Delaware to get an MBA, I continued to fly with the Navy in the Reserves for another almost 20 years, but my first week or two in Delaware, I met, I got instated in an MBA program.

We had to find, one of our assignments in this one course was to find a company in Delaware that was always in the news for getting in trouble with the Delaware Department of Natural Resources or with EPA, and then do a study of that and report back.

I found out that I did not know much about Delaware, but I found that they had an oil refinery called Getty Refinery, as in J. Paul Getty, right at the Delaware River in Delaware City. I decided I was going to do my research project on that refinery, which

was one of the worst polluters on the East Coast. I found out that the person I should talk to about their violations was actually a Deputy Attorney General down in Dover, Delaware, and that if I could track him or her down, I could really get a lot of help on my assignment.

I drove in my Volkswagen Karmann Ghia with a rebuilt engine from Newark, Delaware, where the university was, to Dover, Delaware. I found Dover, Delaware. I found the Department of Natural Resources and Environmental Control. I found the building where the Deputy Attorney General for that agency was working, and I found him on the second floor of that building.

His name was Mike Parkowski. He could not have been more helpful. He welcomed me warmly. I had been in Delaware a couple weeks. He welcomed me warmly, provided access, he had filing cabinet after filing cabinet of violations from the Getty Refinery. He gave me access to that, a desk to work in.

I worked, and I would come back week after week and do my research and all. His wife offered to type my research paper for me. I did not need any help, but I certainly appreciated all the help that he provided.

Mike Parkowski has a son, and I think you might know the son, Anne. His name is also Mike Parkowski. What does he do today? Can you turn on your mic and tell us what he does?

Ms. GERMAIN. Mike is responsible for a lot of the outreach and government affairs and policy work for the Delaware Solid Waste Authority.

Senator CARPER. Just last week, my staff and I visited the educational facility that they have in Dover, Delaware, where thousands, probably tens of thousands of students come every year and learn about recycling and our planet and so forth, and he does a great job. It is nice to see that one generation follows another.

I am going to ask, again, each of you to take just a moment now and just share with us the common ground that I mentioned earlier. Tom, if you want to lead off, that would be great. Just briefly.

Mr. FRANKIEWICZ. Thank you, Senator Carper, for that story.

Senator CARPER. Isn't that a great story? I just made it up, so. [Laughter.]

Senator CARPER. Not really.

Mr. FRANKIEWICZ. Well, I appreciate the time. It allowed me to get my thoughts together.

Senator CARPER. There you go. That was the idea.

Mr. FRANKIEWICZ. I think, hopefully, what you can see here by the different points we are making, they do not differ very much. I think we agree on more than we disagree on.

Since 2016, the last update of the NSPS standards for landfill gas, the technology has advanced rapidly. There is technology that we could use to better find and fix leaks, identify super emitters, and better inform models and inventory.

We are already collaborating with the waste industry in identifying some of these solutions. We would like to continue that, and we would like to see EPA join us in this effort by incorporating these advances into stronger Section 111 standards.

Senator CARPER. Great. Thanks.

Dr. Scarpelli?

Ms. SCARPELLI. Yes, just to second that, and we have seen here today that landfills are large methane emitters. Not all landfills are large emitters, and there is huge potential for mitigation. The role of advanced monitoring is to guide mitigation practices to identify the leaks, help the operator go through, and also verify that once the mitigation has taken place, that emissions are actually reduced.

There is also a role for accounting for emissions, and this will play a role for climate policy, that we need to know, our models need to be accurate. Using the data as well to help inform models and inventories will also be important.

Senator CARPER. Thank you. Ms. Germain?

Ms. GERMAIN. We have made tremendous progress over the last 30 years, as I stated in my opening remarks. We have reduced our methane emissions by about 45 percent since 1990. However, that still means that we have a long way to go, and we recognize that. We are committed to meeting the global methane pledge made by the Administration of reducing our methane emissions by another 15 percent by 2030. We are committed to using technology to help support those efforts.

Senator CARPER. Great. Thank you.

I am going to wrap it up here, but in wrapping it up, I just want to thank each of our witnesses for your preparation and for taking the time to join us today. I want to thank you for what you do with your lives.

There are a lot of important issues that we consider in the Senate and in this room, but I do not think anything is more important than what we have discussed here today. As we have heard, we have the tools at our disposal to really, I will not say quickly, but expeditiously reduce methane emissions from landfills. We are doing it, we can, as we said earlier, we can always do better.

New technologies to detect and quantify emissions, when combined with techniques to avoid and capture methane emissions, not only drastically or dramatically reduce emissions, but can also create new jobs, new jobs opportunities. I am always about, how do we do good things for our planet and create jobs at the same time, and they actually can work together.

Implementing these tools effectively can improve the health of our communities and slow the progression of climate change, a true win-win situation. I look forward to working with my colleagues, Democrat and Republican, on this committee, and in the full Senate to continue this conversation, and make real progress in reducing landfill methane emissions.

Before we adjourn, just a little bit of housekeeping. Senators may submit questions for the record until the close of business on Wednesday, February 14th. When is Valentine's Day? Is that Valentine's Day? What a day to remember. We will compile those questions and send them to our witnesses. We will ask our witnesses to reply by Wednesday, February 28th.

Before I adjourn, I just want to say to our staff members on both the Republican and Democratic sides, majority and minority, how much we appreciate, on behalf of my colleagues and Senator Capito, how much we appreciate the work that went into making this

hearing occur. It has been a great hearing and, I think, an encouraging hearing.

In the world that we live in, there is a lot to be worried about, concerned about, and this is one, certainly climate change is a big one, but there is good work that is being done, important work that is being done, and we have heard about how we can do that even better going forward.

With that, it is a wrap. This hearing is adjourned. Thank you all very, very much.

[Whereupon, at 11:56 a.m., the hearing was adjourned.]



January 29, 2024

Senator Tom Carper, Chairman
 Senator Shelley Moore Capito, Ranking Member
 Senate Committee on Environment and Public Works
 410 Dirksen Senate Office Building
 Washington, DC 20510

Comments for the Record – Committee Hearing: “Avoiding, Detecting, and Capturing Methane Emissions from Landfills”

Chair Carper and Ranking Member Capito:

The US Circular Economy Coalition would like to offer comment as the Senate Environment and Public Works Committee seeks feedback on methane emissions from landfills and how to mitigate their harm to the environment and local communities.

The US Circular Economy Coalition (CEC) is a network of like-minded and future-conscious companies and institutions dedicated to improving waste and materials management policies in the U.S. We recognize that in order to reach our collective goals to reduce pollution and eliminate carbon emissions, we need stronger policies from our leaders in Washington to create stronger incentives to build a truly circular economy built on science and the waste hierarchy.

Our Mission is to advance a more circular economy as a means to help reach a global goal of net zero greenhouse emissions by 2050 through practical, tangible, and measurable action considering resource and economic efficiency.

The CEC is pleased to see the Committee is examining the effects of methane emissions and how mitigation can help achieve climate goals and improve air quality. As you know, methane is more than 80 times more potent than carbon dioxide over a 20-year period, with the United Nations Environment Programme (UNEP) designating methane emissions reductions as the “strongest lever” for avoiding the most severe impacts of climate change.

Accurately measuring landfill emissions is an essential component to adapt circularity in the US economy. These emissions, often underreported, have significant impacts on local communities by contributing to air pollution and accelerating climate change.

Methane emissions are primarily emitted from decomposition of organic and biodegradable waste placed in landfills. While some landfill systems are able to capture methane, it is often inconsistent and imperfect with frequent flaring and unaccounted emissions. In fact, landfills are not required to measure emissions directly. Instead, they model these emissions as reported in GHG inventories and are often found to be as much as twice the reported value, according to [studies by](#) the Department of the Interior.

While your Committee continues to solicit testimony and gather information, the CEC encourages you to ensure accurate methane emissions data is collected to effectively tackle this challenge. Further, in order to mitigate the release of methane emissions, proper data is essential for any effort to be successful. Toward that end, we ask that this letter be added to the official record of this hearing, as well as a recent study on the efficiency of collecting and measuring of landfill gas (attached).

The CEC and our members appreciate your attention to this critical issue and looks forward to supporting efforts to reduce methane emissions.

Sincerely,

Sean Trambley
VP of Policy



Contents lists available at ScienceDirect

Waste Management

journal homepage: www.elsevier.com/locate/wasman

Research Paper

Landfill gas collection efficiency: Categorization of data from existing in-situ measurements

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ARTICLE INFO

Keywords:

Municipal solid waste
Landfill
Methane emissions
Landfill gas collection efficiency

ABSTRACT

Landfill methane emissions are commonly estimated using cover-type dependent default collection efficiency values, with a first-order decay model or measured gas collection. Current default collection efficiencies used in the United States were predominately derived from 4 studies conducted during or prior to 2007 that relied on flux chambers. Flux chambers are limited by small sample sizes, placement restrictions, and the inability to measure emissions from gas or leachate collection systems. Since 2007, over 14 new studies have been completed using more advanced technologies that allow for direct measurement of methane plumes from most or all of a landfill's surface. On average, these measurements are 2–3 times greater than emissions predicted by current models and collection efficiency defaults. In lieu of measuring emissions from all landfills, updating collection efficiency estimates derived from measured data were categorized into cover types and then adjusted to account for cases where whole plume measurement was an amalgamation of multiple cover types. The resultant adjusted default values were 41% for daily cover, 69% for intermediate cover, and 71% for final cover. Direct measurement of landfill methane emissions is preferable to account for the full range of variables driving landfill emissions, including collection system design and operation. However, applying these updated defaults back into the landfill emission models eliminates underprediction of landfill emissions for the dataset reviewed, and would provide a more accurate estimate of landfill gas emissions where measurements are unavailable.

1. Introduction

1.1. Background

Climate change is a pressing global problem caused largely by anthropogenic emissions of greenhouse gases (IPCC, 2021). Effectively informing policies aimed at addressing climate change requires robust greenhouse gas inventories. Methane is the second greatest driver of human caused climate change, and the subject of recent international agreements, including the Global Methane Pledge with over 100 countries as signatories. The three largest global sources of anthropogenic methane emissions, oil and natural gas, agriculture, and waste management, are fugitive and difficult to be measured directly and

comprehensively. The lack of measured data presents challenges for developing accurate and up-to-date inventories and emission factors for use in lifecycle analysis (LCA).

In lieu of direct measurements, greenhouse gas inventories have largely relied on emission factors and models often based on minimal amounts of data. The potency of methane relative to carbon dioxide amplifies the inherent uncertainty relative to other more reliably vetted sources, such as fossil fuel combustion. Recent studies indicate significant discrepancies between direct atmospheric measurement and emissions estimates currently in inventories, on the local and regional level (Peischl et al., 2013, McKain et al., 2015, Plant et al., 2019), as well as the national level (Miller et al., 2013, Wecht et al., 2014, Turner et al., 2015, 2016, Saunio et al., 2020). Among the leading sources of

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<https://doi.org/10.1016/j.wasman.2023.12.042>

Received 29 March 2023; Received in revised form 11 December 2023; Accepted 22 December 2023

Available online 3 January 2024

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anthropogenic methane, the oil and natural gas industry has received the most attention, with studies finding significantly higher levels of emissions than previous estimates (e.g. Alvarez et al., 2018). However, the data from the oil and gas industry do not fully explain the difference between inventories and direct field measurements.

1.2. Significance of landfill methane

Landfills generate methane through anaerobic decomposition of biodegradable waste by a variety of microorganisms and are the third largest source of anthropogenic methane emissions globally (UNEP, 2021). Emissions from landfills present a special challenge in terms of accurate quantification, because they emanate from point and distributed sources over wide surface areas and exhibit high spatial and temporal variability (Scharff et al., 2005; Monster et al., 2019). Furthermore, landfill emissions are affected by temperature, precipitation and changes in atmospheric pressure and are the net result of a complex system of methane generation, source attenuation through aerobic soil oxidation, and active control through landfill gas collection and management systems (Scharff et al., 2005; Oonk, 2010; Monster et al., 2019).

Landfill cover systems, consisting of soil and geomembranes are installed to contain the waste placed, and vary at different points in time and in different locations, in terms of gas and liquid permeability. Most active municipal solid waste landfills in the United States (US) that report their emissions through the US EPA's Greenhouse Gas Reporting Program (GHGRP) now have gas collection systems in place (74 %), and many of these recover energy from the collected gas (US EPA, 2019). Gas collection is typically through a series of vertical and/or horizontal collection wells operated under a slight vacuum. The extent of vacuum pulled on the system is a balance between effective gas collection and the risk of drawing oxygen into the subsurface which can create fire and explosion hazards. The efficacy of active gas collection can vary significantly, based on system design, as well as operational and maintenance issues, including cap maintenance, wellhead vacuums, and system flooding.

Collected gas, generally about 50 % methane, is routed to either a flare, an energy recovery device (e.g. internal combustion engine), or turbine generator, or processed for direct injection into natural gas pipelines. Leachate, or the liquid that percolates through a landfill, is collected for treatment through separate collection systems. Uncollected gas can be emitted through the cover, gas collection, or leachate collection system, making them all potential sources to consider when measuring or modeling overall emissions from a landfill (Spokas et al., 2006; Monster et al., 2019). A portion of the gas that diffuses through soil covers is also oxidized by methanotrophic bacteria.

1.3. Landfill methane emissions accounting

Landfill methane emissions can be estimated using the First-Order Decay (FOD) Method (Eggleston et al., 2006) and assumed rates of gas collection and oxidation in cover soils. The FOD Method estimates the total methane generation of a landfill based on the amount of biodegradable organic carbon in place (DOC), an assumed fraction of biodegradable waste that can decompose under anaerobic conditions (DOC_g), the fraction of methane generated in landfill gas (F), and a climate dependent first-order decay rate (k). In some model implementations, the DOC, DOC_g, and F terms are combined into a methane generation potential term (L₀). Emissions are calculated by subtracting both the amount of gas collected, measured directly or estimated based on an assumed collection efficiency, and an assumed rate of methane oxidation within the cover soils, from the modeled generation (Eggleston et al., 2006). The FOD Method is commonly used for inventories given its simplicity, acceptance in the IPCC Guidelines for National Greenhouse Gas Inventories, and ubiquity in regulations, emissions models, and lifecycle models (Eggleston et al., 2006), despite IPCC's recognition of

its relatively high uncertainty. Prior to the availability of GHGRP data, which use somewhat different models, the US National GHG Inventory (GHGI) used the FOD Method.

The GHGRP, applicable to landfills with annual emissions in excess of 25,000 tonnes of carbon dioxide equivalents, offers an alternative approach. In addition to the FOD method, methane emissions can be calculated based on measurements of gas collected at a landfill, assumed rates of soil oxidation, and an assumed overall collection efficiency based on the spatial distribution of three cover types (daily, intermediate, and final) in place at the landfill (US EPA, 2013a). Daily cover refers to soil or other materials placed atop the working face(s) of a landfill at the end of the day, which are meant to control odors, pests, fire hazards and reduce scattering litter and dust. Daily cover is typically used for operational areas of the landfill, until an intermediate cover is placed, for a total duration of three to five years after initial gas collection system installation (Levis and Barlaz, 2014).

Intermediate cover is used to keep areas of the landfill covered that are not then currently receiving waste but that are not yet ready for installation of a final cover. Under the GHGRP for US landfills, intermediate cover is defined as at least 30 cm (12 in.) of soil and final cover is 91.44 cm (3 feet) or thicker of clay or other materials as approved by the relevant authority, or a 'geomembrane' cover system (US EPA, 2013b). A final cover which does not meet these requirements is considered an intermediate cover for the purposes of the GHGRP. Models used through the GHGRP, which rely on recovered gas quantities and default parameter values, do not provide for separate accounting of methane emissions that may come from the gas or leachate collection systems.

Approximately 70 % of landfills with gas collection systems covered by the GHGRP used the alternative default collection efficiency-reliant approach described above with the remaining 30 % of landfills using the typical FOD-derived method. The two approaches can yield substantially different results. Modeled estimates from the FOD approach (Equation HH-6) for 2021, were on average 8.7 times higher than those made from the default collection efficiency approach (Equation HH-8, see Supplementary Material, SM-1). Landfill operators are allowed to choose an approach based on what they deem more representative (US EPA, 2019) and can switch approaches from year to year.

The above methods are useful in modeling emissions from a landfill in a given year, such as in a GHG inventory. For LCA, where the functional unit is typically a mass of waste managed through landfilling or other means, the sum of emissions over time are generally considered. This approach is useful in comparing the climate impacts of different waste management approaches, as is done in the US EPA's Waste-Reduction Model (WARM, US EPA, 2013a) or in the US EPA's waste management-specific LCA tool, the Municipal Solid Waste Decision Support Tool (MSW DST, RTI, 2021). Lifetime methane emissions are calculated based on estimated generation, adjusted based on an assumed lifetime collection efficiency (WARM) or a temporally variable collection efficiency (MSW DST), and assumed soil oxidation. Lifetime collection efficiencies are calculated based on the FOD rate constant and specific collection efficiencies assumed for various cover conditions that exist for the life of a mass of waste in a landfill. These values account for time before and after collection systems are operational in an area of the landfill where waste is placed.

In addition to collection efficiency defaults, models also rely on default soil oxidation values. Currently, both the GHGRP and WARM use default soil oxidation factors that are a function of cover type and predicted emissions flux, with slight differences between cover type descriptions and default values (US EPA, 2009, US EPA, 2020). MSW DST applies a uniform 15 % soil methane oxidation across landfill alternatives, though the user can override this default with a separate value, provided they can also supply adequate rationale for the change (RTI, 2021).

The US EPA LCA and inventory models apply different collection efficiencies based on cover materials in place (see SM-2). The GHGRP

applies an average landfill gas collection efficiency weighted by the relative area under each cover type and collection system combination (US EPA, 2009). The GHGI for all years since 2010 uses emissions values reported through the GHGRP, with a scale-up factor, of 9 % for years 2005–2016, and 11 % for years 2017–2021 (US EPA, 2023). The scale-up factor is applied to the total emissions reported through the GHGRP, to account for landfills not subject to reporting through the GHGRP (US EPA, 2023).

The EPA's lifecycle inventory and screening tools take a different approach, since they take the perspective of a functional unit of a ton of waste managed, instead of emissions from an entire landfill. WARM applies different values as a function of time since waste is placed in a landfill, for varied scenarios that reflect an assumed rigor of collection (e.g. aggressive, typical). WARM also specifies a separate collection efficiency for landfills with cover still not meeting standards of final cover, but having remained in place over 14 years in most scenarios, or more than 7 years in the 'California regulatory scenario' (US EPA, 2020). The figure used to represent the collection efficiency for this portion falls between the assumed collection efficiency values for the intermediate and post-closure phases. The MSW DST takes a similar approach; however, the user can modify the specific assumptions for landfill gas collection efficiency by year.

1.4. Landfill methane emissions measurement

Methane emissions from landfills can be directly measured. Recent work has indicated landfills to be a more dominant source of methane than agricultural sources or oil and gas infrastructure according to such direct measurements (Duren et al., 2019). To date, nearly all measurements have been performed using one of four techniques: flux chambers, vertical radial plume mapping (VRPM), ground plume, or aerial plume.

Historically, most measurements were made using flux chambers. Typically consisting of a nominal, less than 1-square-meter box secured into the landfill surface, emissions fluxes through the landfill are calculated by monitoring the concentration of methane over time (Monster et al., 2019). Dynamic flux chambers incorporate a steady gas flow through the box to eliminate any effects of increased methane concentration or pressure on methane fluxes (Monster et al., 2019). Flux chambers are easy to deploy and can provide some degree of spatial resolution to enable comparison of different cover materials or construction. However, flux chambers are limited by small sample sizes, omission of finite point sources including surface imperfections and collection system components, and potential influence or interference with methane transport mechanisms. As a result, they have been identified as potentially underestimating emissions (SWICS, 2012, SWANA, 2013, US EPA, 2008b, 2011a, CalRecycle, 2012, Monster et al., 2019, Amini et al., 2013, Babilotte, 2011). Despite their limitations, current default collection efficiencies were largely informed by flux chamber data (US EPA, 2009).

VRPM, described in EPA Other Testing Method-10 (US EPA, 2011b, Green et al., 2011), determines a path integrated concentration of methane using an optical instrument, such as an open path tunable diode laser, and meteorological measurements to estimate methane flux across a vertical plane. Determination of an area contributing to flux (ACR) translates the measured methane flux through the vertical plane to that from the landfill surface. VRPM introduces uncertainties mainly through its inability to measure emissions from an entire landfill. VRPM instead measures flux for a single area, which is then interpreted as representative of either a larger section of the landfill with similar properties, or for the whole site.

Ground plume techniques include tracer-dispersion methods, as well as stationary or mobile whole-plume monitoring, which all attempt to measure emissions from the entire landfill at a downwind location on the ground surface. Tracer-dispersion involves release of a tracer gas at the source and downwind measurement of both the tracer gas and methane within the plume to determine emissions (Galle et al., 2001).

Mobile whole-plume monitoring generally involves driving an automobile downwind of a landfill on a horizontal transect to measure methane concentration of the entire plume (Oonk, 2010). Stationary plume monitoring instead relies on measurements from static fixtures, still located downwind of the landfill. For both stationary and mobile plume monitoring, dispersion models are in some cases also applied to reach a total landfill emissions estimate (e.g. Aronica et al., 2009).

Aerial plume measurements have become more common for measuring flux from area sources, including landfills (e.g. Peischl et al., 2013). Aerial measurements involve use of an aircraft flown downwind on a linear path or in a circular or elliptical path around a landfill (e.g. Hanson et al., 2020), measuring concentrations of methane at varying altitudes against a background using onboard analysis equipment. Both the linear and encircling methods have been demonstrated to be effective, but the latter is preferred for capturing both upwind and downwind measurements. Depending on obstacles such as terrain and air traffic restrictions however, encircling flight paths are not always practical (Hanson et al., 2020).

Aerial measurements can be supplemented with measurements of other gases, including carbon monoxide, carbon dioxide, propane, and ethane to differentiate between different sources of methane, including combustion, natural gas, agricultural, and landfill sources of methane (Peischl et al., 2013). Overall, the advent of aerial measurement in recent years has been groundbreaking, allowing environmental regulators and researchers to measure emissions from landfills that previously would not have been possible.

Several other methods exist for use in the field to measure landfill methane emissions. These include eddy covariance, integrated surface monitoring, and surface monitoring. The eddy covariance method involves simultaneously measuring flux of a target gas species (i.e. methane) as well as wind velocity across a horizontal plane cast above the landfill and quantifying covariance between the two variables in order to determine an emissions estimate (Monster et al., 2019). Integrated surface monitoring combined with dispersion modeling is a technique that has been applied by US landfill operators and regulators (CARB, 2009), which incorporates surface methane concentration and meteorological measurements with dispersion modeling to calculate an overall emissions estimate for the entire landfill (Huitric et al., 2007). Surface monitoring also measures emissions directly above the surface of a landfill, but instead utilizes a flame ionization detector (FID) to measure emissions from the center of uniform-sized cells all along the surface of a landfill (Mohsen, 2019). Individually and cumulatively, these techniques have been applied sparingly for landfill emissions measurement.

In the US, the current defaults for landfill gas collection efficiency and soil oxidation used for the GHGRP were adopted in 2009 (US EPA, 2009). The US EPA adopted a series of cover-type dependent instantaneous collection efficiency defaults to apply in models used for GHG inventories, which was based on a 2007 industry report using flux chamber data from 6 published studies dated from 1999 to 2007 that covered 11 landfills, 3 in the US and 8 in Europe (SWICS, 2007, US EPA, 2009). The changes were proposed and finalized as an improvement over the historical approach of a single 75 % collection efficiency default typically referenced in the EPA's emission factor database and LandGEM model. Default collection efficiencies were later revised downward for use in lifecycle inventories (e.g. EPA WARM) based on an updated review of the available data (Barlaz, 2012). The EPA has also used a default efficiency of 85 % in a 2013 study, regulatory impact analysis for landfill New Source Performance Standards, and its emission factor database, AP-42 (US EPA, 2006a, 2013a, 2016).

New measurements have added significantly to our understanding of landfill emissions, but have not been reflected in the current collection efficiency defaults widely used in GHG inventories and lifecycle assessments. A growing body of peer-reviewed studies and a prominent report by UNEP (2021) have reported measured landfill emissions significantly greater than current models. Therefore, a comprehensive

review was completed in this study to determine if changes to collection efficiency defaults were needed to bring measurements and models into better alignment.

2. Materials and methods

Landfill methane measurement data from 26 studies conducted between 1999 and the present were assembled into a comprehensive dataset covering variation in landfill size, cover materials, annual precipitation, geographic location (region), and measurement technique deployed (see Table SM-3–1). Essentially all measurements for these studies were done during operational hours of the landfills, which is typically an 8–10 h period during the day. Studies were selected based on geographic location of the landfills studied, as well as availability of data necessary for calculating collection efficiency from emissions measurements where one was not provided in the respective study. Studies from Europe, Canada, and the US were selected because they generally represent similar wastes, landfill design and operation, although years of biodegradable waste diversion in many European countries could have a significant impact on methane generation. Calculation required an emissions measurement made using any of the techniques described in the introduction and a contemporary figure for the recovered quantity of methane. Oxidation estimates based on measurements were also extracted and utilized for calculation of collection efficiency where available.

Review of each study was done to extract available data, including landfills studied, their locations, time when measurements took place, the measurement technique(s) deployed, emissions measurements, cover type(s) present at the time, as well as oxidation measurements. Data were categorized by measurement technique, all of which fell into four groups: flux chamber, ground plume, aerial plume, and VRPM. Three studies were based on eddy covariance, integrated surface monitoring, and surface monitoring techniques, and were excluded from the analysis, given the small sample size.

Consistent with current modeling practice, landfill measurement data were categorized into daily, intermediate, and final cover types. Categorizations were made for each landfill based on information regarding cover properties either already extracted from the published study or reported to regulatory agencies, namely the US EPA. Landfills measured using techniques with smaller sample sizes (i.e. VRPM), were assigned a cover type based on the area(s) of the landfill from which emissions were measured (e.g. US EPA, 2011b). For those landfills where the measurement approach covered more than one cover type at the time measurements were made, a single cover type was assigned based on the surface area (m²) of each cover type. Where data through the GHGRP were not available for surface area of each cover type (e.g. landfills in Europe), description offered in the corresponding study was used to estimate percentage coverage by the different cover types. In order to better understand potential effects of this assumption, particularly in terms of the influence of daily cover, a comparison was made between collection efficiency results for these landfills where daily cover was also present at the time whole-plume measurements were made, and those where daily cover was not present.

Each individual emissions estimate (or collection efficiency estimate) expressed as a unique value in a study was likewise categorized as its own data point, consistent with the review by Barlaz (2012), which informed the selection of collection defaults for the EPA's LCA tools and considered all collection efficiency estimates for each landfill included, as separate data points. A separate sensitivity analysis was also performed to determine the impact of this approach, by creating an average data point for each landfill, instead of each emissions estimate.

Emissions, gas collection, and soil oxidation data were used to calculate collection efficiencies for each data point, both for individual measurements, and, as a sensitivity analysis, each landfill. For the sensitivity analysis, an average landfill collection efficiency was calculated by taking the average of each individual collection efficiency

associated with each individual emissions estimate. In several studies, gas collection data were available in the published manuscript. However, for many studies, additional data were required. For US-based studies, gas collection data from the GHGRP were used where no collection data were presented (US EPA, 2021).

Where collection efficiency was calculated from reported data, the following equations were used:

$$\text{CollectionEfficiency} = \frac{\text{Collected}}{\text{Collected} + \text{Emitted} + \text{Oxidized}} \quad (1)$$

$$\text{CollectionEfficiency} = \frac{\text{Collected}}{\text{Collected} + \text{Emitted}} \quad (2)$$

Equation (1) mirrors how collection efficiency data are used in the prevailing emissions and lifecycle models, including the GHGRP, WARM, and the MSW DST, where separate assumptions for gas collection efficiency and soil oxidation are applied. Eq. (1) was therefore applied to calculate a collection efficiency estimate for as many data points as possible, pending the availability of oxidation data from the study. Where oxidation data were not made available by the study and the given landfill was located in the US, oxidation defaults from the US EPA were applied to calculate collection efficiency using Eq. (1). Eq. (1) was ultimately applied to most landfills included in the study (69 % overall).

Equation (2) was applied when no soil oxidation data were available and the US EPA oxidation defaults would not be viable (i.e. the landfill was not located in the US). Given that soil oxidation is not included in the denominator, the total gas generation is underestimated slightly. Therefore, for a given measured emission, the calculated collection efficiency is biased high, resulting in an underestimation of emissions when the resultant gas collection efficiency is applied to a modeling approach where a separate soil oxidation factor is applied.

Each data point was categorized into various subsets based on cover type, consistent with the methodology used by the GHGRP described above, as well as annual precipitation, geographical region, measurement technique, and a sample size range category. For annual precipitation, landfills were grouped by ranges (<20 in/y, 20–40 in/y, and > 40 in/y) consistent with the method employed by GHGRP, the MSW DST, and WARM for selection of first order decay rate constants (US EPA, 2009, 2020). Ultimately landfills were divided into 'Dry', 'Average', and 'Wet' groups for assessing the relationship between annual precipitation and measured collection efficiency. Notably, differing decay rate constants were not collected or used and did not directly factor into this analysis. The same method used to determine differing decay rate constants by the above-mentioned models was merely used to categorize landfills by annual precipitation.

Regional analysis was conducted by separating landfills into three groups: California, N. America – other, and Europe. These groups were chosen to be broadly representative of the three most prominent systems of landfill regulation within the sample of landfills included. While California landfills are also covered under the federal New Source Performance Standard requirements, the state has added significantly greater requirements around the commencement of collection, surface monitoring, and collection duration that have been theorized to result in greater collection efficiency (US EPA, 2020).

Cover-dependent collection efficiencies were calculated using an arithmetic mean for each of the 153 individual emission estimates, and, as a sensitivity, each of the 97 individual landfills. Other descriptive statistics including standard deviations and sample sizes were also calculated for the entire dataset as well as various subsets. Additional statistical analyses were conducted to determine whether differences between cover types, measurement techniques, sample size of measurements, annual precipitation, and region, were statistically significant. The Kolmogorov-Smirnov test was used to test for normal distributions and homogeneity within each subset of the overall dataset. The Kruskal-Wallis non-parametric test was then applied to determine

significance of each independent variable for collection efficiency. Finally, a multiple linear regression was performed to test significance of each predictor variable on estimated collection efficiency.

2.1. Analysis of landfills with multiple cover types

Except in very limited cases, landfill whole-plume measurements typically aggregate emissions from areas of the landfill surface with different cover types in place (see SM-4.1 for the percentage breakdown of each cover type for landfills measured using whole-plume measurements). The approach to categorize landfills as a single cover type could have potentially biased results, especially for intermediate and final cover landfills where daily cover was also present at the time whole plume measurements were made and therefore could have disproportionately contributed to the total flux measured from the landfill.

To ascertain the impact of this simplification, a subset of 42 landfills with data available for cover type by area and quantity of collected methane from the GHGRP were identified. Emissions were recalculated using the methodology of the GHGRP using the average cover-type dependent default collection efficiency values from the complete dataset developed through this analysis, in place of the GHGRP defaults. The recalculated emissions were compared against the measured emissions from the underlying published studies. Microsoft Excel's Solver function was then used to find adjusted cover-type dependent collection efficiency defaults that minimized both the aggregate total deviation between the measured emissions and the recalculated modeled emissions for the data subset, as well as balance the over and underprediction compared with the measured values.

3. Results

Average collection efficiency by cover type of the entire dataset, for which each individual collection efficiency estimate was treated as a separate data point, were 40 % for daily cover, 60 % for intermediate, and 74 % for final cover, all below current defaults of the GHGRP (see Table 1). The default values applied through GHGRP are here used as a point of comparison due to their direct translation to US landfill emissions estimates reported to the US EPA.

The measurement techniques used for quantifying landfill emissions had a statistically significant impact on results, particularly for flux chamber measurements (see Fig. 1). The exclusion of flux chamber measurements (micro-scale measurements), resulted in collection efficiency values of 40 % for daily cover, 55 % for intermediate, and 64 % for final cover.

Kolmogorov-Smirnov tests were used to test for normal distributions within the dataset. All arrangements according to subsets representing independent variable categories, including cover type, were found to be non-normally distributed. Therefore, a Kruskal-Wallis non-parametric test was performed to test for significance of cover type for collection efficiency, which indicated a statistically significant relationship at a 99 % confidence interval ($H(2) = 12, P = 2.0 \times 10^{-3}$). Bonferroni correction was applied for multiple comparisons of Kruskal Wallis tests. Kruskal-Wallis test results indicated no significant difference between daily and intermediate cover for collection efficiency ($H(1) = -36, P = 1.6 \times 10^{-1}$), but significant differences between daily and final ($H(1) = -64, P$

$= 5.0 \times 10^{-3}$), and between intermediate and final ($H(1) = -28, P = 1.7 \times 10^{-3}$), both at 99 % confidence intervals respectively. For all quantitative results demonstrated throughout this section, the full list of referenced sources for the entire dataset is provided in the [Supplementary Material](#) (see SM-3).

Measurement technique also had a statistically significant relationship to resulting measured collection efficiency at a 99 % confidence level, per results of a Kruskal-Wallis test ($H(3) = 54, P < 0.001$). The different measurement techniques have very different sample sizes, which range from whole-site measurements that can capture emissions from an entire landfill to micro-scale measurements that measure flux from an area of less than 1 m^2 (see Table 2).

A statistically significant relationship was found between sample size of measurement and resulting collection efficiency at a 99 % confidence level, per results of a Kruskal-Wallis test ($H(3) = 48, P < 0.001$) with data grouped according to scales of measurement technique. A homogeneous group was formed between collection efficiency estimates made from micro-scale (flux chamber) and macro-scale (VRPM) measurements according to results of a Kruskal-Wallis nonparametric test ($H(1) = -4.8, P = 1.0 \times 10^{-3}$). Collection efficiency values calculated from measurements made using techniques with smaller sample sizes (e.g. flux chambers) were higher, while they were lower for values calculated from measurements made using whole-plume methods. Collection efficiency estimates from whole site (aerial and ground plume) measurements differed significantly with a 99 % confidence interval from both micro-scale ($H(1) = 54, P < 0.001$) and macro-scale ($H(1) = 49, P < 0.001$) measurement-based estimates.

Separated results demonstrated variability of collection efficiency estimates based on the measurement technique used, as well as cover properties of a given landfill (see SM-3–2). Landfills were separated by cover type using the method described in the above Materials and Methods section.

Sensitivity analysis revealed no large effect to results from maintaining individual data points from measurements made at the same landfill relative to including only one data point per landfill, in terms of both average collection efficiency by cover type and standard deviation within these subsets (see SM-5). These results could, however, be an indication of uncertainty in the underlying emissions and derived collection efficiency estimates.

A statistically significant relationship at a 99 % confidence level was found between annual precipitation and measured collection efficiency according to results of a Kruskal-Wallis non-parametric test ($H(2) = 20, P < 0.001$). Landfills in dry climates had the highest average collection efficiency values for both intermediate and final cover. Insufficient data were available for daily cover in both dry and wet climates to make a distinction between the groups for this category. Similarly, a statistically significant relationship at a 99 % confidence level was found between region and measured collection efficiency according to results of a Kruskal-Wallis non-parametric test ($H(2) = 27, P < 0.001$), when divided between landfills in California, N. America – other, and Europe. California landfills had the highest collection efficiencies for both intermediate and final cover, followed by N. America – other, and then Europe. Again, insufficient data were available for daily cover to make any distinctions between these groups for that category of cover type.

A multiple linear regression was used to test significance of cover

Table 1
Comparison: Results and Currently Applied EPA GHGRP Default Values Including and Excluding Flux Chamber Data.

Cover	Measurements								GHGRP Default Collection Efficiency
	Including Flux Chamber Data				Excluding Flux Chamber Data				
	μ	95th Percentile	σ	n	μ	95th Percentile	σ	n	
Daily	40.4 %	69.0 %	21.7 %	6	40.4 %	69.0 %	21.7 %	6	60 %
Intermediate	59.6 %	92.7 %	22.5 %	124	55.4 %	86.0 %	21.2 %	98	75 %
Final	74.2 %	98.7 %	19.9 %	23	64.4 %	82.5 %	16.4 %	14	95 %

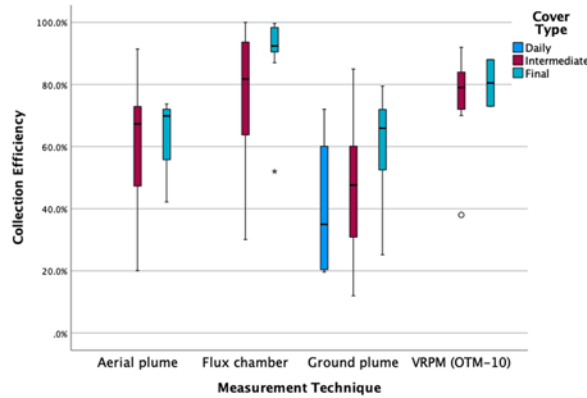


Fig. 1. Estimated Collection Efficiency by Measurement Technique and Cover Type. Star indicates extreme value and hollow circle indicates outlier.

Table 2
Measurement Technique Scale and Sample Size.

Technique	Scale	Sample Size (m ²)		Measurements (n)	Reference
		Min.	Max.		
Aerial plume	Whole site	259,606	>4 million	42	This analysis ^a
Ground plume	Whole site	30,000	751,000	63	This analysis ^a
VRPM	Macro	11,500	40,000	13	US EPA 2012
Flux chamber	Micro	N/a	< 1	35	Hanson et al., 2020

^a Minimum and maximum sample size figures represent respective figures reported in studies making up the dataset collected and analyzed for this study. For the full dataset including surface area covered in each respective study used, see SM-3.

type, measurement technique, sample size, annual precipitation, and region, for predicting estimated collection efficiency. The overall regression was statistically significant ($R^2 = 0.44$, $F(5,147) = 24$, $P < 0.001$). Micro-scale sample size (flux chamber measurements) had the greatest magnitude of impact on estimated collection efficiency of those predictor variables tested ($\beta = 25$, $P < 0.001$). Other significant predictors included California for region ($\beta = 19$, $P < 0.001$), daily cover ($\beta = -19$, $P = 2.0 \times 10^{-2}$), intermediate cover ($\beta = -12$, $P = 2.0 \times 10^{-3}$), and macro-scale measurements (i.e. VRPM, $\beta = 20$, $P < 0.001$).

3.1. Landfills with multiple cover types

To account for potential bias introduced from assumptions around classifying landfills as a single cover type, adjusted default collection efficiencies were developed to minimize overall deviation between the GHGRP model and measurements for a subset of 42 landfills for which the needed data on landfill area by cover type were available from the GHGRP (see Table 3).

Two landfills were excluded from the model as outliers, for falling outside the 95th percentile for percent deviation between measured

emissions and modeled emissions using data-derived recommended defaults. Adjusted defaults resulting from the analysis were 41 % for daily cover, 69 % for intermediate, and 71 % for final. The model adjusted defaults were calculated from the full dataset, to minimize the aggregate difference between modeled and measured emissions, as well as balance over and underprediction compared with measured emissions.

4. Discussion

Since the defaults for collection efficiency currently used under the US EPA's GHGRP were established in 2009, there has been an increased level of attention paid to methane generally and landfills specifically, as well as availability of new, more precise measurement technologies. Together these developments have resulted in a significantly larger dataset than was previously available. Furthermore, there have been significant advancements in measurement approaches for landfills, culminating in the viability of aerial plume measurements, taken from aircraft using cavity ring-down spectrometers to measure low concentrations of methane quickly and accurately. Moreover, new methods

Table 3
Landfill Gas Collection Efficiency Model Default Values Comparison.

Collection Efficiency Defaults	Daily	Intermediate	Final	Avg. Percent Deviation from Measured	Overall Percent Underprediction	Overall Percent Overprediction
EPA GHGRP	60 %	75 %	95 %	~38 %	83 %	18 %
Full Dataset	40 %	55 %	64 %	24 %	38 %	63 %
Adjusted Defaults	41 %	69 %	71 %	4 %	50 %	50 %

involving use of unmanned aerial vehicles (UAVs) and satellites to measure whole landfill emissions more accurately and efficiently are developing quickly (Cusworth et al., 2019; Münster et al., 2019). These new measurement approaches, as well as previously applied ground-based methods, allow for the measurement of an entire landfill's emissions.

While the advent of whole-landfill measurement is an important step forward in quantifying landfill emissions, it presents a challenge with regard to informing cover-type specific model defaults, since most landfills have areas with different cover types in place. The presence of daily cover areas at a landfill otherwise categorized as an “intermediate cover” or “final cover” landfill may significantly affect overall emissions measurements and derivative collection efficiency estimates. As well, it is possible that emissions could differ significantly at night and therefore bias the results of corresponding measurements, as Duren et al. also indicated (2019). However, even when we adjust for different cover types in a model optimized to reduce overall variation relative to actual measurements, the resultant adjusted defaults remain significantly below currently applied defaults through the GHGRP (See Table 4).

There were statistically significant differences in average collection efficiencies observed between data collected with different measurement techniques. Normally, this would be cause for significant alarm in a scientific study, as the measurement approach should be independent of the value being measured. However, the measurement techniques used for quantifying landfill emissions are not capturing the same information, as there are significant uncertainties associated with both the (landfill) areas contributing emissions and the measurement techniques applied. As described, the measurable area differs significantly. As sample size relative to total landfill area increases from flux chambers to whole site methods, it not only becomes more likely that hotspots are captured, but the sample will also include source terms not covered by flux chambers. These include the landfill working face, and the gas and leachate collection and management systems (Spokas et al., 2006; Münster et al., 2019).

Static flux chambers can impact the diffusion of methane across the soil column through increased concentration of methane over time above the surface of the landfill. Lastly, flux chambers can only capture advective flux if the placement of the chamber coincides with a preferential pathway and static flux chambers can obfuscate any measurement of advective flux even if a preferential pathway is present. While flux chamber measurements may bias resultant collection efficiency estimates high, inclusion of terms noted by methods capturing the entire landfill plume may also bias resultant collection efficiency estimates low. Overall, significant differences may be driven by the area being measured, potentially more so than the measurement technique itself.

As a result, the cover-specific gas collection efficiencies found here are no longer necessarily only capturing the efficacy of the cover material. Rather, these defaults should be viewed as values to accurately express a lumped parameter where the model does not provide for separate source terms for hot-spots and gas collection equipment leaks. A well installed geomembrane final cap will have a very low flux through the cover (Spokas et al., 2006); however, diffusion through a

final cover is very unlikely to be the predominate means of methane emissions from a landfill (Chen et al., 2022). Furthermore, the collection efficiency data within a cover type also capture a significant variation in system design, operation and maintenance that is not readily defined in a modeling parameter.

A comparison of data from landfills for which multiple measurement techniques have been applied is illustrative. Börjesson et al., (2000) estimated collection efficiency of the Falköping landfill (Sweden) from three days of flux chamber measurements in 1997 as 30–60 %. Using plume measurements coupled with dispersion modeling in 1998 and 1999, Galle et al., (2001) estimated collection efficiency of the same landfill to be 18 %. More recent results from California exhibit a similar pattern where flux chamber measurements indicated higher collection efficiency estimates, than those resulting from aerial plume measurements (Hanson et al., 2020). This was true for five landfills included by Hanson et al., (2020), where in comparison, collection efficiency estimates made from flux chamber measurements were on average 1.6 times higher than those from aerial measurements.

4.1. Conclusions

The proper quantification of emissions is critical for developing and guiding appropriate policy mechanisms to help reduce GHG emissions. The growing focus on methane, including in the recent Global Methane Pledge, underscores the need for better quantification of its sources, including from the waste sector. Current modeling approaches for landfill emissions, including those used in the GHGRP and current LCA models are significantly underestimating actual emissions (UNEP, 2021). While measurement data are preferred, modeling approaches will remain important given constraints of measurement-based approaches.

Revised default collection efficiency values for use both in inventory and lifecycle models can significantly reduce the currently observed disparity between actual measurements of landfill emissions and model estimates. Based on this review of all available data, average values for collection efficiency excluding flux chamber measurements, are 40 % for daily cover, 55 % for intermediate cover, and 64 % for final cover. These values were adjusted via model application because many landfills included had more than one cover type in place at the time whole-plume measurements were made. Per these results, adjusted values of 41 % for daily cover, 69 % for intermediate, and 71 % for final cover are recommended for use in reporting schemes.

Until such time as direct measurement of landfill methane emissions becomes commonplace, existing data support the basic conceptual underpinnings of existing modeling approaches, namely, the assumption that collection efficiency is dependent on cover type. While cover type is but one of several independent variables shown to affect collection efficiency, a relationship between cover type and collection efficiency, assumed present by the FOD Method and its various iterations globally, was indeed shown to be statistically significant.

A statistically significant relationship was also found between measurement technique used and measured collection efficiency. This does

Table 4
Comparison: Recommended and Adjusted Results against Model Default Collection Efficiency Values.

Cover	This Study			GHGRP	MSW DST/WARM*	AP-42
	Full Data Set		Adjusted for Multiple Cover Types			
	Including Flux Chamber Data	Excluding Flux Chamber data				
Daily	40 %	40 %	41 %	60 %	50 %	75 %
Intermediate	60 %	55 %	69 %	75 %	75 %	
Long-term	N/a	N/a	N/a	N/a	82.5 %	
Final	74 %	64 %	71 %	95 %	90 %	

Sources: (US EPA, 2008a, 2008b, 2009; 2011a, 2020, 2021b, RTI, 2021).

* Values shown are applied according to years since waste is placed in a landfill, based on assumed changes in landfill operational practices including changes to cover.

not necessarily imply that any of the measurement techniques captured here are inaccurate or lack value. In contrast, it uncovers a mismatch in earlier available data from flux chambers, which characterized diffusion of methane through a homogeneous soil cap, and how we apply those data to landfilling in practice, which represents a complex amalgamation of diffusion through cover soils together with small scale point sources such as cracks, surface imperfections, cap penetrations, and gas and leachate collection systems; and significant variation in system design, operations, and maintenance over time and between landfills.

Current models ignore the complexity of these individual source terms in lieu of a blended collection efficiency by cover type. However, we can substantially improve the alignment of our models with actual measurements by considering default cover-dependent collection efficiencies more as lumped modeling parameters. These can, in their aggregate, reasonably simulate the complex conglomeration of sources present at modern landfills, at least until such point that more ubiquitous measurement is possible.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data used has been included in [Supplementary Material](#) with corresponding references provided.

Appendix A. Supplementary material

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.wasman.2023.12.042>.

References

- Alvarez, R.A., Zavala-Ariza, D., Lyon, D.R., Allen, D.T., Barkley, Z.R., Brandt, A.R., Davis, K.J., Herrndon, S.C., Jacob, D.J., Karion, A., Kort, E.A., Lamb, B.K., Lauvaux, T., Massakkers, J.D., Marchese, A.J., Omara, M., Pacala, S.W., Peischl, J., Robinson, A.L., Shepson, P.B., Sweeney, C., Townsend-Small, A., Wofsy, S.C., Hamburg, S.P., 2018. Assessment of methane emissions from the U.S. oil and gas supply chain. *Science* 361, 186–188. <https://doi.org/10.1126/science.127204>.
- Anani, H.R., Reinhard, D.R., Niskanen, A., 2013. Comparison of first-order-decay modeled and actual field measured municipal solid waste landfill methane data. *Waste Manage.* 33, 2720–2728. <https://doi.org/10.1016/j.wasman.2013.07.025>.
- Aronica, S., Bonanno, A., Piazza, V., Pignato, L., Trapani, S., 2009. Estimation of biogas produced by the landfill of Palermo, applying a Gaussian model. *Waste Manage.* 29, 233–239. <https://doi.org/10.1016/j.wasman.2008.02.026>.
- Babilotte, A., 2011. Field comparison of methods for assessment of methane fugitive emissions from landfills. *Environ. Res. Educ. Foundation*. <https://erdfn.org/wp-content/uploads/2015/12/FugitiveEmissionsFinalReport.pdf>.
- Barlaz, M.A., 2012. Critical Analysis of Literature on Landfill Gas Collection Efficiency. *Bioprocess, G., Danielsson, A., Svensson, B.H., 2000. Methane fluxes from a Swedish landfill determined by geostatistical treatment of static chamber measurements. Environ. Sci. Technol.* 34, 4044–4050. <https://doi.org/10.1021/es991350a>.
- California's Department of Resources Recycling and Recovery (CalRecycle), 2012. CalRecycle Review of Waste to Energy and Avoided Landfill Methane Emissions. https://prc.lacounty.gov/wp-content/uploads/2019/08/CalRecycle_Review_of_WTE_Avoided_Emissions_07032012.pdf.
- California Air Resources Board (CARB), 2009. Staff Report: Initial Statement of Reasons for the Proposed Regulation to Reduce Methane Emissions from Municipal Solid Waste Landfills, Appendix D: Evaluation of Landfill Gas Collection Efficiency. <https://www.arb.ca.gov/regs/2009/landfill99/tee.pdf>.
- Chen, Z., Kamchoon, V., Chen, R., 2022. Landfill gas emission through compacted clay considering effects of crack pathway and intensity. *Waste Manage.* 143, 215–222. <https://doi.org/10.1016/j.wasman.2022.02.032>.
- Cusworth, D.H., Jacob, D.J., Varon, D.J., Chan Miller, C., Liu, X., Chance, K., Thorpe, A. K., Duren, R.M., Miller, C.E., Thompson, D.R., Frankenberg, C., Gunter, L., Bandele, C.A., 2019. Potential of next generation imaging spectrometers to detect and quantify methane point sources from space. *Atmos. Meas. Tech.* 12, 5655–5668. <https://doi.org/10.5194/amt.12.5655.2019>.
- Duren, R.M., Thorpe, A.K., Foster, K.T., Rafiq, T., Hopkins, F.M., Yadav, V., Bue, B.D., Thompson, D.R., Conley, S., Colombi, N.K., Frankenberg, C., McCabbin, I.B., Eastwood, M.L., Falk, M., Hermer, J.D., Croes, B.E., Green, R.O., Miller, C.E., 2019. California's methane super-emitters. *Nature* 575, 180–184. <https://doi.org/10.1038/s41586-019-1720-3>.
- Eggleston, H.S., Intergovernmental Panel on Climate Change, National Greenhouse Gas Inventories Programme, Chikyo Kankyo Sonryaku Kenkyu Kikan, 2006. 2006 IPCC guidelines for national greenhouse gas inventories. <https://www.ipcc-nggip.iges.or.jp/public/2006gl/>.
- Galle, B., Samuelsson, J., Svensson, B.H., Björsson, G., 2001. Measurements of methane emissions from landfills using a time correlation tracer method based on FTIR absorption spectroscopy. *Environ. Sci. Technol.* 35, 21–25. <https://doi.org/10.1021/es011008>.
- Green, R.B., Chanton, J.P., Hater, G.R., Goldsmith, C.D., Swan, N., 2011. Estimates of methane emissions from western landfills using OTM 10.
- Hanson, J.L., Yesiller, N., Manheim, D.C., 2020. Methane, nitrous oxide, and trace volatile organic compound emissions and gas collection system efficiencies in California landfill. California Air Resources Board. <https://ww2.arb.ca.gov/resources/documents/landfill-gas-research>.
- Huitric, R., Kong, D., Maguin, S., Sullivan, P., 2007. Field comparison of landfill gas collection efficiency measurements. Los Angeles County Sanitation Districts; SCS Engineers. <https://www.scsengineers.com/scs-white-papers/field-comparison-of-landfill-gas-collection-efficiency-measurements-by-ray-huitric-dung-long-lisa-scales-and-steven-maguin-all-of-los-angeles-county-sanitation-districts-whittier-county-and/>.
- Intergovernmental Panel on Climate Change (IPCC), 2021. Assessment Report 6. URL: <https://www.ipcc.ch/report/ar6/wg1/#SPM>.
- Levis, J., Barlaz, M., 2014. Landfill Gas Monte Carlo Model Documentation and Results. https://www.epa.gov/sites/default/files/2016-03/documents/landfill_gas_mont_carlo_model.pdf.
- McKain, K., Down, A., Raciti, S.M., Budney, J., Hutya, L.R., Floerchinger, C., Herndon, S.C., Nehrkorn, T., Zahniser, M.S., Jackson, R.B., Phillips, N., Wofsy, S.C., 2015. Methane emissions from natural gas infrastructure and use in the urban region of Boston, Massachusetts. *PNAS* 112, 1941–1946. <https://doi.org/10.1073/pnas.1410261112>.
- Miller, S.M., Wofsy, S.C., Michalak, A.M., Kort, E.A., Andrews, A.E., Biraud, S.C., Dlugokencky, E.J., Eluszkiewicz, J., Fischer, M.L., Janssens Maenhout, G., Miller, B. R., Miller, J.B., Montzka, S.A., Nehrkorn, T., Sweeney, C., 2013. Anthropogenic emissions of methane in the United States. *PNAS* 110, 20018–20022. <https://doi.org/10.1073/pnas.1214392110>.
- Mohsen, R.A., 2019. Estimation of Greenhouse Gas Emissions in Municipal Solid Waste Landfills in Ontario Using Mathematical Models and Direct Measurements. https://atrium.lib.uoguelph.ca/xmlui/bitstream/handle/10214/17659/A.Mohsen_Riham_201912_phd.pdf?sequence=3&isAllowed=y.
- Monster, J., Kjeldsen, P., Scheutz, C., 2019. Methodologies for measuring fugitive methane emissions from landfills – A review. *Waste Manage.* 87, 835–859. <https://doi.org/10.1016/j.wasman.2018.12.047>.
- Onak, H., 2010. Literature review: methane from landfills: methods to quantify generation, oxidation, and emission. Sustainable Landfill Foundation; NV Afvalzorg Holding. <https://www.afvalzorg.nl/content/uploads/2018/03/Methane-from-landfills-Methods-to-quantify-generation-oxidation-and-emission.pdf>.
- Peischl, J., Ryerson, T.B., Brioude, J., Aikin, K.C., Andrews, A.E., Atlas, E., Blake, D., Daube, B.C., de Gouw, J.A., Dlugokencky, E., Frost, G.J., Gentner, D.R., Gilman, J.B., Goldstein, A.H., Harley, R.A., Holloway, J.S., Koffler, J., Kuster, W.C., Lang, P.M., Novelli, P.C., Santoni, G.W., Trainer, M., Wofsy, S.C., Parrish, D.D., 2013. Quantifying sources of methane using light alkanes in the Los Angeles basin. *California J. Geophys. Res.: Atmos.* 118, 4974–4990. <https://doi.org/10.1002/jgrd.50413>.
- Plant, G., Kort, E.A., Floerchinger, C., Gvakharia, A., Vimont, I., Sweeney, C., 2019. Large fugitive methane emissions from urban centers along the U.S. East Coast. *Geophys. Res. Lett.* 46, 8500–8507. <https://doi.org/10.1029/2019GL082635>.
- Research Triangle Institute (RTI), 2021. MSW DST v2. <https://mswdata.rti.org/msw-dst-v2/model-v2.htm>.
- Saunio, M., Stavert, A.R., Poulter, B., Bousquet, P., Canadell, J.G., Jackson, R.B., Raymond, P.A., Dlugokencky, E.J., Houveling, S., Patra, P.K., Gais, P., Arora, V.K., Bastviken, D., Bergamaschi, P., Blake, D.R., Brailsford, G., Bruhwyler, L., Carlson, R. M., Carroll, M., Castaldi, S., Chandra, N., Crovisier, C., Oll, P.M., Covey, K., Curry, C.L., Eltise, G., Frankenberg, C., Gedney, N., Hegglin, M.I., Höglund-Isaksson, L., Hugelius, G., Ishizawa, M., Ito, A., Janssens Maenhout, G., Jensen, K.M., Joos, F., Kleinen, T., Krummel, P.B., Langenfelds, R.L., Laruelle, G.G., Liu, L., Machida, T., Maksyutov, S., McDonald, K.C., McNorton, J., Miller, P.A., Melton, J.R., Morino, I., Müller, J., Murguía Flores, F., Naik, V., Niwa, Y., Nioce, S., O'Doherty, S., Parker, R.J., Peng, C., Peng, S., Peters, G.P., Prigent, C., Pison, R., Ramonet, M., Regnier, P., Riley, W.J., Rosestretre, J.A., Segers, A., Simpson, J.J., Shi, H., Smith, S. J., Steele, L.P., Thornton, B.F., Tian, H., Tohjima, Y., Tubiello, F.N., Tsuruta, A., Viovy, N., Voulgarakis, A., Weber, T.S., van Vleet, M., van der Werf, G.R., Weiss, R. F., Worthy, D., Wunch, D., Yin, Y., Yoshida, Y., Zhang, W., Zhang, Z., Zhao, Y., Zheng, B., Zhu, Q., Zhu, Q., Zhuang, Q., 2020. The Global Methane Budget 2000–2017. *Earth Syst. Sci. Data* 12, 1561–1623. <https://doi.org/10.5194/essd.12.1561.2020>.
- Scharif, H., Jacobs, J., Onak, H., Hensen, A., 2005. Methods to ascertain methane emission of landfills. NV Afvalzorg Holding. <https://www.afvalzorg.nl/content/uploads/2017/09/Paper-methods-to-ascertain-methane-emission.pdf>.
- Spokas, K.A., Bogner, J.E., Chanton, J.P., Morcet, M., Aran, C., Graff, C., Golván, Y.-M. L., Hebe, I., 2006. Methane mass balance at three landfill sites: what is the efficiency of capture by gas collection systems? *Waste Manage.* 26, 516–525. <https://doi.org/10.1016/j.wasman.2005.07.021>.
- Solid Waste Association of North America (SWANA), 2013. Practical Methods for Measuring Landfill Methane Emissions and Cover Soil Oxidation.

- Solid Waste Industry for Climate Solutions (SWICS), 2007. Current MSW Industry Position and State-of-the-Practice on LFG Collection Efficiency, Methane Oxidation, and Carbon Sequestration in Landfills.
- Solid Waste Industry for Climate Solutions (SWICS), 2012. SWICS 2.2 Methane Oxidation Addendum 2012. Addendum to SWICS (2009) Current MSW Industry Position and State-of-the-Practice on LFG Collection Efficiency, Methane Oxidation and Carbon Sequestration in Landfills, Version 2.2. <https://www.scsengineers.com/wp-content/uploads/2015/03/Sullivan-SWICS-White-Paper-Version-2.2-Final.pdf>.
- Turner, A.J., Jacob, D.J., Wecht, K.J., Maasakkers, J.D., Landgren, E., Andrews, A.E., Brand, S.C., Boesch, H., Bowman, K.W., Deutscher, N.M., Dabey, M.K., Griffith, D. W.T., Hase, F., Kuze, A., Notholt, J., Ohyama, H., Parker, R., Payne, V.H., Sussmann, R., Sweeney, C., Velasco, V.A., Warneke, T., Weinberg, P.O., Wunch, D., 2015. Estimating global and North American methane emissions with high spatial resolution using GOSAT satellite data. *Atmos. Chem. Phys.* 15, 7049–7069. <https://doi.org/10.5194/acp-15-7049-2015>.
- Turner, A.J., Jacob, D.J., Benmergui, J., Wołosz, S.C., Maasakkers, J.D., Butz, A., Hasenkamp, O., Brand, S.C., 2016. A large increase in U.S. methane emissions over the past decade inferred from satellite data and surface observations. *Geophys. Res. Lett.* 43, 2218–2224. <https://doi.org/10.1002/2016GL067987>.
- Environment, U.N. (UNEP), 2021. Global Methane Assessment: Benefits and Costs of Mitigating Methane Emissions [WWW Document]. UNEP - UN Environment Programme. <http://www.unep.org/resources/report/global-methane-assessment-benefits-and-costs-mitigating-methane-emissions>.
- United States Environmental Protection Agency (US EPA), 2008. Background Information Document for Updating AP42 Section 2.4 for Estimating Emissions from Municipal Solid Waste Landfills. <https://www3.epa.gov/ttn/chief/ap42/v40/2/draft/d02d04.pdf>.
- United States Environmental Protection Agency (US EPA), 2008. AP-42, Compilation of Air Pollutant Emission Factors, Chapter 2.4 Solid Waste Landfills, October 2008 Draft. <https://www.epa.gov/sites/default/files/2020-10/documents/d02d04.0.pdf>.
- United States Environmental Protection Agency (US EPA), 2009. Protection of Environment; Mandatory Reporting of Greenhouse Gases; Subpart HH - Municipal Solid Waste Landfills; 74 Fed. Reg. 56374, (October 30, 2009). <https://www.federalregister.gov/documents/2009/10/30/E9-23315/mandatory-reporting-of-greenhouse-gases>.
- United States Environmental Protection Agency (US EPA), 2011. Final Background Information for Life-Cycle Inventory Landfill Process Model.
- United States Environmental Protection Agency (US EPA), 2011. Quantifying Methane Abatement Efficiency at Three Municipal Solid Waste Landfills; Final Report. http://cfpub.epa.gov/si/si_public_record_report.cfm?Lab=NRMRL&dirId=23437 (accessed August 11, 2021).
- United States Environmental Protection Agency (US EPA), 2013. Global Mitigation of Non-CO₂ Greenhouse Gases: 2010–2030. https://www.epa.gov/sites/default/files/2016-06/documents/mac_report_2013.pdf (accessed April 11, 2022).
- United States Environmental Protection Agency (US EPA), 2013. Protection of Environment; Mandatory Reporting of Greenhouse Gases; Subpart HH - Municipal Solid Waste Landfills; 78 Fed. Reg. 71968, (November 29, 2013). <https://www.govinfo.gov/contest/pkg/CFR-2020-title40-vol23/pdf/CFR-2020-title40-vol23-part98.pdf>.
- United States Environmental Protection Agency (US EPA), 2016. Protection of Environment; Standards of Performance for Municipal Solid Waste Landfills; 81 Fed. Reg. 59061, (August 29, 2016). <https://www.govinfo.gov/contest/pkg/FR-2016-08-29/pdf/2016-17687.pdf>.
- United States Environmental Protection Agency (US EPA), 2019. Greenhouse Gas Reporting Program Industrial Profile: Waste Sector, https://www.epa.gov/sites/default/files/2019-10/documents/waste_industrial_profile_9.30.2019.pdf (accessed August 8, 2021).
- United States Environmental Protection Agency (US EPA), 2020. Documentation for Greenhouse Gas Emission and Energy Factors Used in the Waste Reduction Model (WARM): Management Practices Chapters. https://www.epa.gov/sites/default/files/2020-12/documents/warm_management_practices_v15_10-29-2020.pdf (accessed December 20, 2021).
- United States Environmental Protection Agency (US EPA), 2021. Greenhouse Gas Reporting Program: Facility Level Information on Greenhouse Gases Tool (FLIGHT). <https://ghgdata.epa.gov/ghgp/main.do>.
- United States Environmental Protection Agency (US EPA), 2023. Draft Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2021. Annex 3.14: Methodology for Estimating CH₄ Emissions from Landfills. <https://www.epa.gov/system/files/documents/2023/02/US-GHG-Inventory-2023-Annex-3-Additional-Source-or-Sink-Categories-Part-B.pdf> (accessed March 7, 2023).
- Wecht, K.J., Jacob, D.J., Frankenberg, C., Jiang, Z., Blake, D.R., 2014. Mapping of North American methane emissions with high spatial resolution by inversion of SCIAMACHY satellite data. *J. Geophys. Res.: Atmos.* 119, 7741–7756. <https://doi.org/10.1002/2014JD021551>.



**Statement for the Record before the
U.S. Senate Committee on Environment and Public Works:
Avoiding, Detecting, and Capturing Methane Emissions from Landfills**

Introduction

GHGSAT is pleased to submit this statement to the U.S. Senate Committee on Environment and Public Works as part of the record for the hearing on January 31, 2024, titled “Avoiding, Detecting, and Capturing Methane Emissions from Landfills.” GHGSAT’s existing and operational commercial capability for monitoring of methane emissions, including from landfills, would be a key element for monitoring that was described in the hearing.

Established in 2011, GHGSat operates an existing and operational constellation of satellites and aircraft-based sensors that routinely perform facility-level greenhouse gas monitoring around the world. GHGSat currently has 11 operational commercial satellites in orbit and four more are under contract. Ten of the current GHGSat satellites are equipped with an advanced methane sensor with a spatial resolution of less than 30 meters and a detection threshold of 100 kg/hr of methane (CH₄), and one of the recently launched satellites is equipped with a carbon dioxide (CO₂) sensor with a similar spatial resolution and a detection threshold of 100 tonnes/hr of CO₂. With its current number of operational satellites, the constellation-level revisit rate is 1-2 days which is expected to be further reduced to daily revisit as more capacity is added. GHGSat is currently the only commercial or government entity capable of high-resolution greenhouse gas measurements from individual facilities such as landfills – a crucial aspect for attribution of emissions.

Emissions Monitoring

As an example of our methane emissions monitoring of landfills, GHGSat recently concluded a demonstration project with the University of Rochester funded by the New York State Energy Research and Development Authority (NYSERDA) to use its satellites to quantify methane emissions from the five largest active landfills in New York over the course of a year to understand how landfill emissions change over time (see Figure 1). Emission rates observed by the satellites have been shown to be consistent with measurements made by airborne and ground-based sensors. The Climate Leadership and Community Protection Act (CLCPA) of the state of New York was signed into law in June 2019, making New York the first state to mandate greenhouse gas reductions in legislation. Results from the University of Rochester / NYSERDA demonstration project will soon be published in the scientific literature and are expected to assist the state of New York in meeting its statutory requirements.

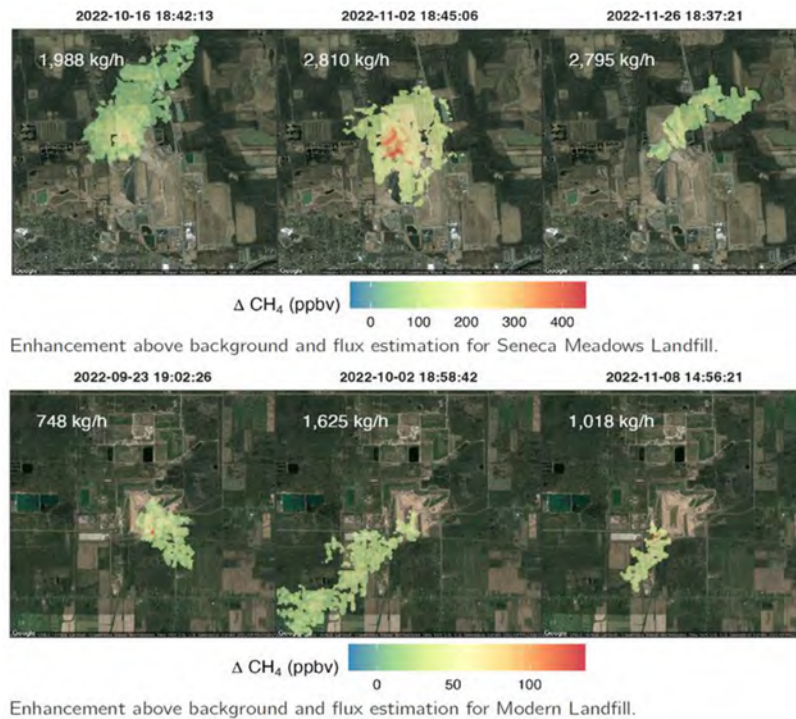


Figure 1: Example Satellite Observations of Landfill Methane Emissions
[Reproduced with permission from Dr. Lee Murray (University of Rochester)]

GHGSat's capabilities for monitoring methane emissions extend well beyond landfills. Figure 2 shows an observation made on June 15, 2022, by the GHGSat-C3 (Luca) satellite of livestock methane emissions from enteric fermentation at an agricultural feedlot in California. The emission rate was 698 kg/hr, which if sustained for a year would result in 5,300 metric tons of gas being released – enough to power more than 16,000 homes. California's 1.4-million cows are the biggest source of dairy-related methane in the United States. In 2017, state rules came into effect targeting a 40% reduction in levels of methane and fluorinated gases in the atmosphere by 2030 compared with 2013 values. Agriculture remains a major source of methane, with beef production responsible for 3.7% of all emissions. Globally, the world's 1.4-billion cows each burping up to 500 liters of methane per day.



Figure 2: GHGSat observation of agricultural methane emissions in California

GHGSat monitoring of emissions also includes a wide range of oil and gas facilities. Figure 3 shows an onshore greenhouse gas observation made on September 24, 2022, by the of methane emissions from an oil and gas facility northeast of Carlsbad, New Mexico. The measured emission rate was 190 kg/hr.

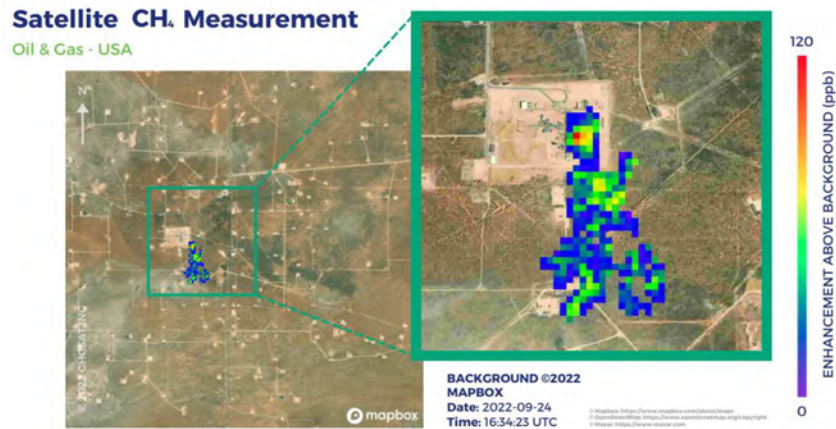


Figure 3: Example of GHGSat methane concentration map of an oil and gas facility in New Mexico

The accuracy of the satellite-based measurements has been independently validated on several occasions. For example, in October 2020 GHGSat performed a blind controlled release with



TotalEnergies of France to validate the performance of GHGSat's first commercial satellite less than two weeks after its launch. Analysis of the data collected identified the precise location of the methane release and the satellite rate estimate of 250 ± 140 kg/hr proved to be very close to the ground truth release rate of 234 kg/hr. More recently, a paper led by researchers at Stanford University reported on the single-blind validation of a GHGSat satellite achieving quantification accuracy of better than $\pm 20\%$ for each methane plume that was observed as part of the study [Sherwin et al., *Nature Sci Rep* 13, 3836 (2023)]. Another recent paper addressed the cost-effectiveness and efficacy of a tiered monitoring approach using GHGSat's satellite constellation and aircraft-based instruments [Esparza et al., *RSER* 178, 113265 (2023)].

In addition to observations of onshore facilities as shown above, GHGSat also has an operational capability to observe greenhouse gas emissions from offshore oil and gas facilities. Observing emissions over water is more challenging than over land because the surface of the ocean reflect poorly in the shortwave infrared, requiring satellites to perform offshore measurements at larger viewing angles and target the "glint spot" where the Sun reflects most strongly off the surface.

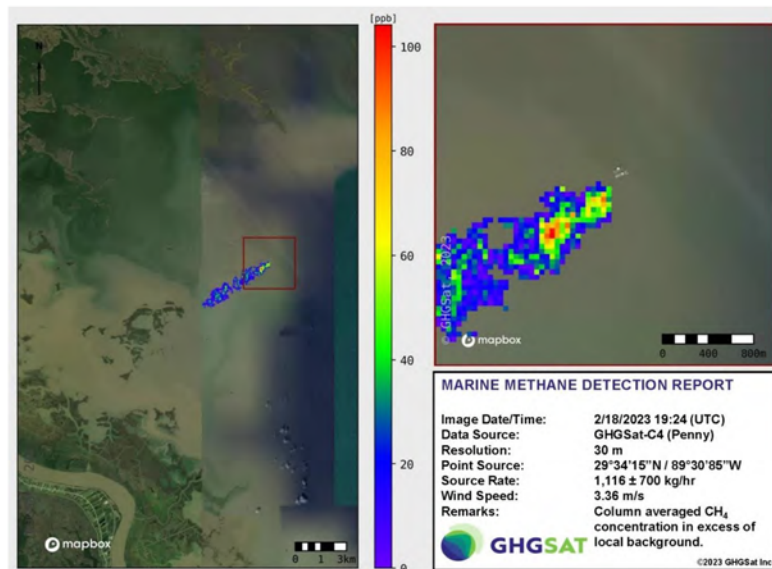


Figure 4: GHGSat observation of methane emissions in the Gulf of Mexico

Since May 2023, GHGSat has been working with the Satellite Analysis Branch (SAB) of NOAA to provide observations of methane emissions from offshore facilities in U.S. territorial waters. These observations are provided through SAB's participation in the scientific evaluation of



GHGSat's methane data under the NASA Commercial Smallsat Data Acquisition (CSDA) program as well as a parallel direct contract with SAB. Prototype reporting products will be developed by SAB from these observations, which will be assessed for potential ongoing operational utilization by NOAA, the Bureau of Safety and Environmental Enforcement (BSEE), and the Bureau of Ocean Energy Management (BOEM) in accordance with a formal user request from BSEE to NOAA. Figure 4 shows an observation made on February 18, 2023, by a GHGSat satellite of methane emissions from a platform off the coast of Louisiana, formatted as a hypothetical marine methane detection reporting product.

GHGSat has also demonstrated this capability of monitoring methane emissions from offshore platforms in September 2022 by monitoring the Nord Stream 2 pipeline leak in the Baltic Sea (see Figure 5), tasking its satellites to make 35 observations of the incident over the course of three days.

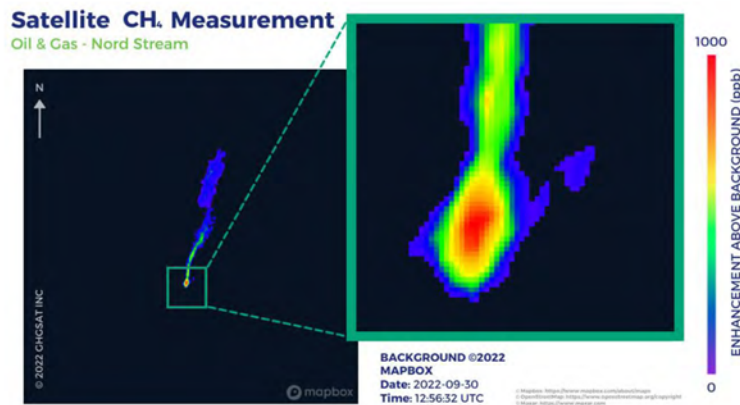


Figure 5: GHGSat observation of the Nord Stream 2 pipeline leak in September 2022

National Plan for Earth Observations

GHGSat recently submitted comments to the Draft National Plan for Earth Observations ("National Plan"), in which we noted that Objective 1.1 includes a focus on observations of greenhouse gas emissions, with the goal of reducing U.S. greenhouse gas emissions by 50-52% from 2005 levels by 2030 and reaching net-zero emissions by 2050. To achieve this goal, the U.S. cannot afford to spend years planning and demonstrating an observational system that could then take even more years to implement. According to the Sixth Assessment Report (AR6) of the U.N. Intergovernmental Panel on Climate Change (IPCC) that was released in August 2021, "All global modelled pathways that limit warming to 1.5°C...involve rapid and deep and, in most cases,



immediate greenhouse gas emissions reductions in all sectors... There is a rapidly closing window of opportunity to secure a livable and sustainable future for all... The urgency of the climate crisis demands that where operational and validated capabilities already exist, the Federal government should forgo demonstrations and proceed directly to operational utilization. " [emphasis added]

The National Plan also notes the importance of the Earth Observations Enterprise providing the needed spatial and temporal resolutions, as well as reduced data latency, in order to improve sustained monitoring and observational density. GHGSat has been providing facility-scale satellite methane emissions infrastructure monitoring services on an operational commercial basis since 2020, and the growing satellite constellation provides the resolution and latency that the National Plan requires.

As noted earlier, GHGSat recently launched the first orbital sensor able to pinpoint carbon dioxide (CO₂) emissions from individual industrial facilities such as cement or power plants. This sensor is the precursor to a new generation of space instruments that will build on GHGSat's extensive experience with methane emissions to provide frequent, accurate and independent high-resolution CO₂ data from individual sites. For the first time, operators of steel mills, power plants and petrochemical complexes will have access to independent, accurate and globally standardized emissions monitoring and data. Although many will have Continuous Emissions Monitoring Systems (CEMS) in place, independent verification can help them optimize day-to-day operations to reduce emissions. It will also improve the quality of Environmental Social and Governance reporting.

Non-U.S. Commercial Earth Observation Systems

The National Plan addresses U.S. government, international, and commercial systems, but does not specifically address international (non-U.S.) commercial systems. Non-U.S. commercial Earth Observation systems from trusted Five Eyes (FVEY) allies must be equally considered and integrated alongside U.S. commercial systems in order to meet the National Plan's requirements for "a defensible and resilient digital ecosystem" and to "improve national security by reducing risks of supply chain disruptions caused by conflict." Non-U.S. commercial remote sensing systems can fill gaps in domestic capabilities in a complementary manner, enabling novel capabilities and strengthening operational resilience in a manner that would not otherwise be possible with domestic government and commercial systems alone.

As an example, there are currently no U.S. systems with operational capabilities, products, services, and temporal and geographical coverage that are comparable to GHGSat's unique capabilities for global high-resolution greenhouse gas quantification from space. Even when comparable U.S. commercial capabilities become available in a few years, having access to data and analytics from both domestic commercial systems and trusted foreign commercial systems effectively creates a larger proliferated constellation that increases coverage and revisit frequency while also being more robust against disruption or degradation by adversaries.



Such an approach is consistent with the Administration's [Space Priorities Framework](#) which states that "as part of bolstering space mission assurance, the United States will leverage new commercial space capabilities and services to meet national security requirements and will *deepen the integration of U.S. national security space capabilities and activities with those of our allies and partners.*" [emphasis added] It is also consistent with the earlier [Commercial Remote Sensing Space Policy](#) which states that "foreign commercial remote sensing space capabilities...may be integrated in United States Government imagery and geospatial architectures, consistent with national security and foreign policy objectives."

Initiative B in the National Plan (Equitable Access and Ethical Use of Earth Observations Data) includes a focus on the democratization of data access, as well as expanding commercial data access. This would be best served by an even greater emphasis on the use of existing and operational commercial capabilities. In many cases, the private sector has capabilities that are well ahead of government, hence the importance for the government to look at partnerships with the private sector and not reinvent the wheel.

A crucial element of partnership with the private sector that is absent from both the National Plan and the National Strategy to Advance an Integrated U.S. Greenhouse Gas Measuring, Monitoring, and Information System (GHGMMIS) is that of anchor tenancy or guaranteed government business. This would be instrumental to commercial stability by providing predictable revenue, validating operational systems, and reducing future uncertainty. Anchor tenancy is a particularly important approach to encouraging the private sector both to maintain existing capabilities and to invest in new capabilities. To maximize the effectiveness of the GHGMMIS strategy, *the Federal government should consider procuring all the greenhouse gas data obtained by commercial satellites, aircraft and mobile monitoring platforms, and then making that data transparently available to all relevant stakeholders in government, industry and academia*, thereby accelerating implementation while mitigating risk and reducing compliance cost.

Conclusion

GHGSat greatly appreciates the opportunity to submit this statement for the record to the U.S. Senate Committee on Environment and Public Works and would welcome an opportunity for further discussions on how our monitoring capabilities would further U.S. Government goals related to greenhouse gas emissions.

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