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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 CO_2 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 CO_2 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 CO_2 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 landfills[1]. 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 States[2].

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.

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[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 methods[3] 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 measurements[3] 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 2016-2023[4]. 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

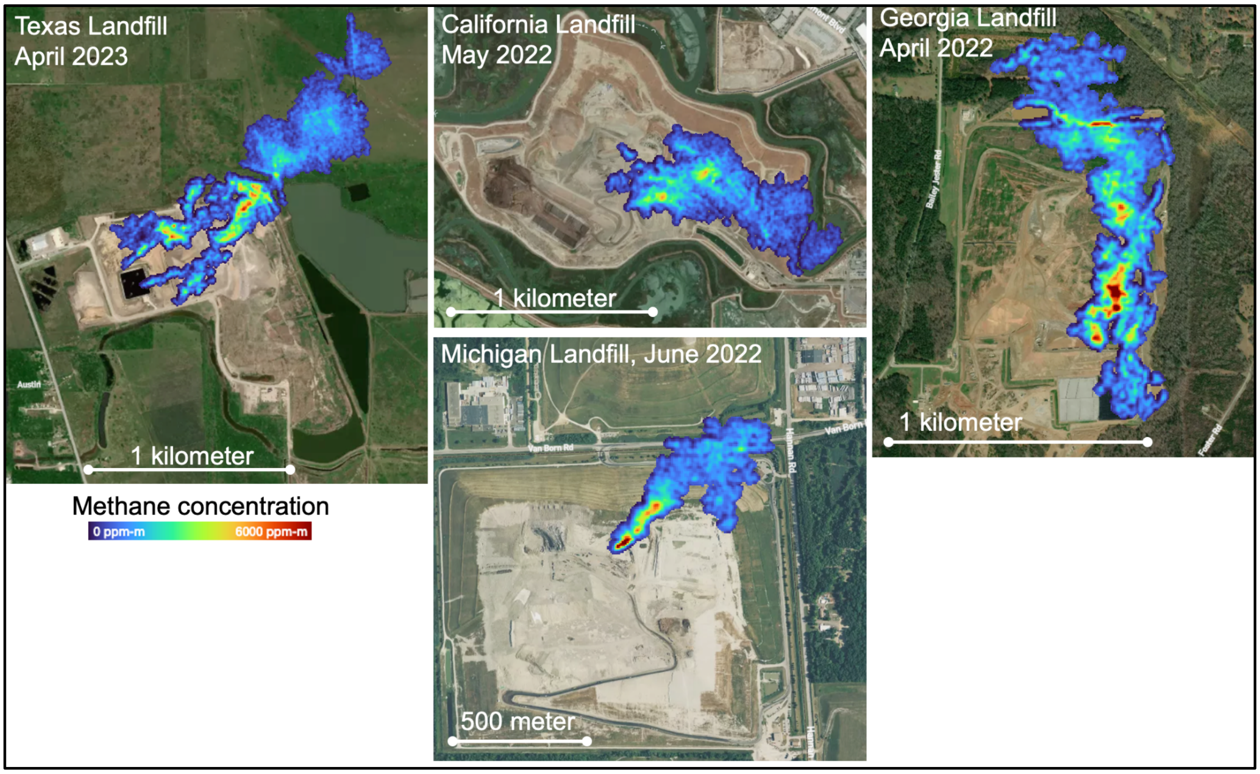

Figure 1. Examples of methane plumes at US landfills observed by Carbon Mapper (https://data.carbonmapper.org/). All methane plumes shown here have emission rates greater than 1000 kilograms of methane per hour.

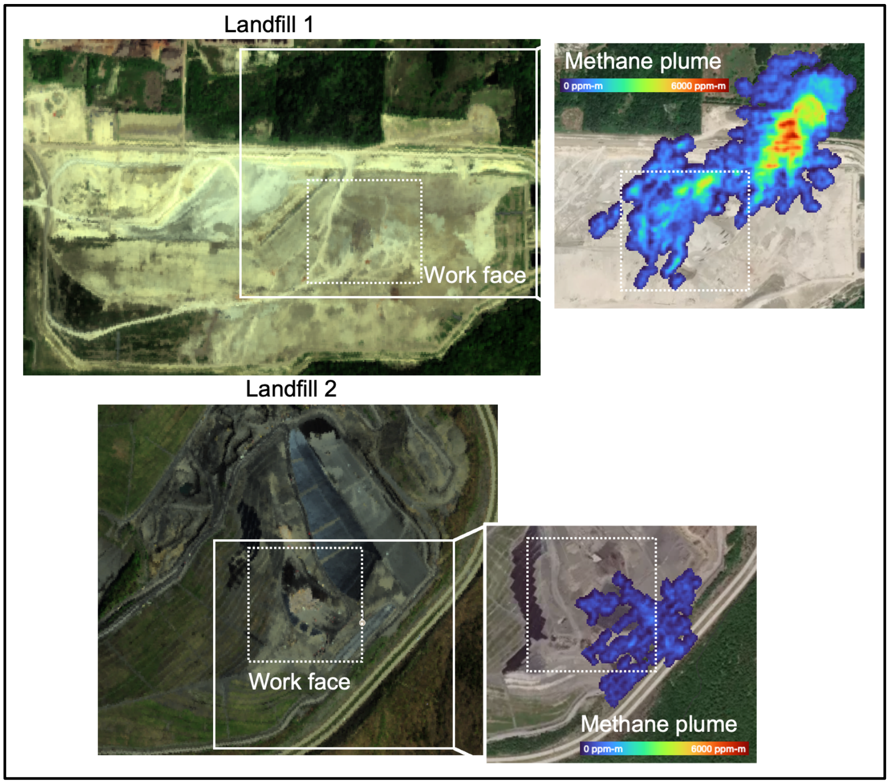

Figure 2. Landfill methane plumes originating from the work face. The images show the landfill surface at the time of the observation with the work face outlined in the white dotted line. Inset images show the methane plumes observed.

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