RMI | WASTEMAP

Deploying Advanced Monitoring Technologies at US Landfills

How landfill operators and municipalities can leverage new tools to reduce methane emissions and deliver powerful benefits

UNITED STATES PLAYBOOK

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ABOUT US

About RMI

RMI is an independent nonprofit, founded in 1982 as Rocky Mountain Institute, that transforms global energy systems through market-driven solutions to align with a 1.5°C future and secure a clean, prosperous, zero-carbon future for all. We work in the world's most critical geographies and engage businesses, policymakers, communities, and nongovernmental organizations to identify and scale energy system interventions that will cut greenhouse gas emissions at least 50 percent by 2030. RMI has offices in Basalt and Boulder, Colorado; New York City; Oakland, California; Washington, D.C.; and Beijing.

About WasteMAP

The Waste Methane Assessment Platform (WasteMAP), a joint initiative by RMI and Clean Air Task Force, is an open online platform that brings together waste methane emissions data with decision support tools for stakeholders in the waste sector. The platform is supported by country engagement that involves collaboration with national and subnational governments, waste management officials, and other key decision makers to provide capacity building and technical assistance — providing a pathway to reduce solid waste methane emissions. Please visit our website www.wastemap.earth to learn more.

About GMH

The Global Methane Hub organizes the field of philanthropists, experts, nonprofits, and government organizations to ensure we unite around a strategy to maximize methane reductions. We have raised over $200 million in pooled funds from more than 20 of the largest climate philanthropies to accelerate methane mitigation across the globe. Visit www.globalmethanehub.org to learn more about organizations that support the commitment.

About EREF

The Environmental Research & Education Foundation (EREF) is an independent, non-advocacy 501(c)(3) research foundation whose mission is to advance scientific research and create educational pathways that enable innovation in sustainable waste management practices, with a vision to light the way to a more circular economy. EREF is one of the largest sources of research funding in the US with more than 45 active research projects internally and at academic institutions across North America.

About WM

WM is North America's leading provider of comprehensive environmental solutions. Previously known as Waste Management and based in Houston, Texas, WM is driven by commitments to put people first and achieve success with integrity. The company, through its subsidiaries, provides collection, recycling and disposal services to millions of residential, commercial, industrial and municipal customers throughout the U.S. and Canada. With innovative infrastructure and capabilities in recycling, organics and renewable energy, WM provides environmental solutions to and collaborates with its customers in helping them achieve their sustainability goals. WM has the largest disposal network and collection fleet in North America, is the largest recycler of post-consumer materials and is the leader in beneficial use of landfill gas, with a growing network of renewable natural gas plants and the most landfill gas-to-electricity plants in North America. WM's fleet includes more than 12,000 natural gas trucks – the largest heavy-duty natural gas truck fleet of its kind in North America. To learn more about WM and the company's sustainability progress and solutions, visit Sustainability.WM.com.

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Introduction

The waste sector is a major contributor to methane emissions, a powerful climate pollutant. In the United States, municipal solid waste (MSW) landfills are the third-largest source of human-caused methane emissions.[1] Methane is generated as organic matter decomposes without oxygen in landfills.

Reducing methane emissions is the strongest lever we have to slow global warming in the near term while improving local air quality and public health. There are proven, low-cost strategies that landfill operators and municipalities can adopt today to reduce methane emissions and deliver powerful co-benefits. These strategies include keeping organic materials out of landfills to prevent methane generation from future waste streams and improving landfill gas controls to reduce methane emissions from waste-in-place.

Advancements in methane monitoring technology — from satellites to aircraft to drones and fixed sensors — are making landfill emissions more visible and can provide valuable data for mitigation. This playbook serves as a practical guide for municipalities and landfill operators to leverage readily available advanced monitoring technologies to more quickly find and fix leaks and make continuous improvements to landfill design and operations to prevent fugitive emissions from occurring in the first place.

About this Playbook

- **Audience:** This resource is geared toward landfill operators, waste districts, local governments, policymakers, and others involved in the sustainable management of municipal solid waste.

- **Scope:** Reducing disposal of organic waste in landfills — through waste prevention, food recovery, composting, and anaerobic digestion — is the most effective way to prevent methane leakage from future waste streams. But as communities scale up programs to reduce and recycle organic waste, it is also important to **implement best management practices (BMPs) at the landfill to minimize fugitive methane emissions** from previously landfilled organic waste and any future organic waste that will still end up in landfills. This playbook is intended to provide an overview of strategies to monitor and mitigate emissions that may be appropriate for sites to consider based on their evaluation of site-specific, technological, and operational conditions. We also share case studies and highlight the community and economic benefits of reducing methane emissions.

- **Goals:** Landfills present a significant untapped opportunity for methane abatement. Through this playbook, we hope to equip stakeholders with the information they need to be part of the solution.

Reducing methane emissions is crucial to slow temperature rise and will deliver local benefits

Methane is a short-lived climate pollutant and the second-most-abundant greenhouse gas after carbon dioxide (CO_2). The concentration of methane in the atmosphere has more than doubled over the past 200 years, and scientists estimate that methane is responsible for about 30% of global warming since preindustrial times.[2]

Methane has outsized impacts on near-term temperature rise. In the first 20 years after its release, methane has more than 80 times the heat-trapping power of CO_2. But since it lingers in the atmosphere for only about a decade, compared with centuries for CO_2, reducing methane emissions today provides an immediate opportunity to slow global warming and limit the risk of dangerous climate tipping points.

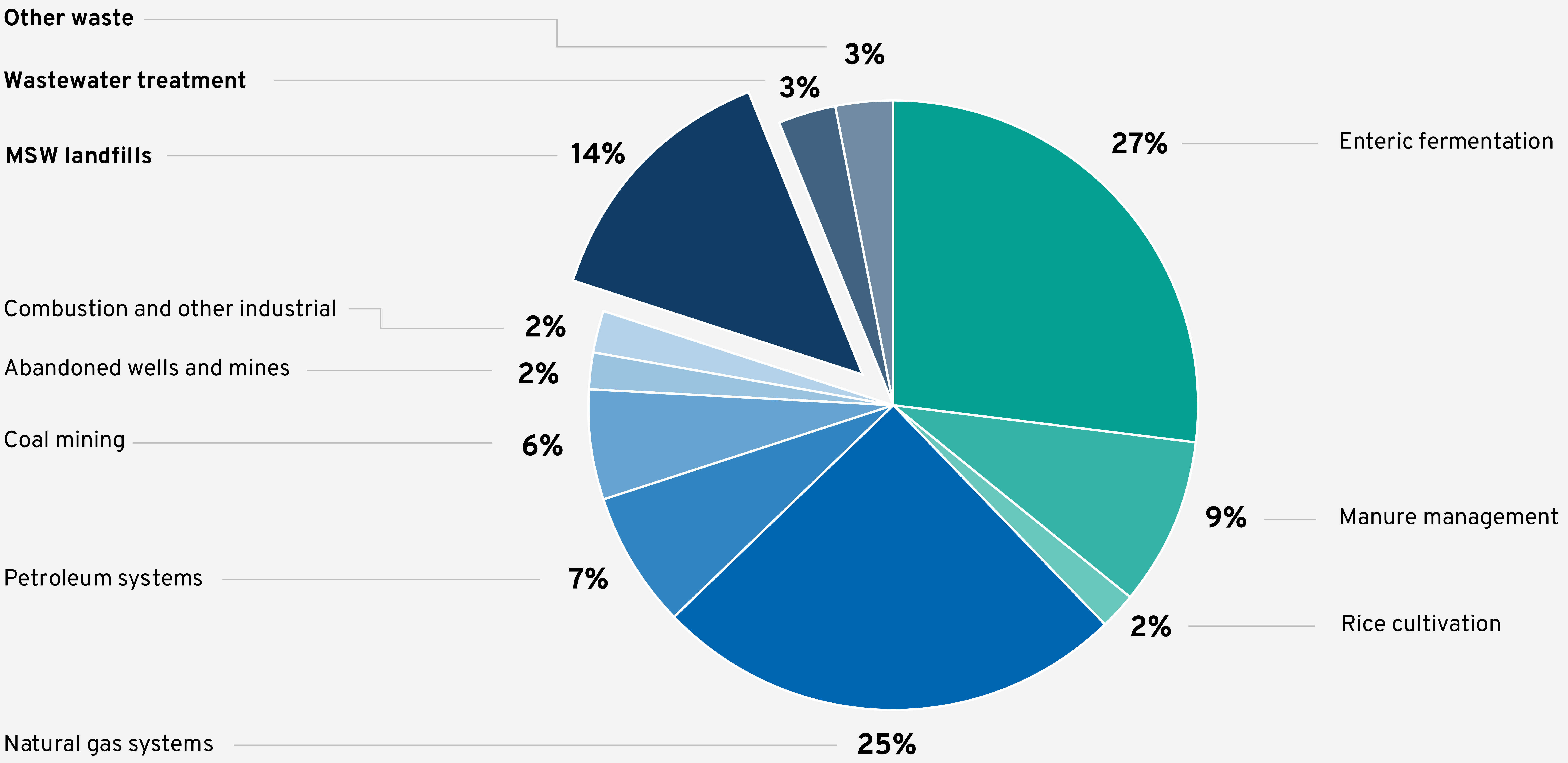
Accelerated action to cut methane is one of the strongest, fastest, and most achievable strategies to limit temperature rise over the near term and avoid the worst impacts of climate change. Cutting methane and other short-lived climate pollutants alongside decarbonization strategies can slow warming one to two decades sooner than CO_2-focused mitigation strategies alone.[3] That is why the United States and 150 other countries have signed onto the Global Methane Pledge, which targets at least a 30% reduction in global methane emissions from 2020 levels by 2030.

Reducing methane emissions will bring local benefits. In addition to slowing temperature rise, reducing methane emissions also addresses toxic co-pollutants and smog-forming compounds, helping to improve local air quality, public health, and quality of life. Further, it can create local economic benefits through job creation and the beneficial use of captured methane.

Curbing methane emissions will require interventions across all three major methane sources: agriculture, oil and gas, and waste.

A 3-dimensional image of global methane emissions.
Source: NASA's Scientific Visualization Studio, https://climate.nasa.gov/news/2961/new-3d-view-of-methane-tracks-sources-and-movement-around-the-globe/

2021 US anthropogenic methane emissions by source



RMI Graphic. Source: U.S. Environmental Protection Agency, https://www.epa.gov/system/files/documents/2023-04/US-GHG-Inventory-2023-Main-Text.pdf

Landfills are a significant source of methane emissions in the United States

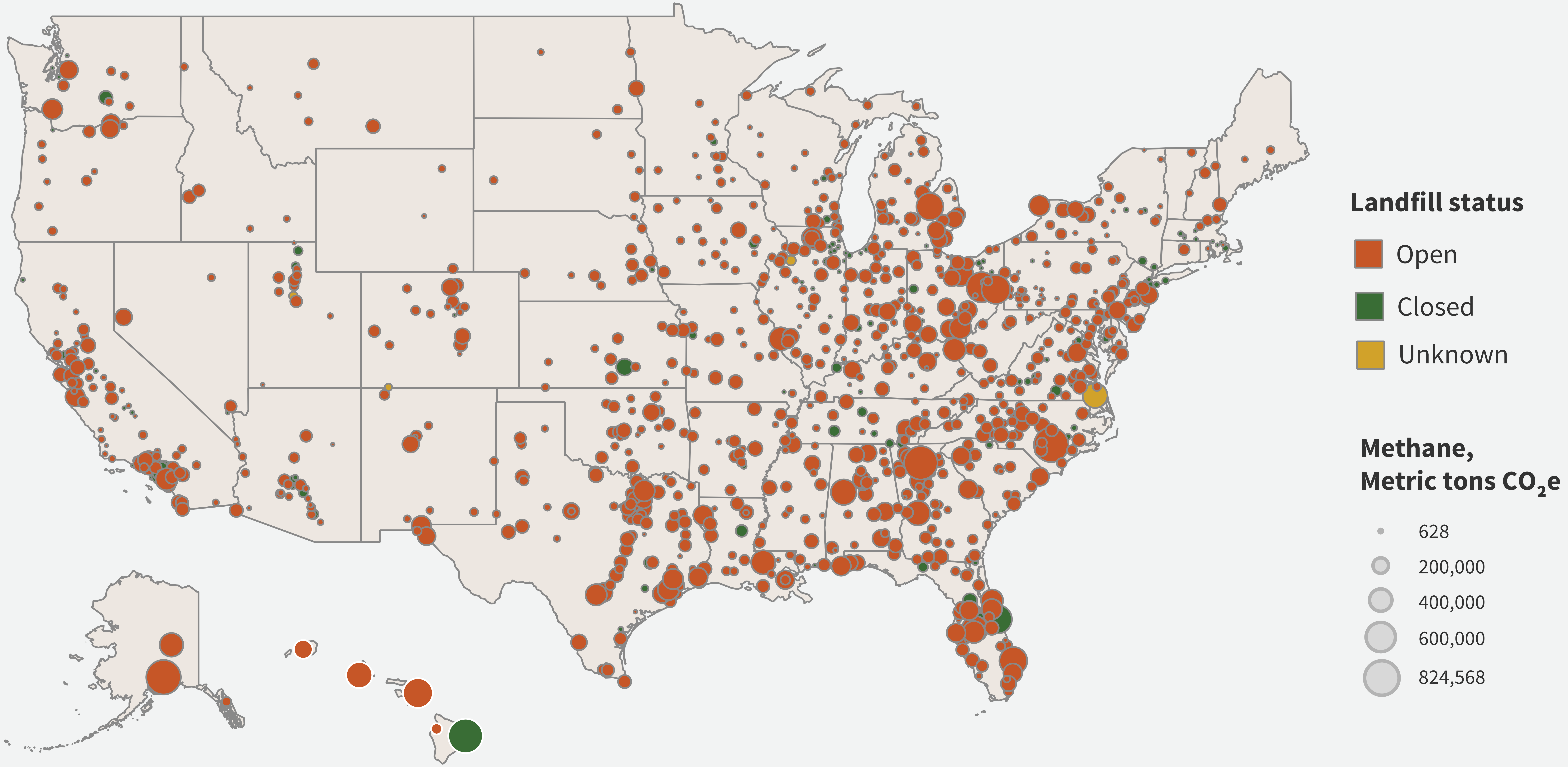
Landfills generate methane when buried organic waste (waste-in-place) decomposes in the absence of oxygen. In the United States, organic waste — such as food, paper, and yard waste — makes up more than half of the MSW stream.[4] Food waste is the single most landfilled material, responsible for 58% of fugitive landfill methane emissions, according to recent US Environmental Protection Agency (EPA) research.[5] Methane production typically begins within the first year after the waste is landfilled and can continue for 10 to 50 or more years as the degradable waste decomposes.[6]

There are more than 2,600 MSW landfills across the country, according to data collected by the EPA's Landfill Methane Outreach Program. About half of these landfills are open and accepting waste. US landfills that meet a certain threshold are required by federal and/or state regulations to capture and control their emissions and conduct quarterly surface emissions monitoring (SEM) to remediate methane hot spots. More than 1,200 landfills have a gas collection system in place, and 487 landfills with gas collection systems have a beneficial use project, using captured gas to generate electricity, for direct use, or upgrading landfill gas (LFG) to renewable natural gas (RNG) for pipeline injection or transportation fuel.[7] Otherwise, captured gas is routed to flare systems where it is combusted into less-potent carbon dioxide.

Despite collection and control systems, methane escapes from landfills into the atmosphere diffusely through the landfill surface (area source emissions) and in more concentrated hot spots (point source emissions), which can result from equipment malfunction, cover integrity issues, construction activities, or the active working face (see slide 10). Overall, MSW landfills are the third-largest source of methane in the United States, representing about 14% of methane emissions.[8] According to the EPA's inventory, MSW landfills released 3.7 million metric tons of methane to the atmosphere in 2021, or about 295 million metric tons of carbon dioxide equivalent (MMT CO_2e) on a 20-year time horizon.[9] Furthermore, recent airborne methane surveys suggest that emissions may be higher and more persistent than previously expected.[10]

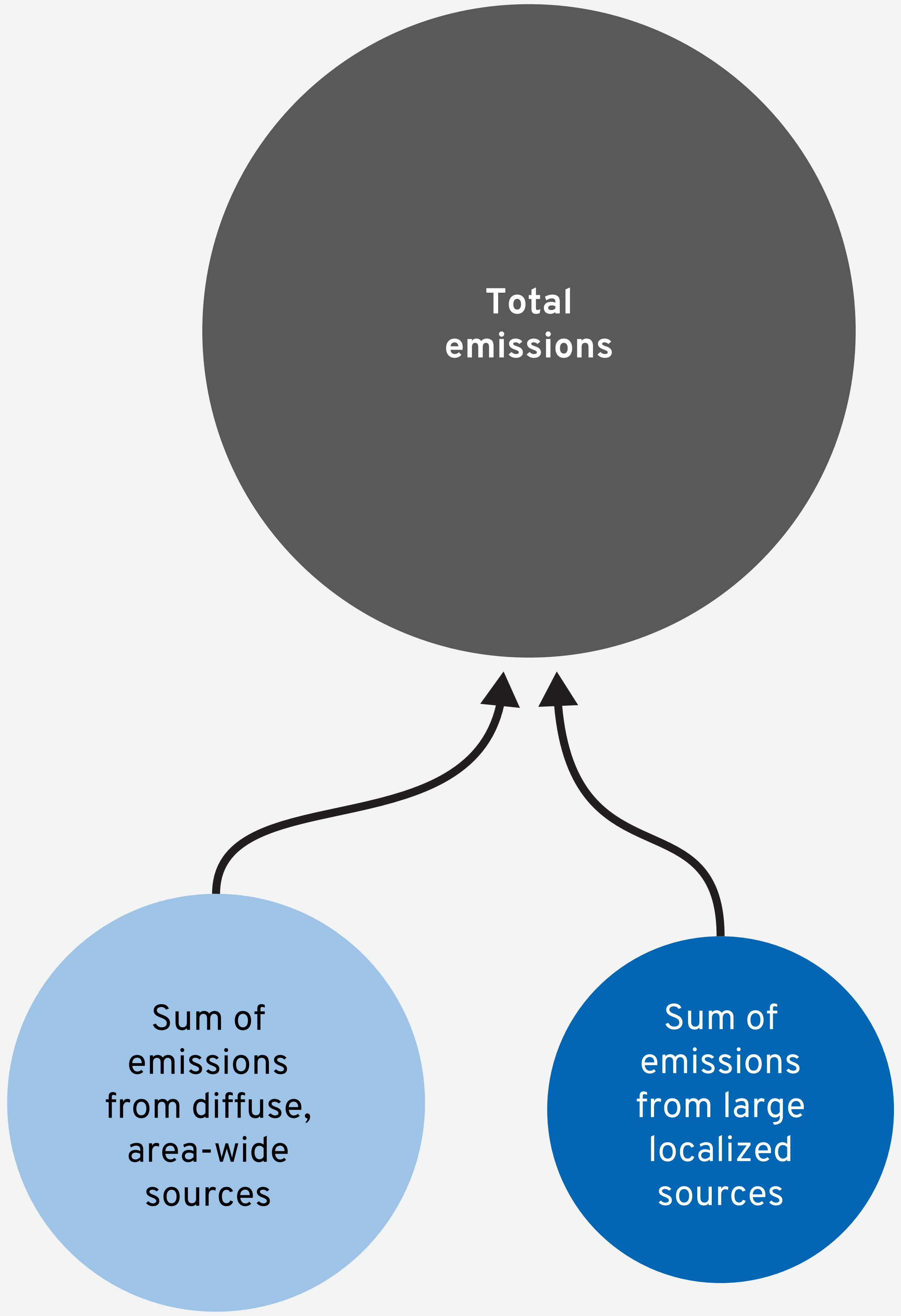
These numbers underscore the substantial opportunity for methane reductions from landfills — by reducing incoming organic waste to avoid methane generation, increasing methane capture at landfills with gas collection systems in place, and installing gas collection systems at landfills that are not currently collecting their gas.

US landfill emissions map



Source: Industrious Labs, https://dontwasteourfuture.org

Landfill methane point and area source emissions

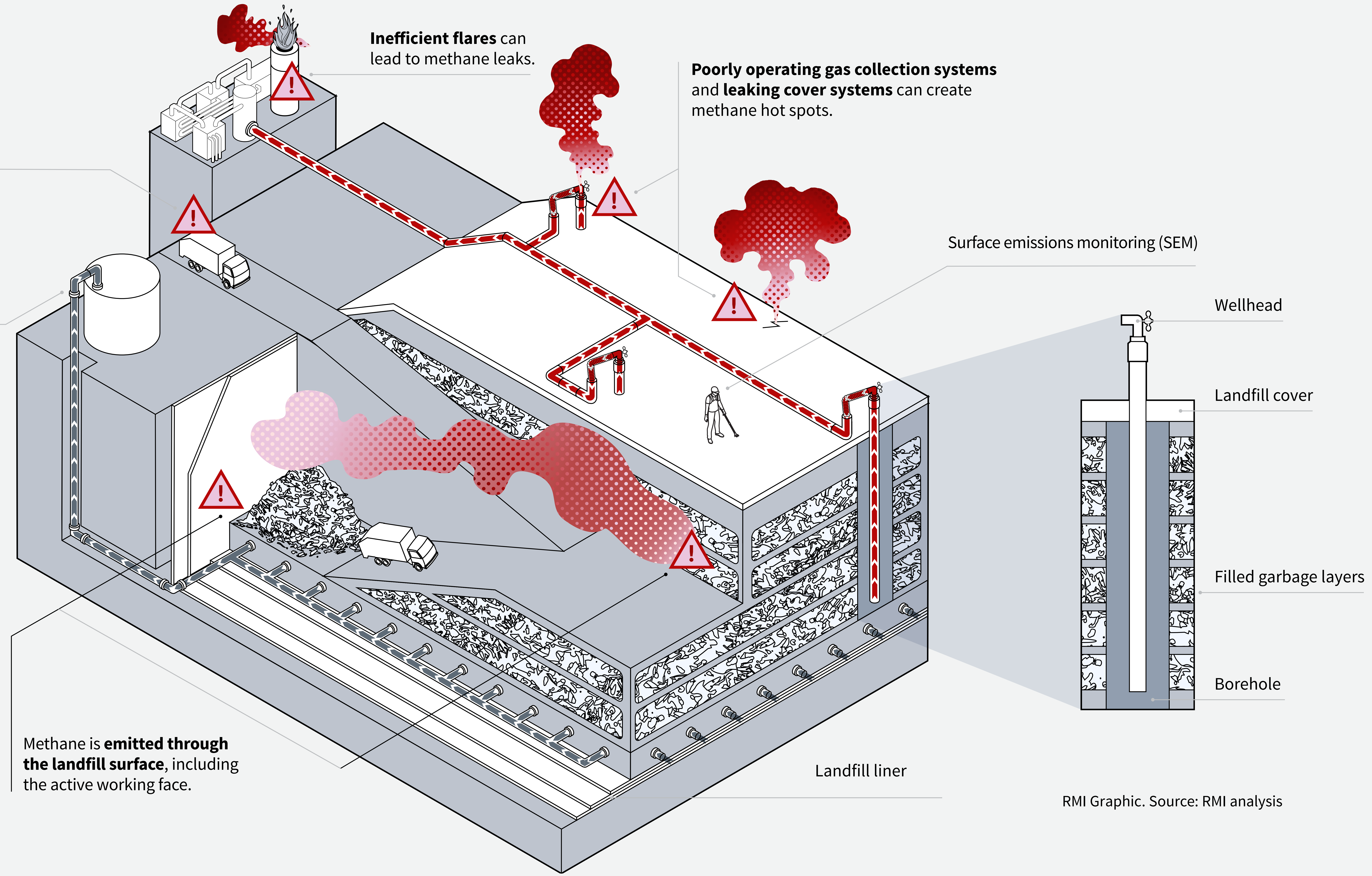


RMI Graphic. Source: California Air Resources Board, https://ww2.arb.ca.gov/sites/default/files/2022-12/Methane%20Remote%20Sensing.pdf

Common sources of landfill methane emissions

Landfill gas is generated when buried **organic waste** decomposes without oxygen. Over half of material sent to US landfills is organic.

Key landfill components and common emissions sources



Landfill gas
Leachate

RMI Graphic. Source: RMI analysis

There are viable solutions to reduce landfill methane emissions today

Strategies to reduce landfill emissions fall into two broad categories:

1. **Preventing methane generation from future waste streams** by reducing organic waste disposal

2. **Reducing methane emissions from waste-in-place** by minimizing leakage and improving LFG capture

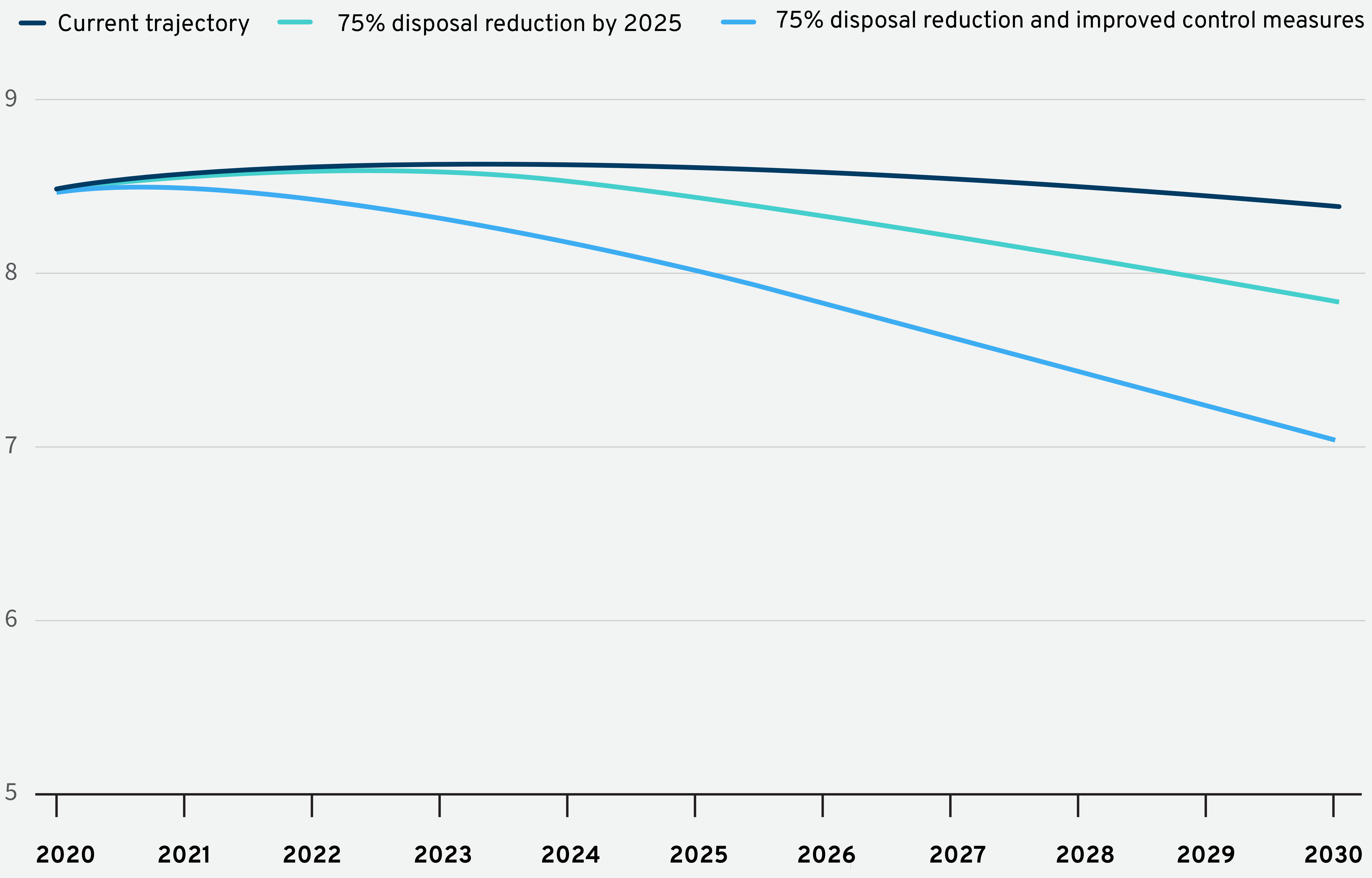
Methane prevention strategies center the EPA's Wasted Food Scale and prioritize source reduction, edible food donation, and recycling of residual organic waste into animal feed, compost, or biogas for nutrient and energy recovery. Diverting organic waste to compost or anaerobic digestion can achieve up to 95% methane reduction efficiency when compared with landfilling, depending on operational practices, and strategies to prevent waste generation further reduce greenhouse gas emissions throughout the supply chain.[11] Reducing organic waste disposal also brings significant benefits to communities and ecosystems in terms of food security, soil health, and green job creation.

Methane reduction strategies focus on capturing methane and stopping leaks at the landfill by implementing BMPs for landfill monitoring, design, and operations. This includes installing gas collection systems or biocovers at landfills that do not currently have them, and improving collection efficiency and beneficial use at the landfills that do. **Methane monitoring** is a key tool to inform and assess landfill methane reduction strategies, providing operators with valuable data on emissions sources. A 30% reduction in methane emissions across US MSW landfills — through expanded gas collection and control, improved cover practices, and more comprehensive leak detection and repair — would cut more than a million metric tons of methane per year based on the EPA's inventory data.[12]

Prevention avoids locking in future methane emissions, while reduction strategies are critical to cutting methane and other harmful co-pollutants quickly from waste-in-place. **Implementing both strategies in tandem will maximize methane reductions and community benefits.** Climate-leading states like California are pursuing both aggressive organics disposal reduction and improved waste-in-place control measures to accelerate overall emissions reductions this decade.

California's waste sector strategies

Landfill Methane Emissions (MMT CO_2e)



Improved control measures

- Improvements in operational practices
- Use of lower permeability covers
- Advanced landfill gas collection systems
- Increased monitoring to detect and repair leaks

RMI Graphic. Source: California Air Resources Board, https://ww2.arb.ca.gov/sites/default/files/2023-05/LMR-workshop_05-18-2023.pdf

This playbook focuses specifically on **methane reduction strategies for waste-in-place.** Although reducing organic waste disposal is critical, the benefits of organic waste diversion take time to materialize. Reducing methane from waste-in-place is a vital complement that can deliver immediate benefits this decade, a critical window for climate action. Waste-in-place methane mitigation strategies can be deployed relatively quickly, at modest cost, across a relatively small number of high-emitting landfill sites. We believe this is an underutilized emissions reduction approach and hope this resource spotlights the potential.

PART ONE

Monitoring and Reducing Methane Emissions from Landfills

Implementing BMPs at the landfill will reduce methane emissions from waste-in-place

Once organic waste is buried, there are several design and operational practices that can minimize methane emissions from the landfill. These approaches, shown on the next slide, include early and expanded gas collection, automated well tuning, enhanced landfill cover practices, comprehensive monitoring, and efficient destruction or beneficial use of captured gas. These approaches entail basic, standardized technology that can be deployed swiftly and at modest cost to reduce methane emissions today. Analysis shows that implementing select best practices — such as earlier gas collection, reduced cell size, and more robust cover — can reduce methane emissions relative to business-as-usual by 16%–44%.[13]

Installing a gas collection system carries capital and operational costs ($1.3 million for a 40-acre gas collection and control system [GCCS], plus ~$5,500 in annual operations and management costs per acre), which can be offset in part through revenue from beneficial use projects and in some cases may be eligible for federal funding or tax incentives.[14] Otherwise, many of the strategies to reduce emissions from landfilled waste do not involve purchasing equipment but rather improving existing practices around cover, well-field management, control devices, 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.[15]

BMPs to reduce landfill methane emissions

Expand Gas Collection System Coverage: Install and expand the gas collection system early, within one year after waste is placed, to maximize gas collection. Installing horizontal collectors during the disposal of waste can help capture gas as the lifts are being constructed. Optimize well spacing (approximate 30% overlap of radius of influence) to ensure full coverage.

Boost Gas Collection System Performance: Optimize well-field tuning with automated systems and pressure/flow sensors to increase gas recovery while avoiding air intrusion. Actively manage liquid levels and maintain the well seal. Using gabion cubes on the bottom liner can help with drainage.

Enhance Landfill Cover Materials and Practices: Increase thickness and compaction of daily and intermediate covers to decrease permeability and allow for greater vacuum. Consider a vegetative layer or biocover to enhance microbial oxidation of methane escaping to the surface. Install intermediate and final cover early and on an ongoing basis. Minimize the exposed surface area of the daily uncovered working face.

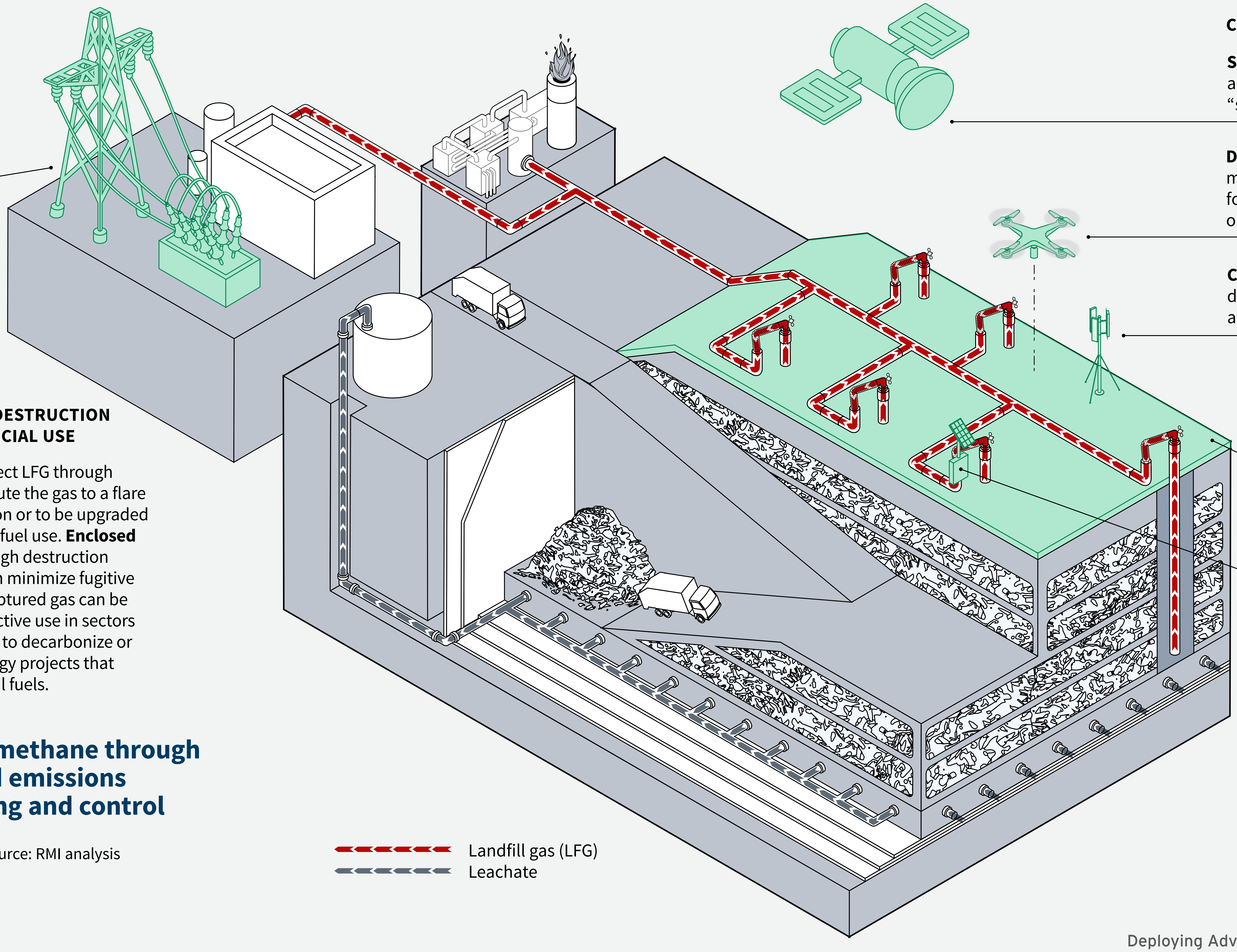
Ensure Beneficial Use or Efficient Destruction of Captured Gas: Route captured gas to an energy project (e.g., electricity or RNG) that displaces fossil-based fuels. Ensure that any excess gas is routed to an enclosed flare with high destruction efficiency (>99%) to avoid methane slip. Pressure/temperature sensors can help confirm a flare is lit.

Conduct Comprehensive Methane Monitoring: Regularly survey the landfill surface and components to identify and mitigate any leaks and inform operational decisions to minimize surface methane. Leverage advanced monitoring technologies to improve the frequency, coverage, and scope of methane detection and improve response times.

In the following slides, we focus on leveraging advanced methane monitoring technologies as a critical tool to inform methane emissions reductions from waste-in-place.

RMI Graphic. Source: RMI analysis

BMPs to address common sources of methane emissions



COMPREHENSIVE MONITORING AND LEAK REPAIR

Satellites or aircraft can scan broad geographic areas to detect large methane emissions sources or "super-emitter" activity.

Drones, and other near-ground approaches, provide more granularity. These methods identify hot spots for mitigation and inform smart landfill design and operational practices.

Continuous sensors support rapid and ongoing leak detection and repair. Operators can respond quickly to a rise in methane concentration.

ROBUST AND EFFECTIVE COVER PRACTICES

Well-maintained covers can help boost collection efficiency and reduce fugitive emissions. **Biocovers** can be applied to improve methane oxidation.

OPTIMIZING GAS COLLECTION SYSTEM PERFORMANCE

Automated well tuning, actively managing liquid levels, and tight well seals can all help operators optimize gas collection and reduce fugitive emissions. Earlier installation of gas capture systems, increasing well density, and adding horizontal collectors can also help achieve methane emissions reductions.

EFFICIENT DESTRUCTION AND BENEFICIAL USE

Landfills collect LFG through pipes that route the gas to a flare for destruction or to be upgraded for energy or fuel use. **Enclosed flares** with high destruction efficiency can minimize fugitive methane. Captured gas can be put to productive use in sectors that are hard to decarbonize or through energy projects that displace fossil fuels.

Mitigate methane through improved emissions monitoring and control

RMI Graphic. Source: RMI analysis

Regulatory SEM, which is typically conducted manually, has limitations

About 600 landfills in the United States are federally required to conduct **quarterly SEM surveys** to comply with regulations under the Clean Air Act, administered by the EPA.[16] In addition, some landfills may conduct SEM voluntarily or as required by more stringent state regulations. SEM surveys are intended to help landfills assess how the GCCS is performing.

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.[17]

Three states — California, Maryland, and Oregon — have adopted rules that require more robust SEM than current EPA regulations. These states require tighter walking patterns (25-foot intervals versus EPA's ~100-foot intervals), integrated monitoring (with corrective action if surface methane averaged across gridded sections of the landfill exceeds 25 ppm), and more detailed reporting requirements.[18]

Although SEM requirements are commendable in a global context, this framework has several limitations, including its **incomplete coverage** (hazardous areas, construction areas, and the active working face are exempt from monitoring), **infrequency** (quarterly), and **subjectivity** (dependent on operator, process, regulatory interpretation, the level of vacuum applied to the GCCS, and other environmental conditions). Furthermore, traditional SEM surveys are physically demanding with many miles of walking and are potentially hazardous for technicians due to terrain, weather conditions, and exposure risks.

Due to these limitations, traditional SEM surveys may miss methane leaks that could be mitigated. For example, aircraft and drone surveys have detected methane plumes coming from the landfill's active working face, an area currently excluded from SEM due to safety concerns.[19]

A technician conducting SEM survey at a landfill.

Source: Construction & Demolition Recycling, https://www.cdrecycler.com/news/surface-emissions-monitoring-landfill-technology/

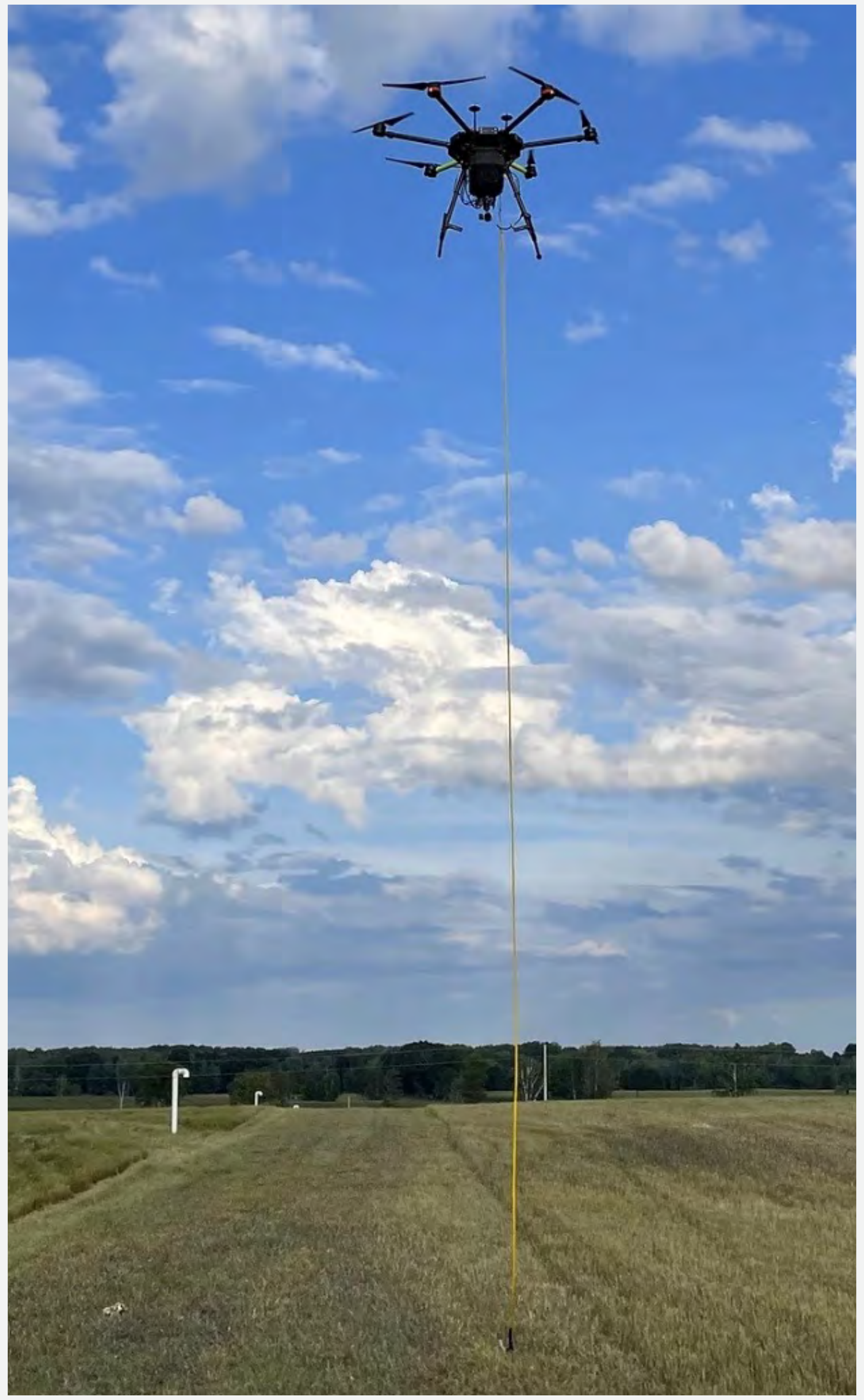
However, the US regulatory framework is evolving to reflect technology advancements and accommodate a more automated approach

In December 2022, the EPA approved the first advanced alternative technology for regulatory landfill surface emissions monitoring. Now, operators can use a drone-based alternative test method (OTM-51/ALT150) with a methane detection payload on a drone, coupled with a ground-level-to-drone sampling system.[20] There is currently one commercial provider (Sniffer Robotics) that meets these requirements, but other vendors can apply for approval. In some cases, operators may need additional state approvals.

Field studies performed for EPA approval of this technology demonstrated strong performance in detecting 500 ppm exceedances by the drone-based SEM approach when compared with traditional walking SEM.[21] Furthermore, drone-based systems can provide operators with more timely, comprehensive, and objective data to inform mitigation activities while keeping workers safe.

The EPA drone approval is a major step forward for landfill methane monitoring efficiency and replicability in a regulatory context — underscoring the opportunity for advanced technologies to supplement or potentially replace traditional monitoring methods. That said, the approval fits a new technology into an existing framework (SEM); there is also potential for the framework to evolve in future regulations to better reflect the capabilities of new methane detection technologies and incentivize their adoption, as in the recently finalized oil and gas regulations under the Clean Air Act.[22]

Other nonregulatory technologies are being used for enhanced monitoring at landfills, conducted by landfill operators and municipalities on a voluntary basis or by researchers.



A drone is deployed to conduct a SEM survey.

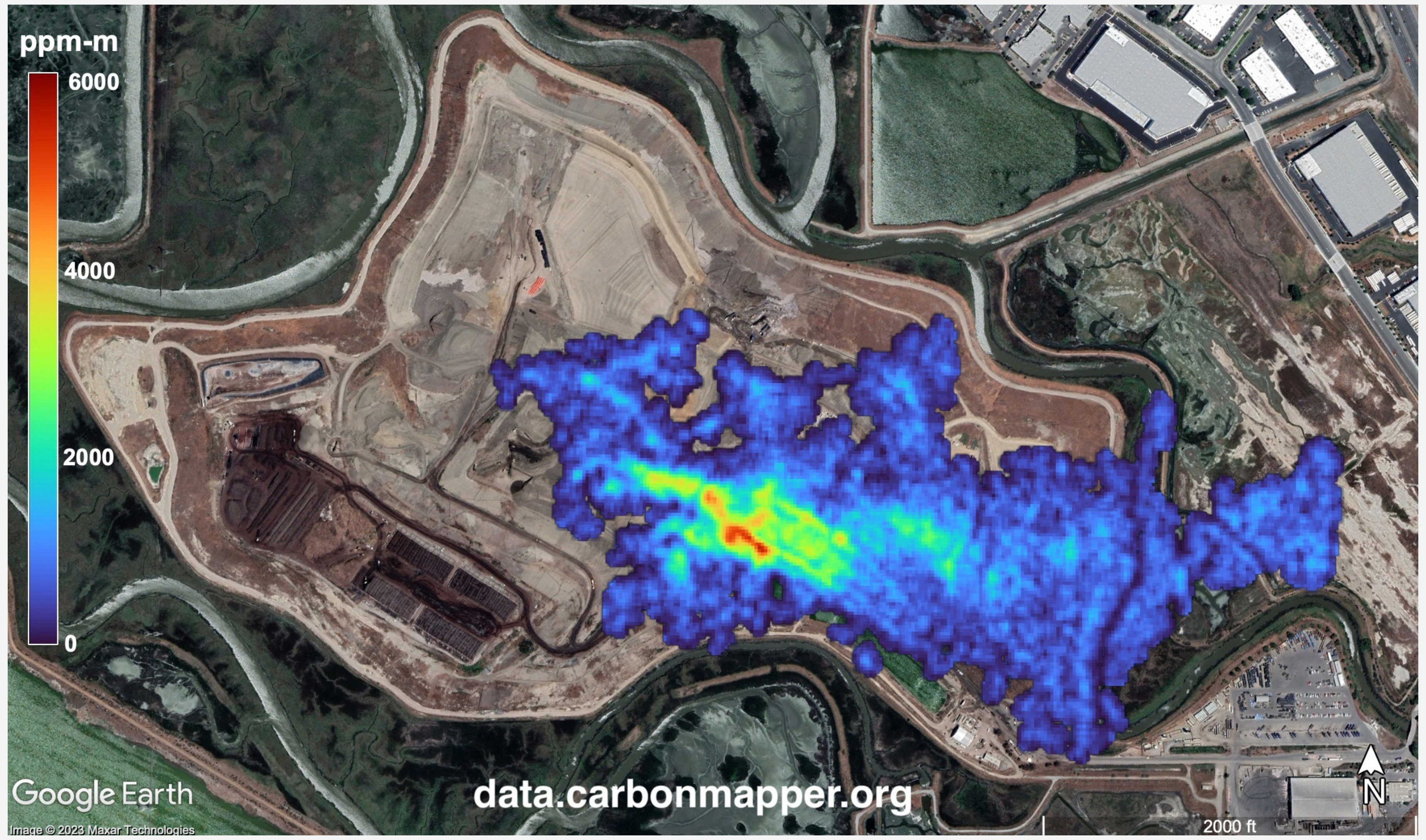
Source: Sniffer Robotics, https://www.snifferrobotics.com/otm-51

New methane monitoring technologies can detect leaks and inform operations

Recent advancements in methane monitoring technology — from satellites to aircraft to drones to fixed sensors — are transforming landfill operators' ability to detect, locate, and reduce their emissions in real time. Conventionally, landfill operators monitor for fugitive methane emissions by traversing the landfill with a handheld gas analyzer to find hot spots. There are now dozens of companies — often originating from the oil and gas sector — that provide equipment and/or services for methane detection at landfills. Agencies and operators are adopting these technologies to find and fix leaks.

Aerial remote sensing instruments have surveyed more than 300 landfills across the United States to date and identified large methane emissions sources at over 200 of these sites.[23] Overflights conducted by Carbon Mapper in coordination with the California Air Resources Board and the Pennsylvania Department of Environmental Protection (DEP) found large methane releases, often referred to as super-emitters, at multiple landfills. Operators were alerted and took voluntary actions that resulted in successful emissions reductions.[24]

Landfill operators have also started integrating **near-ground advanced methane monitoring technologies** into their operations, using drone surveys or rovers to monitor for areas of elevated methane concentration and inform leak repairs and operational decisions. One drone provider has already deployed its technology at more than 150 landfills.[25] In addition, fixed sensor systems positioned across the landfill surface can provide methane concentration data continuously. Although adoption in the waste sector has been limited so far, these technologies show promise for finding leaks in real time and evaluating emissions trends over time.



Landfill methane plume detected by a Carbon Mapper airborne survey using NASA Jet Propulsion Laboratory AVIRIS-NG.
Source: Carbon Mapper, data.carbonmapper.org

Advanced monitoring technologies can be categorized by their sensor and platform

Methane monitoring technologies for leak detection can be broadly categorized by their detection method (sensor) and deployment approach (platform).[26] Different sensors can be paired with different platforms.

The sensors and platforms, outlined in the boxes to the right, have different strengths and limitations as they pertain to spatial coverage, temporal relevance, and precise localization. Together, they have tremendous potential to provide landfill operators, local governments, and the public with timely information on the underlying causes of landfill emissions and opportunities for reductions. When combined with wind data and modeling, these technologies can also quantify emissions, deriving an emissions rate or flux in kilograms per hour (kg/h). **In this playbook, we focus primarily on detection (find and fix) applications, rather than emissions quantification.**

Sensor: Detection Method

Point sensing (in-plume sensing), using various sensors such as metal oxide, nondispersive infrared (NDIR), flame ionization (FID), cavity ringdown spectrometers (CRDS), and off-axis integrated cavity output spectroscopy (OA-ICOS). Sensors measure methane concentration in parts-per-million (ppm) as they pass through the methane plume.

Active imaging (remote sensing), such as tunable diode laser absorption spectroscopy (TDLAS), light detection and ranging (lidar), and dual-frequency comb laser detection. Active imaging systems generate light that traverses the methane plumes, reflects off a remote surface, and returns to a detector. Changes in the reflected light are used to infer methane concentrations along the path, measured in parts-per-million-meter (ppm-m), based on the elevation from where the measurement is taken.

Passive imaging (remote sensing), such as advanced infrared imaging spectrometers, detects methane absorption of solar radiation reflected off the Earth's surface. The absorption signal is then translated into a methane column concentration (ppm-m).

Platform: Deployment Approach

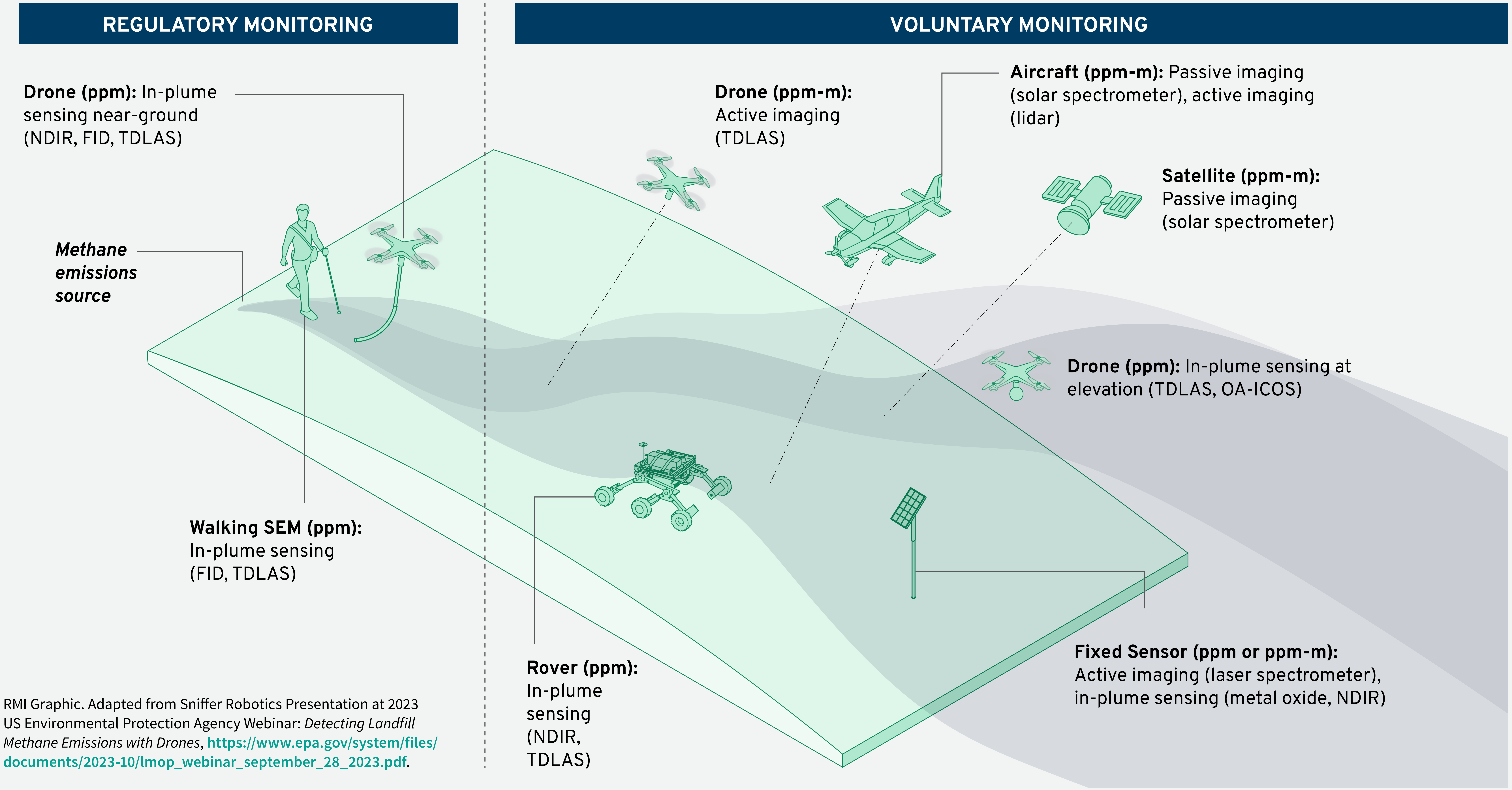
Aerial technologies (aircraft/satellites) can scan broad areas for methane emissions to detect large, potentially intermittent emissions sources. These methods do not require site access and can be conducted by third parties.

On-site mobile approaches (drones, rovers, vehicles) typically have higher sensitivity than aerial technologies and can survey the landfill footprint with more precision. Near-ground approaches require operator involvement.

Fixed sensor systems (towers, tripods, sensors on wellheads) are positioned across the landfill surface and can detect methane concentration continuously. Operators can respond quickly to rises in methane concentration, but coverage and precise localization depend on the sensor configuration across the site.

Source: Adapted from Highwood Emissions Management, *Technical Report: Leak Detection Methods for Natural Gas Gathering, Transmission, and Distribution Pipelines*, 2022, and discussions with experts, https://highwoodemissions.com/reports/leak-detection-methods-for-natural-gas-gathering/

Advanced methane monitoring technologies deployed today

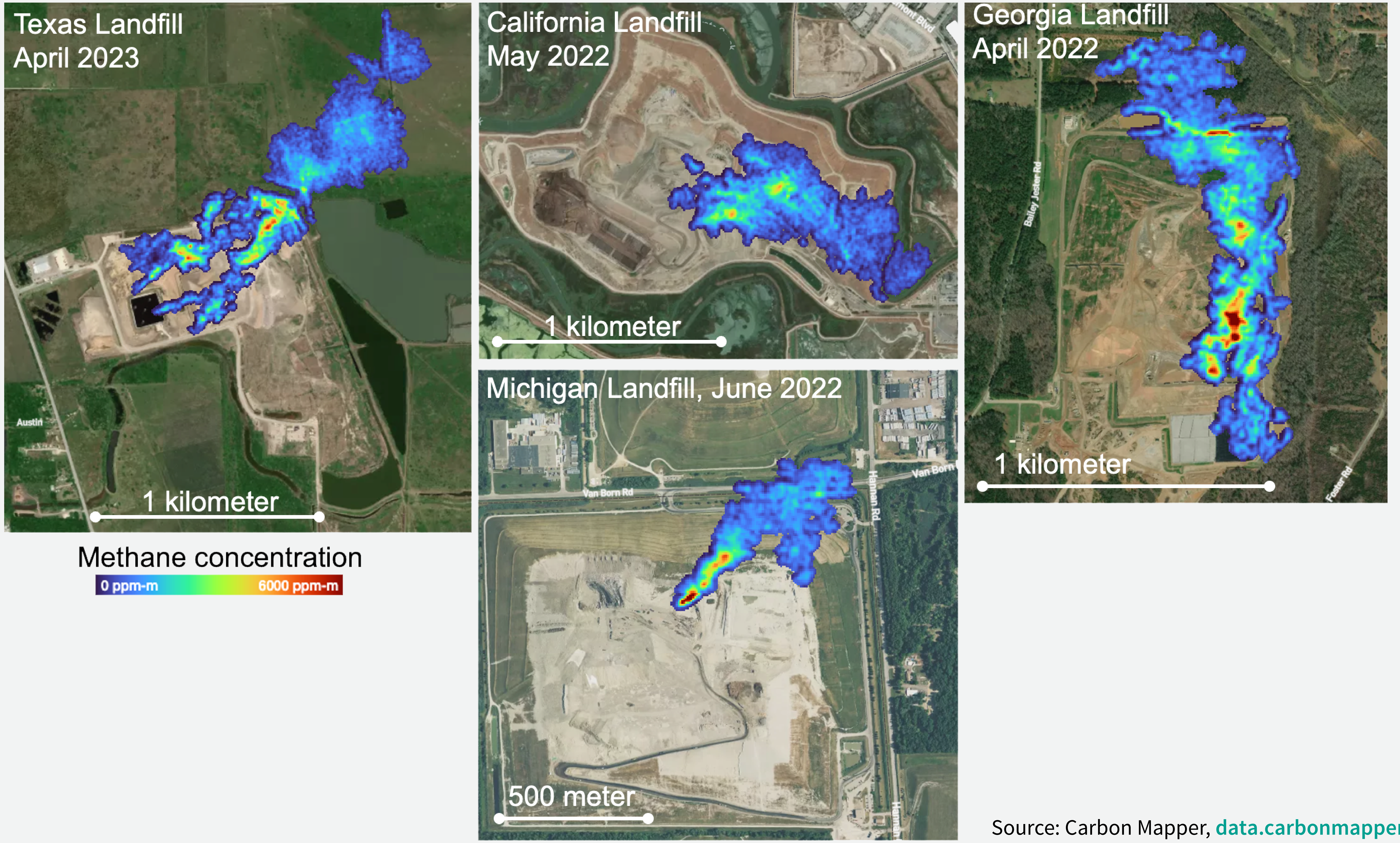


RMI Graphic. Adapted from Sniffer Robotics Presentation at 2023 US Environmental Protection Agency Webinar: *Detecting Landfill Methane Emissions with Drones*, https://www.epa.gov/system/files/documents/2023-10/lmop_webinar_september_28_2023.pdf.

See *Appendix* for more details on advanced methane monitoring technologies deployed today.

Examples of methane plumes at US landfills

All methane plumes shown here have emissions rates greater than 1,000 kg of methane per hour.



Source: Carbon Mapper, data.carbonmapper.org

From left: Examples of drone flight path, pinpointed leaks, and heat map interpolation

Source: Sniffer Robotics Presentation at 2023 US EPA Webinar: Detecting Landfill Methane Emissions with Drones, https://www.epa.gov/system/files/documents/2023-10/lmop_webinar_september_28_2023.pdf

Advanced methane detection technologies offer several advantages…

Conducting landfill surveys with advanced methane detection technologies — such as satellites, aircraft, drones, rovers, and fixed sensors — can provide several benefits over conventional walking approaches. These advantages are summarized below, though they may vary by detection method (sensor) and deployment approach (platform).

Coverage: Advanced technologies can safely survey areas of the landfill excluded from current SEM, such as challenging walking terrain, steep slopes, construction areas, and the active working face. Aerial methods can efficiently scan the entire landfill surface area, enabling more extensive coverage of the landfill site.

Worker safety and efficiency: Advanced monitoring alternatives save workers from hazardous, physically demanding conditions. Walking a landfill can take multiple days, whereas an aerial survey can take less than an hour. Landfill technicians can instead focus on analyzing emissions data from advanced monitoring technologies and making the appropriate repairs, maintenance, or design improvements.

Frequency: Advanced monitoring methods can provide more frequent data than quarterly walking SEM. Fixed sensor networks can provide operators with continuous data on potential leaks across a wide variety of environmental and operating conditions. Current and planned satellite constellations also have the capability to scan large areas and identify high-emission events at frequent cadences, such as days to weeks. Drone-based surveys can be conducted more frequently, given the time savings and lower labor intensity.

Objectivity: Advanced monitoring technologies limit the risk of human error and minimize potential uncertainties around process and regulatory interpretation. Precise flight routes can also be more easily replicated.

Fast, actionable data: Advanced monitoring surveys can support and expedite the creation of more detailed monitoring reports that map measured methane concentration to specific GPS locations. Landfill operators can leverage these maps to inform quick repairs and guide operational decisions that maximize emissions reductions. This data can also support more robust recordkeeping in case of audits.

Transparency: Data collected by advanced methane detection technologies can easily be made available to the public to boost transparency, improve relations, and build trust with nearby communities or other stakeholders. For example, Carbon Mapper's detected plumes are visible to the public through their portal.

… and can inform proactive and reactive landfill methane reductions

For landfills already conducting SEM, advanced monitoring approaches can improve coverage and efficiency, replacing walking surveys with drones and/or supplementing them with additional data from aerial, near-ground, or fixed sensors. For landfills that are not monitoring regularly for fugitive emissions, advanced monitoring methods can provide timely, actionable data to inform effective mitigation activities.

Methane concentration data from advanced monitoring surveys can inform reactive and proactive mitigation, and assess efficacy of interventions:

Reactive: Find and Fix — Advanced monitoring technologies can identify and localize landfill methane leaks, prompting fast repairs. For example, state agencies in California and Pennsylvania worked with a third-party airborne remote sensing provider to survey for methane leaks and alerted landfill operators to incidences of large detected plumes.[27] Operators took voluntary action to locate and mitigate the leaks. In addition, near-ground technologies, like drones, can identify high-emitting areas of the landfill and provide granular data for leak repair. Continuous sensors can alert operators in real time of elevated methane concentration, enabling fast responses to potential leaks.

Proactive: Design and Operational Improvements — Beyond leak repair, operators can use advanced monitoring technologies to guide and assess more proactive design and operational choices that maximize gas capture and reduce fugitive emissions. Methane concentration and location data can be aggregated into a grid or heat map to show operators where to deploy different cover materials or increase the density of gas collection wells. Methane monitoring technologies, especially when deployed on a high-frequency or continuous basis, can also be used to measure the efficacy and emissions reduction potential of specific mitigation approaches and gather data on monitoring-informed BMPs. For example, at Sunshine Canyon Landfill in California, aerial flyovers detected large methane plumes from intermediate cover slopes during overpasses in 2016. The landfill then updated its infrastructure and made several changes to the landfill cover and gas collection system to reduce landfill emissions. Subsequent overpasses in 2017 observed a marked decrease in methane emissions (and concurrent increases in LFG collection), and these results were validated by fewer neighborhood odor complaints.[28]

US landfills are already leveraging advanced monitoring technologies to reduce emissions

Some landfill operators and agencies are already deploying advanced technologies at their sites for proactive and reactive mitigation. Here are three examples of aircraft, drone, and continuous monitoring deployment to reduce landfill methane emissions.

Aerial Surveys Prompt Voluntary Leak Repairs, Identify New BMPs

The Pennsylvania DEP partnered with Carbon Mapper and the US Climate Alliance to conduct overflights and identify large methane emissions sources in the state. The surveys identified 10 large methane plumes (>100 kg/h) at municipal landfills. DEP alerted operators, who then located and voluntarily addressed eight of those methane plumes, resulting in a 37% reduction in observed methane emissions. Mitigation activities included using bore seals and gas well de-watering pumps, and installing landfill cover in new areas.[29]

Key takeaways:

- Remote surveys can flag large point source emissions for on-the-ground investigation and mitigation.
- Operator outreach programs collect valuable data on the root causes of large leaks and effective mitigation strategies.

Continuous Sensors Provide Real-Time Data for Timely Mitigation

LoCI Controls has developed a real-time data and control system that takes continuous measurements of LFG composition, flow, temperature, pressure, and liquid levels and makes automated adjustments to the GCCS to increase methane capture and reduce fugitive emissions. In addition, continuous wellhead data can alert operators to other mitigation opportunities, such as remediating an area of damaged cover or de-watering a flooded well. Gas capture data can then verify the efficacy of mitigation activities. LoCI is also adding data from fixed atmospheric methane sensors and drone/aerial surveys to its system, providing greater visibility to inform fast repairs. So far, LoCI has deployed its system at over 65 landfills and has verified an emissions reduction method with the ACR (formerly the American Carbon Registry).[30]

Key takeaways:

- Continuous monitoring and real-time wellhead data can act as "alarm bells" for landfill operators to quickly address and repair leaks.
- Continuous monitoring can also help identify emissions trends over time and assess the efficacy of different mitigation measures.

Leveraging Drones to Inform Gas Collection System Expansion and Cover Practices

In the Great Lakes region, a landfill operator contracted with a drone provider, Sniffer Robotics, to survey its landfill for areas of elevated methane concentration. The drone provider created a heat map with gridded methane concentrations for the operator, superimposed over the gas collection system design. The map identified methane hot spots in areas without gas collection wells, which prompted the operator to install a temporary cover and expand the gas collection system to minimize emissions. Follow-on drone flights, conducted on a monthly basis, confirmed successful mitigation.[31]

Key takeaways:

- Frequent monitoring surveys can inform better cover practices and gas capture system expansion.
- Follow-on surveys can verify methane mitigation and identify new best practices.

Cost considerations and potential funding opportunities for landfill methane monitoring

The cost of advanced monitoring technologies for methane detection varies by deployment method, sensor type, and the size of the facility. Below, we provide an overview of typical cost ranges for a survey. There may be additional costs involved in data processing and subscriptions/dashboards. Depending on the survey frequency and number of sites, it may be more cost-effective to purchase the equipment up front and conduct surveys in-house, rather than outsourcing to a provider.

Satellite
Free from not-for-profit providers for select landfills; $2,500–$7,000 per observation from commercial providers

Aircraft
Free from not-for-profit providers for select landfills; $10,000–$12,000 per observation from commercial providers

Drone- and Ground-Based
$3,000–$5,000 per survey

Fixed Sensor
<$1,000–$8,000 per unit

Source: Discussions with technology providers, landfill engineers/operators, and EREF

Some landfill operators may have budgetary constraints that affect their ability to procure and deploy certain advanced monitoring technologies on a voluntary basis. However, there are several funding opportunities and potential partnerships that can provide financial assistance to expand the adoption of advanced monitoring at municipal landfills.

Summary of available funding opportunities for advanced monitoring technologies

Funding Source	Description
Greenhouse Gas Reduction Fund (EPA)	Provides $20 billion to nonprofit financing entities and community lenders to support clean energy and air-pollution-reducing projects. Financing is distributed on an ongoing basis to eligible projects. Landfill methane monitoring and mitigation is a potential application.
Climate Pollution Reduction Grants (EPA)	$5 billion for states, local governments, tribes, and territories to develop and implement climate action plans. Waste management is a focus area, and funding could support landfill methane monitoring and mitigation efforts, if included in local climate action plans.
Community Change Grants (EPA)	$2 billion to assist community-based organizations and local governments with pollution reduction projects. Monitoring is an eligible use case, and solid waste management is a focus area.
Energy Efficiency and Conservation Block Grants (US Department of Energy)	$550 million to assist states, local governments, and tribes in implementing strategies to reduce energy use and improve energy efficiency. Reducing and capturing greenhouse gases from landfills is a focus area.
Methane Monitoring Funding (EPA)	$20 million to improve landfill methane measurement through grants and by procuring a set of methane measurement equipment that can be loaned to states, local governments, and tribes.
Partnerships	Operators can partner with state and local air agencies on methane monitoring surveys (e.g., California Air Resources Board and Pennsylvania DEP).

Deploying advanced monitoring technologies can bring benefits to landfill operators and communities

Beyond methane reductions, deploying advanced monitoring technologies can bring several benefits to landfill operators and surrounding communities.

Be a good neighbor

Using monitoring technologies to find and fix methane leaks and inform more proactive operational changes to reduce methane emissions can also reduce emissions of volatile organic compounds, odors, and other local air pollutants that affect the health and quality of life of nearby communities. Monitoring can help operators be good environmental stewards and neighbors to nearby residents. Sharing monitoring data and tangible mitigation progress with nearby residents can also improve relations and build trust.

Increase revenue for LFG-to-energy projects

For the US landfills with energy projects (electricity, RNG, and direct use), using advanced technologies can reduce leakage and improve gas capture rates to boost gas flow and project revenue.

Know what is happening on the ground as data visibility expands from above

Deploying advanced monitoring technologies locally can help operators gain a better understanding of their emissions profile, especially as satellites launch in 2024 and beyond.

Identify and promulgate data-informed BMPs

Beyond leak repair, monitoring technologies can identify opportunities for proactive design and operational interventions and evaluate their effectiveness. Operators can implement these data-informed BMPs to save time and money over the long term in repair and compliance/regulatory costs.

Demonstrate progress on sustainability goals

Monitoring technologies can equip operators with empirical data on their emissions reductions to track and demonstrate progress toward climate goals, whether set by landfill operators or outlined in state and local climate action plans.

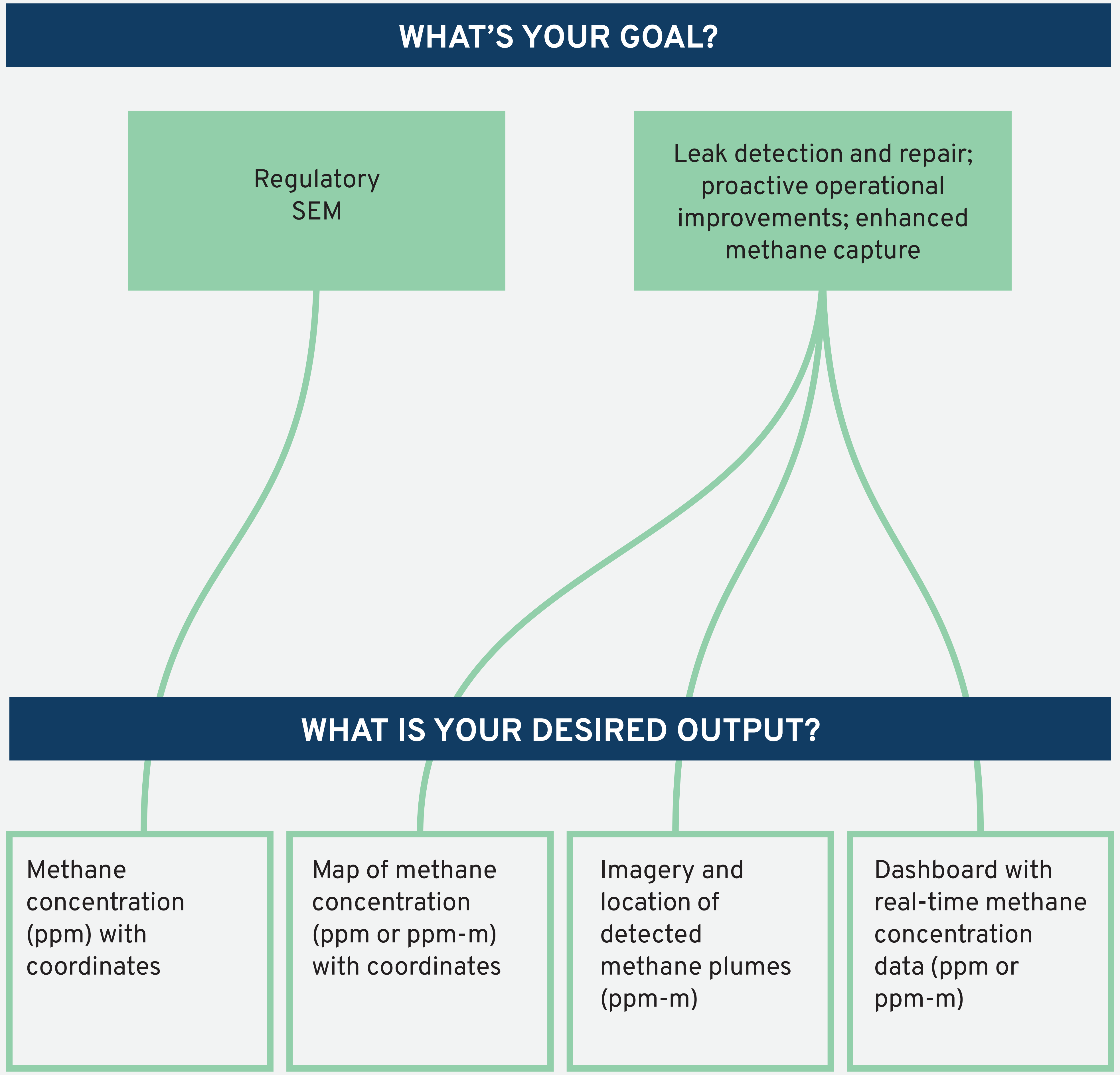
RMI Graphic.Source: RMI research

PART TWO

A Step-by-Step Guide to Monitoring-Informed Landfill Methane Mitigation

Step 1: Select a monitoring system

When using advanced methane monitoring technology at a landfill, it is important first to consider the end goal and desired outputs because this will affect technology selection and deployment.



Once the goal and desired output is established, it is important to assess other parameters that will influence technology selection. The guiding questions below can help.

1. HOW FREQUENTLY WOULD YOU LIKE MEASUREMENTS?

Annual | Quarterly | Monthly | Weekly | Continuous

2. WHAT IS YOUR DESIRED SPATIAL COVERAGE?

Whole facility | Select components

3. WHAT IS YOUR DESIRED DETECTION SENSITIVITY?

Low | Medium | High

4. HOW PRECISELY WOULD YOU LIKE TO LOCALIZE LEAKS?

Low | Medium | High

5. WHAT IS YOUR BUDGET?

Low | Medium | High

Step 1: Select a monitoring system, continued

The flowchart below shows how the goals, desired outputs, and parameters on the previous slide map onto potential monitoring systems (platform and sensor).

GOAL	OUTPUT	PARAMETERS: Frequency (Range)	PARAMETERS: Spatial Coverage	PARAMETERS: Detection Sensitivity	PARAMETERS: Localization Precision	PARAMETERS: Budget	MONITORING SYSTEM
Regulatory SEM	Methane concentration (ppm) with coordinates	Quarterly	Whole facility (near-ground)	High	High	Medium	**Walking** **Drone** Sensor: FID, NDIR, TDLAS
Leak detection and repair; proactive operational improvements; enhanced methane capture	Imagery and location of detected methane plumes (ppm-m)	Monthly (daily to annual)	Whole facility	Low to high	Low to high	Low to high (no cost for publicly accessible data)	**Aircraft** **Satellite** Sensor: Solar or laser spectrometer, lidar
Leak detection and repair; proactive operational improvements; enhanced methane capture	Map of methane concentration (ppm or ppm-m) with coordinates	Quarterly (weekly to annual)	Whole facility	High	High	Medium	**Drone** **Rover** Sensor: Laser spectrometer, NDIR
Leak detection and repair; proactive operational improvements; enhanced methane capture	Dashboard with real-time methane concentration data (ppm or ppm-m)	Continuous	Key components, whole facility	Medium to high	Low to high	Low to high	**Fixed sensor network** Sensor: Metal oxide, NDIR, laser spectrometer

Step 2: Deploy the monitoring system

Once the monitoring system is selected, the next step is planning for deployment. For aerial or mobile near-ground technologies, the operator or technology provider will program the desired flight or surveillance path. For fixed sensors, the operator or technology provider will decide on the ideal number of sensors and their placement to achieve the intended coverage.

Across monitoring systems, it is important to collect data on micrometeorological factors, including wind speed, atmospheric pressure, ambient temperature, and weather conditions (e.g., sunny, cloudy, raining, snowing)[32] — and for a single survey, it is best to conduct measurements under standard micrometeorological conditions.

The chart on the right shows how each monitoring system is typically deployed, the raw outputs, and options for post-processing, data visualization, and quantification. Some quantification approaches may involve a different deployment method (e.g., flying or driving downwind of the source or in concentric circles around the source, rather than across the surface). Our focus here is on monitoring systems and deployment approaches that optimize for leak detection, localization, and repair, rather than quantification. However, as noted in the "End Product" column, data collected from leak surveys can still be used for quantification estimates. In post-processing, by using windspeed data and models (e.g., Gaussian plume model), methane concentration data (ppm or ppm-m) can be translated into an emissions rate (kg/h) for a plume or area source. Note that post-processing can help make the data more actionable for landfill operators but may involve additional costs.

MONITORING SYSTEM	RESULTS		
	Deployment	**Raw Output**	**End Product: Optional Post-Processing and Quantification**
Walking **Drone** Sensor: FID, NDIR, TDLAS	Serpentine path over landfill surface, perimeter, and around key components	Surface methane concentration (ppm) and coordinates	Heat map interpolation; site-wide emissions rate estimate (kg/h)
Aircraft **Satellite** Sensor: Solar or laser spectrometer, lidar	Full surface scan at elevation	Methane concentration (ppm-m) and coordinates	Plume imagery; emissions rate estimate (kg/h)
Drone **Rover** Sensor: Laser spectrometer, NDIR	Serpentine path over landfill surface, perimeter, and around key components	Methane concentration (ppm or ppm-m) and coordinates	Heat map interpolation; site-wide emissions rate estimate (kg/h)
Fixed sensor network Sensor: Metal oxide, NDIR, laser spectrometer	Position near critical components, perimeter, and around landfill surface area	Methane concentration (ppm or ppm-m)	Dashboard with continuous readings of methane concentration; emissions rate estimate (kg/h)

Step 2: Additional considerations for deployment

SATELLITE

- **Site Access:** N/A
- **Micrometeorology:** Observations must be conducted in the daytime with clear line of sight; atmospheric conditions such as cloud cover, weather, and wind may affect detection.
- **Detection Completeness:** Point source imaging satellites can detect emissions above a minimum detection limit (e.g., 100 kg/h) but may not capture diffuse area source emissions or smaller leaks.

  Null detects may mean a source is not emitting at all, or that a source is emitting below the sensor's detection limit.
- **Leak Localization:** Point source imagers can point to an area of the landfill (e.g., active working face, gas infrastructure, cover) but require follow-up with ground or near-ground technologies to pinpoint the exact source.
- **Air Traffic:** N/A
- **Vendor Availability:** Limited to orbit schedule or when the satellite happens to be passing the target. There can be notification latency.
- **Budget:** Cost to landfill operator for commercial services can be moderate, but some data is publicly available to landfill operators at zero cost.

AIRCRAFT

- **Site Access:** N/A
- **Micrometeorology:** Observations must be conducted in the daytime with clear line of sight; cloud cover, weather, and wind may affect detection.
- **Detection Completeness:** May not capture diffuse, low-emissions sources, depending on minimum detection limit (e.g., <5-50+ kg/h).

  Null detects may mean a source is not emitting at all, or that a source is emitting below the sensor's detection limit.
- **Leak Localization:** Depending on spatial resolution, aircraft can geolocate leaks to specific equipment groups but may require follow-up with ground or near-ground technologies to pinpoint the exact source for mitigation.
- **Air Traffic:** Heavy air traffic regions may have an impact on Federal Aviation Administration (FAA) approval to fly aircraft over affected airspace.
- **Vendor Availability:** Limited vendors deploying this technology.
- **Budget:** Cost to landfill operator for commercial services can be moderate to high, but some data is publicly available to landfill operators at zero cost.

DRONES

- **Site Access:** Site access required.
- **Micrometeorology:** Observations must be conducted in the daytime; wind may affect detection but less so for near-ground sensors (e.g., tube method).
- **Detection Completeness:** Detection sensitivity is high (can be parts per billion), but depending on deployment approach, drones may miss emissions between the flight paths, lofted over near-ground sensors, or in active construction areas (if flying with the tube method).
- **Leak Localization:** Can pinpoint methane concentration measurement locations along the flight path or use wind data and inverse modeling to estimate leak location based on downwind measurements. Local wind speed information can reduce uncertainties in localization for sensors flown at elevation.
- **Air Traffic:** Heavy air traffic regions may have an impact on FAA approval to fly drone over affected airspace.
- **Vendor Availability:** For regulatory drone SEM (OTM-51), limited vendor approval may affect vendor availability to deploy technology, though there are other providers for nonregulatory monitoring.
- **Budget:** Cost of deploying regulatory drone SEM (OTM-51) technology is comparable to walking SEM, while nonregulatory monitoring can be low in comparison.

Step 2: Additional considerations for deployment, continued

ROVER

- **Site Access:** Site access required.
- **Micrometeorology:** Wind may affect detection.
- **Detection Completeness:** Detection sensitivity is high (parts per billion), but rovers may miss emissions between the paths or lofted over sensors. Topography may constrain driving path.
- **Leak Localization:** Can pinpoint methane concentration measurement locations along the driving path.
- **Air Traffic:** N/A
- **Vendor Availability:** Limited vendors deploying this technology.
- **Budget:** Cost of deploying technology is comparable to walking SEM.

FIXED SENSOR NETWORK

- **Site Access:** Site access required.
- **Micrometeorology:** Wind may affect detection. Sensors may require calibration.
- **Detection Completeness:** Detection sensitivity is medium to high, but emissions coverage depends on the sensor configuration across the landfill. Topography may constrain detection.
- **Leak Localization:** Requires inverse modeling to infer precise location, which is influenced by wind speed.
- **Air Traffic:** N/A
- **Vendor Availability:** Multiple vendors available
- **Budget:** Deployment cost can be low to high depending on sensor type and configuration, while cost on a per measurement basis is very low given measurement frequency.

Step 3: Pinpoint the emissions source(s)

When emissions are detected by the monitoring system, the next step is to pinpoint the source(s) of the emissions. Depending on spatial resolution, some technologies can attribute emissions only at the facility level (e.g., to a particular landfill or region of the landfill), while others can attribute emissions to an equipment group (e.g., the gas collection system), or a specific component (e.g., a flooded wellhead).

- **Plume imagery** from satellite and aircraft technologies provides a potential source location but often requires ground-based follow-up for more precise localization. Inspection personnel may conduct a walking, drone-, or rover-based survey with a methane detection instrument around the area of the landfill where the elevated emissions were observed to identify the specific source. In addition, trained personnel can often detect the odorous elements in LFG or pick up on other visual indicators of leaks, like distressed vegetation or cracks in the cover.
- **A map of methane concentration with coordinates,** from a drone or rover, may provide the operator with sufficient information to pinpoint the specific source and determine a root cause. Operators may still conduct ground-based walking follow-up to gather more details on the emissions source and guide mitigation activities.
- **A dashboard with real-time methane concentration data** from a continuous emissions monitoring system can provide a source location estimate through inverse modeling. Operators may conduct ground-based walking follow-up to confirm the source location and guide mitigation activities.

Case Study: Landfill A

On March 2, 2023, a satellite detected a plume at Landfill A, after a non-detect the day prior. On March 16, the operator was notified of the plume (two-week satellite processing time). Upon notification, the landfill operator deployed environmental technicians with methane detection instruments to find the source of emissions.

Case Study: Landfill B

On June 16, 2023, Landfill B was notified by a state agency regarding the results of two aircraft flyover events conducted on June 13 and 15. In response, personnel conducted an initial field assessment on June 19. On the same day, a commercial satellite completed a flyover of the site and detected a plume in an area overlapping the aircraft plume detections.

Case Study: Landfill C

On September 25, 2023, a state regulatory air agency conducted an unannounced regulatory inspection with areas of interest informed by historical, publicly available satellite data. The site operator and agency conducted a field investigation.

Case Study: Landfill D

On June 19 and 23, 2023, Landfill D received courtesy notification from the state air agency regarding results of two aircraft flyover events conducted on June 15 and 20. Personnel reviewed the aircraft plume imagery to identify primary causes.

Step 4: Find the root cause of emissions

Following the attribution of elevated emissions levels to their source(s), the operator will work to identify the root cause of these emissions. Regularly documenting site characteristics and upgrades can help operators identify the root cause. This allows operators to analyze historical operational data for changes or anomalies and match the time at which emissions were detected to activities at the landfill. The table below shows parameters that can be documented regularly to help interpret emissions data.

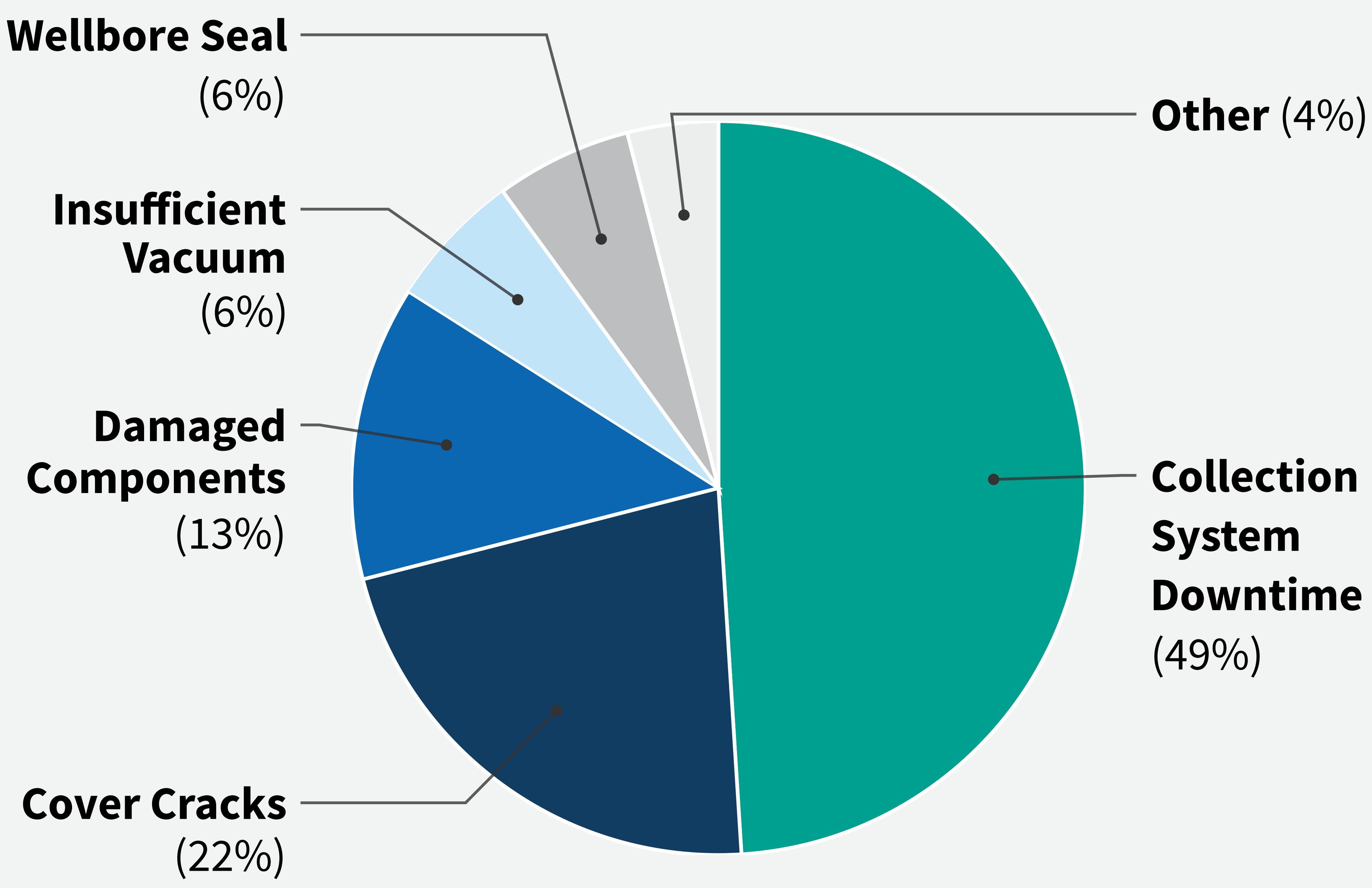
Common data log to aid root cause identification

Type	Parameter
Incoming waste	• Waste-in-place and volume of incoming waste • Areas of active filling, size of working face • Waste composition
Landfill cover	• Cover material (e.g., soil, vegetative cover) • Cover depth/thickness/integrity • Areas under daily vs. intermediate vs. final cover
Gas capture and control systems	• Gas flow and vacuum • Wellhead data (temperature, pressure, oxygen, nitrogen) • Flare system performance
Construction and maintenance	• Construction and maintenance activities, duration, area

Emissions detected by advanced monitoring technologies may be a result of normal operations — such as construction, maintenance, or active filling of waste — that exposes the waste mass and facilitates the uncontrolled release of methane or contributes to downtime of the gas collection system. In other cases, observed emissions may reveal an equipment malfunction or other operational issue that can be promptly addressed, such as cracks in the landfill cover, an unlit flare, or a flooded well. The California Air Resources Board conducted aerial surveys at California landfills in 2020 and 2021 and found the greatest number of incidences resulted from collection system downtime, cover cracks, and damaged components.[33]

Step 4: Find the root causes of emissions, continued

Leak causes identified by operators during 2020-21 airborne survey in California



RMI Graphic. Source: California Air Resources Board: https://ww2.arb.ca.gov/sites/default/files/2023-05/LMR-workshop_05-18-2023.pdf

Case Study: Landfill A
After surveying the landfill, the environmental technicians discovered three 1-inch pipes, part of a gas system construction project, that had become unsealed.

Case Study: Landfill B
The primary causes of the plume detections varied: thinning cover in one area, an exposed operations layer in another area, and trenching for GCCS expansion in an area where gas collection pipe installation was underway.

Case Study: Landfill C
Upon field investigation, the site and agency identified three areas in close proximity with elevated methane concentration where the site had recently completed cover repair work.

Case Study: Landfill D
The primary cause of one aircraft detection was due to the exposed liner system and operations layer. Site personnel had already partially identified surface emissions in these areas during the routine quarterly SEM on June 8. The primary cause of the other aircraft detection was due to the area being a new waste cell.

Step 5: Evaluate options and deploy optimal mitigation measure

Following the identification of the root cause of an emissions event, the operator, often in consultation with a landfill engineer, can develop a mitigation plan. Mitigation plans should consider and evaluate the effectiveness of potential solutions and constraints that might affect deployment. Further, a whole-systems approach to designing a mitigation solution is important to ensure that interactions within the system do not counteract each other to result in a negative outcome. Below are some recommended solutions for five major sources of landfill emissions. More comprehensive mitigation solutions are provided in RMI's report on Key Strategies for Mitigating Methane Emissions from Municipal Solid Waste.[34]

Common sources and solutions to reduce methane emissions

Area	Common Sources	Potential Solutions
Landfill Cover	Cracks or erosion in landfill cover, cover penetration leaks	Recompact soil cover
	Cover materials with limited oxidation capabilities	Install biocovers; reduce lag time between daily, interim, and final cover
Gas Collection System	Flooded wells or damaged components	Use well de-watering pumps; re-seal/replace components
	Insufficient vacuum	Adjust vacuum; use automated well tuning
	Inadequate well coverage or density	Expand gas collection system
	System downtime	Minimize system downtime
Control Device	Inefficient or unlit flares, venting	Use enclosed flares with high destruction efficiency
Normal Operations	Active filling of waste, working face	Minimize surface area of active working face
	Construction, maintenance	Limit duration of construction, maintenance; use a vacuum box

RMI Graphic. Source: RMI analysis

Step 5: Evaluate options and deploy optimal mitigation measure, continued

Mitigation solutions can be either reactive or proactive. Reactive strategies focus on repairing leaks. Examples of leveraging advanced monitoring for reactive repairs include fixing a fissure in landfill cover or dewatering a flooded gas well. Operators can also leverage monitoring data to inform and assess the efficacy of more proactive design and operational changes at the landfill site to increase gas capture and reduce fugitive emissions. Examples of more proactive measures include installing a biocover system to boost methane oxidation, upgrading the flare system, or expanding the gas collection system.

Case Study: Landfill A

The pipes were properly capped, and repairs were made until the contractor completed the project.

Case Study: Landfill B

Remediation measures were initiated June 23 (five-business-day response time) and completed by July 26. These measures included adding soil to seal up cover areas, sealing the exposed operations layer, and backfilling and compacting the gas collection pipe installation trenches.

Case Study: Landfill C

Site operations personnel completed additional cover repairs in areas where cover appeared disturbed from construction activities (two-day corrective action response time).

Case Study: Landfill D

For the first plume, the site had initiated remediation measures on June 9 (five business days prior to the agency aircraft flyover), which included placing soil and compacting over the exposed operations layer. For the new waste cell, the site had initiated design for the GCCS and scheduled installation of new gas collectors and system expansion for August/September 2023, which are expected to control surface emissions in this cell.

Step 6: Verify emissions reduction

Verifying emissions reduction constitutes the final step in emissions monitoring and mitigation. This involves validating the efficacy of a mitigation solution that has been deployed. Here, follow-up observations may be conducted to verify that the underlying root cause of the emissions event has been fixed. These follow-up observations may be carried out via SEM instruments to verify that emissions do not exceed the regulatory threshold of 500 ppm.

Verification may also be conducted via remote sensing and can be carried out by an independent third party. Reduction in emissions may be verified through reduced methane concentration readings in the affected area, increase in the LFG collected, and/or non-detects or limited detection in the affected area. For example, as part of the 2021 overflight study conducted by the Pennsylvania DEP in conjunction with Carbon Mapper, several operators took action to remediate large emission sources identified by Carbon Mapper and then verified the methane reductions with follow-up SEM readings below 500 ppm.[35]

Case Study: Landfill A

After repairs, the satellite completed its next flyover on April 19 and did not detect a plume.

Case Study: Landfill B

Follow-up surface monitoring of the area resulted in no exceedances above the regulatory standard of 500 ppm. Follow-up satellite monitoring on July 26 did not detect any plumes (same day remediation efforts were completed).

Case Study: Landfill C

The regulatory agency returned September 27, and all regulatory findings with ground monitoring equipment were below 5 ppm methane (regulatory threshold is 500 ppm). A satellite observation conducted on October 5 did not detect a plume at the site.

Case Study: Landfill D

The site conducted final confirmatory SEM with locations observed at or below 150 ppm. In addition, the aircraft flyover had a non-detect on June 21.

Methane detection and mitigation timeline

Below, we show how the detection and mitigation timelines for Landfills A and B map on to the six-step process described on the previous slides.

STEP 1	STEP 2	STEP 3	STEP 4	STEP 5	STEP 6
Select a monitoring system	Deploy the monitoring system	Pinpoint the emissions source(s)	Find the root cause of emissions	Evaluate options and deploy optimal mitigation measure	Verify emissions reductions

LANDFILL A

Timeline: March to April, 2023

March 2: Satellite detects a plume at Landfill A

March 16: Landfill A is notified of plume observation

Upon notification, Landfill A deploys field resources (environmental technicians and methane detection instruments) to identify source

Technicians discover three 1-inch pipes, part of a GCCS construction project, that have become unsealed

Pipes are properly capped and repairs made until the contractor completes the project

April 19: Satellite completes flyover and does not detect a plume

LANDFILL B

Timeline: June to July, 2023

June 13, 15: Aircraft flyover detects plumes at Landfill B

June 16 State air agency notifies Landfill B of plume detection

June 19: Commercial satellite detects plume at Landfill B, overlapping aircraft plume detection

June 19: Landfill B personnel conduct an initial field assessment

Field assessment identifies thinning cover, an exposed operations layer, and trenching for GCCS expansion expansion as the primary causes

June 23–July 26: Landfill B implements remediation measures: adding soil to seal cover areas, sealing the exposed operations layer, and backfilling and compacting the GCCS pipe installation trenches

July 26: Follow-up satellite monitoring detects no plumes; follow-up SEM results in no exceedances above 500 ppm

RMI Graphic. Source: RMI research

Conclusion

As the third-largest contributor to methane in the United States, MSW landfills represent an untapped opportunity to reduce methane emissions, slow global warming, and lower the risk of dangerous climate tipping points. Reducing methane emissions from landfills requires a two-pronged approach that includes (1) preventing methane generation from future waste streams through waste prevention and diversion efforts, and (2) mitigating emissions from waste-in-place in landfills across the United States.

Methane monitoring technologies enable the prompt detection of emissions events and can inform deployment of mitigation measures. In the United States, many landfills already conduct regulatory SEM to detect and address any methane exceedances within a stipulated period. However, the traditional approach of conducting these monitoring surveys can be very labor intensive, time consuming, subjective, and limited in their coverage of the landfill. Advanced monitoring technologies are increasingly being used to detect methane emissions at US landfills and can complement existing deployment approaches to improve efficiency, coverage, and frequency to inform more timely and effective mitigation measures.

This playbook serves as a resource for landfill operators, municipalities, and local governments in the United States to leverage advanced monitoring technologies to address methane leaks and inform more proactive improvements. It provides an overview of technologies that are readily available today and walks through the key considerations for deployment, including data availability, site coverage, detection sensitivity, localization potential, cost, and funding sources.

Further, it provides a step-by-step guide to monitoring-informed methane mitigation, which includes selecting a suitable technology, deploying the technology, attributing emissions to a source, finding the root cause, evaluating and deploying the optimal mitigation measure, and verifying emissions reduction. The playbook showcases real-world case studies at US landfills.

As the regulatory landscape evolves to accommodate advanced monitoring technologies, landfill operators and municipalities can deploy these technologies voluntarily today to supplement or replace the traditional walking SEM surveys. These advanced technologies can improve coverage, worker safety, and efficiency, provide actionable data more frequently, and enhance emissions transparency. At the same time, deploying advanced monitoring technologies provides other benefits to the operator, which include expanding or improving revenue streams through LFG-to-energy projects, identifying and deploying cost-saving BMPs, improving understanding of emissions, and demonstrating industry leadership and progress on sustainability goals.

Reducing methane emissions provides a critical opportunity to slow near-term warming, and the waste sector is full of easy-to-implement solutions. The technologies to facilitate and enhance methane capture from landfills already exist and can be comparable in cost to technologies already deployed. Landfill operators and municipalities can play a unique role in scaling adoption of these technologies while improving air quality and providing climate, environmental, and public health benefits. We hope this playbook empowers landfill operators and municipalities with the information they need to be a part of the solution.

APPENDIX

Advanced Methane Monitoring Technologies Deployed Today

Advanced methane monitoring technologies deployed today

SATELLITE

Passive imaging (solar spectrometer)

ppm-m

Typical Temporal Resolution (Range)	Site Coverage	Detection Sensitivity	Leak Localization Precision
Monthly (daily-annual)	**Whole facility**	**Low**	**Low**

- **Deployment:** Scans landfill surface from above
- **Typical Use Case:** Detecting large emission events, informing and assessing mitigation, evaluating trends over time
- **Typical Data Product:** Imagery, emission rate, and location for detected methane plumes
- **Considerations:** Point source only; localization typically requires on-the-ground follow-up; snow; wind; cloud cover; potential notification latency
- **Examples of Technology/Data Providers Deploying at Landfills:** Carbon Mapper (EMIT), GHGSat

AIRCRAFT

Passive imaging (solar spectrometer)

ppm-m

Typical Temporal Resolution (Range)	Site Coverage	Detection Sensitivity	Leak Localization Precision
Quarterly (monthly-annual)	**Whole facility**	**Medium**	**Medium**

- **Deployment:** Scans landfill surface from above
- **Typical Use Case:** Detecting large emission events, informing and assessing mitigation
- **Typical Data Product:** Imagery, emission rate, and location for detected methane plumes
- **Considerations:** Point source only; localization typically requires on-the-ground follow-up; snow; wind; cloud cover; potential notification latency; air traffic
- **Examples of Technology/Data Providers Deploying at Landfills:** Carbon Mapper (AVIRIS-NG, GAO), Kairos, MethaneAIR, GHGSat

Active imaging (lidar)

ppm-m

Typical Temporal Resolution (Range)	Site Coverage	Detection Sensitivity	Leak Localization Precision
Quarterly (monthly-annual)	**Whole facility**	**High**	**High**

- **Deployment:** Scans landfill surface from above
- **Typical Use Case:** Characterizing site-wide emissions to inform leak repair and operational improvements to boost methane capture
- **Typical Data Product:** Imagery, emission rate, and location for detected methane plumes
- **Considerations:** May miss diffuse low-emission sources; wind; weather; air traffic
- **Example of Technology Provider Deploying at Landfills:** Bridger Photonics

In-plume sensing (CRDS)

ppm

Typical Temporal Resolution (Range)	Site Coverage	Detection Sensitivity	Leak Localization Precision
Quarterly (monthly-annual)	**Whole facility**	**Medium**	**N/A**

- **Deployment:** Flies in concentric circles around landfill
- **Typical Use Case:** Quantifying site-wide emissions
- **Typical Data Product:** Total flux (kg/h)
- **Considerations:** Not a localization approach; wind; weather; air traffic
- **Example of Technology Provider Deploying at Landfills:** Scientific Aviation (ChampionX)

Advanced methane monitoring technologies deployed today, continued

DRONE

Active imaging (TDLAS)

ppm-m

Typical Temporal Resolution (Range)	Site Coverage	Detection Sensitivity	Leak Localization Precision
Quarterly (weekly-annual)	Whole facility	High	High

- **Deployment:** Flies serpentine path over landfill surface at elevation
- **Typical Use Case:** Characterizing site-wide emissions to inform leak repair and operational improvements to boost methane capture
- **Typical Data Product:** Map of methane concentration with coordinates
- **Considerations:** Site access; wind; air traffic; may miss emissions between flight path
- **Examples of Technology Providers Deploying at Landfills:** Aerometrix (Pergam Falcon Laser), SCS Engineers (Pergam), Firmatek (Pergam)

In-plume sensing at elevation (TDLAS, OA-ICOS)

ppm

Typical Temporal Resolution (Range)	Site Coverage	Detection Sensitivity	Leak Localization Precision
Quarterly (weekly-annual)	Whole facility	High	Medium to high

- **Deployment:** Flies downwind of landfill, along perimeter, and/or in serpentine path over surface at elevation
- **Typical Use Case:** Characterizing site-wide emissions to inform leak repair and operational improvements to boost methane capture
- **Typical Data Product:** Facility/component emission rate, methane heatmap
- **Considerations:** Site access; wind; air traffic; localization may involve modeling
- **Examples of Technology Providers Deploying at Landfills:** ABB, SeekOps

In-plume sensing near-ground (NDIR, TDLAS)

ppm

Typical Temporal Resolution (Range)	Site Coverage	Detection Sensitivity	Leak Localization Precision
Quarterly (weekly-annual)	Whole facility (near ground)	High	High

- **Deployment:** Flies serpentine path over landfill surface with a tube collecting ground-level samples
- **Typical Use Case:** Regulatory surface emission monitoring (SEM); characterizing site-wide emissions to inform leak repair and operational improvements to boost methane capture
- **Typical Data Product:** Map of methane concentration with coordinates
- **Considerations:** Site access; air traffic; may miss emissions between flight path, lofted over sensor, or in active construction areas
- **Example of Technology Provider Deploying at Landfills:** Sniffer Robotics

ROVER

In-plume sensing (NDIR, TDLAS)

ppm

Typical Temporal Resolution (Range)	Site Coverage	Detection Sensitivity	Leak Localization Precision
Quarterly (weekly-annual)	Whole facility (near-ground)	High	High

- **Deployment:** Moves in serpentine path over landfill surface with ground-based sensor
- **Typical Use Case:** Characterizing site-wide emissions to inform leak repair and operational improvements to boost methane capture
- **Typical Data Product:** Map of methane concentration with coordinates
- **Considerations:** Site access; topography; may miss emissions between driving path, lofted over sensor, or in active construction areas
- **Examples of Technology Providers Deploying at Landfills:** HATS Consoar, Specialized Robotic Solutions

Advanced methane monitoring technologies deployed today, continued

FIXED SENSOR NETWORK

Active imaging (laser spectrometer)

ppm-m

Typical Temporal Resolution (Range)	*Site Coverage*	*Detection Sensitivity*	*Leak Localization Precision*
Continuous	**Configuration dependent**	**High**	**Medium to high**

- **Deployment:** Laser system and reflectors positioned across landfill surface
- **Typical Use Case:** Rapid response to elevated methane concentration; informing operational improvements; evaluating trends over time
- **Typical Data Product:** Dashboard with real-time methane concentration data, estimated emission rate
- **Considerations:** Site access; coverage depends on sensor configuration; wind; topography; localization requires modeling
- **Examples of Technology Providers Deploying at Landfills:** LongPath, Boreal Laser

In-plume sensing (metal oxide, NDIR)

ppm

Typical Temporal Resolution (Range)	*Site Coverage*	*Detection Sensitivity*	*Leak Localization Precision*
Continuous	**Configuration dependent**	**Medium to high**	**Medium to high**

- **Deployment:** Positioned across landfill surface area, on wellheads, near critical components, or along perimeter
- **Typical Use Case:** Rapid response to elevated methane concentration; informing operational improvements; evaluating trends over time
- **Typical Data Product:** Dashboard with real-time methane concentration data, estimated emission rate
- **Considerations:** Site access; calibration; coverage depends on sensor configuration; wind; topography; localization requires modeling
- **Examples of Technology Providers Deploying at Landfills:** SOOFIE, Sensirion, LoCI Controls, EarthView, Qube

In-plume sensing (eddy covariance)

ppm

Typical Temporal Resolution (Range)	*Site Coverage*	*Detection Sensitivity*	*Leak Localization Precision*
Continuous	**Configuration dependent**	**High**	**Low to medium**

- **Deployment:** Positioned downwind of landfill or downwind of specific components
- **Typical Use Case:** Quantifying emissions; evaluating emissions trends over time
- **Typical Data Product:** Dashboard with real-time methane concentration data, estimated emission rate
- **Considerations:** Site access; coverage depends on sensor configuration; wind; topography; localization requires modeling
- **Example of Technology Provider Deploying at Landfills:** Li-COR

Advanced methane monitoring technologies deployed today, continued

VEHICLE

In-plume sensing (CRDS, laser spectrometer)

ppm

Typical Temporal Resolution (Range)	*Site Coverage*	*Detection Sensitivity*	*Leak Localization Precision*
Annual (monthly-annual)	**Whole facility**	**High**	**N/A**

- **Deployment:** Drives along roads downwind of landfill or along perimeter
- **Typical Use Case:** Quantifying site-wide emissions
- **Typical Data Product:** Total flux (kg/h)
- **Considerations:** Road access; wind; topography; time-intensive
- **Examples of Technology Providers Deploying at Landfills:** ABB, mAIRsure

HANDHELD

In-plume sensing (FID, TDLAS)

ppm

Typical Temporal Resolution (Range)	*Site Coverage*	*Detection Sensitivity*	*Leak Localization Precision*
Quarterly	**Whole facility (traversable)**	**High**	**High**

- **Deployment:** Walks serpentine path over landfill surface with near-ground sensor
- **Typical Use Case:** Regulatory SEM; follow-up to remote sensing detection
- **Typical Data Product:** Methane concentration with coordinates
- **Considerations:** Labor intensive; misses areas of landfill between walking path and that are dangerous or difficult to traverse; may miss emissions lofted over sensor; subjective
- **Examples of Technology Providers Deploying at Landfills:** Elkins Earthworks, Landtec

RMI Graphic. Source: RMI research

Notes: We show the unit for methane detection (ppm or ppm-m), but note that many of these monitoring systems can also quantify an emissions rate (kg/h). List of technology providers is not comprehensive; it shows selected providers with services at US landfills today.

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