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Aerial Monitoring for Examining Landfill Methane Emissions

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White Paper for Evaluating Revisions to the Municipal Solid Waste (MSW) Landfills New Source Performance Standards (NSPS) and Emission Guidelines (EG)

- This series of white papers examines ways to improve the NSPS/EG for MSW landfills using new information and new technology to further control and reduce landfill gas (LFG) emissions.
- Topics include applicability (size of landfill), controls (emission rate and timing of controls), operating practices (cover practices, working face), waste composition (organic waste), and monitoring (technology).

Topic: Aerial Monitoring for Examining Landfill Methane Emissions

This white paper reviews aerial monitoring technologies and approaches that use aircraft and satellites to examine landfill methane emissions, examines recent studies, and summarizes major findings and observations. This paper also examines how aerial monitoring technologies and the data they can produce could be used in an updated NSPS/EG rule. This paper focuses on both the quantification of methane and identifying a concentration. This paper identifies possible rule revisions, benefits and potential drawbacks of such revisions, and next steps for further evaluating the potential use of aerial monitoring in the upcoming NSPS/EG rulemaking.

Rationale and Possible Results

The Clean Air Act (CAA) requires EPA to review and, if necessary, revise the NSPS/EG on a regular basis. As part of this technology review, EPA plans to examine the requirements and available technology to control LFG emissions, including strategies for monitoring methane emissions from landfills. In recent years, new state and international rules have introduced ways to reduce LFG emissions, particularly methane, from being emitted into the atmosphere. These actions are a result of growing environmental awareness and focus on reducing greenhouse gas (GHG) emissions and air quality concerns. Further reducing LFG emissions could also assist with meeting the goals in the U.S. Methane Emissions Reduction Action Plan (White House, 2021), which aims to achieve a gas collection and control rate for all landfills of 70 percent nationally by 2030 (as of 2022, that figure was at 60 percent) (U.S. EPA, 2024a).

Since the NSPS/EG CAA review in 2016, several studies (Krautwurst et al., 2017; Duren et al., 2020; Smith, 2021; Duren et al., 2022; Pennsylvania DEP, 2022; Balasus et al., 2024; Cusworth et al., 2024; Nesser et al., 2024) have detected methane emissions in the United States using aircraft and satellites. Landfill methane plumes detected using these technologies have shown methane emissions are greater than predicted based on GHG emission inventory assumptions and modeling, such as those reported in the Greenhouse Gas Reporting Program, suggesting that landfills may emit greater amounts of methane than previously estimated.

Currently, the NSPS/EG requires quarterly surface emission monitoring (SEM) (i.e., once every three months) to detect methane emissions at landfills required to install controls. This requirement is not intended to provide methane emission quantification but to ensure that the gas collection and control system (GCCS) is well designed and well operated. SEM identifies “hot spots” where significant methane emissions occur, possibly as a result of inadequate design (e.g., gas collection well spacing), inadequate GCCS operation (e.g., insufficient vacuum), or insufficient cover practices (e.g., erosion, cracks, fissures). Ground-based SEM is performed using Method 21 of Appendix A-7 to 40 CFR part 60 (Method 21), Determination of Volatile Organic Compound Leaks, which is a labor-intensive process, exposes personnel to potentially hazardous conditions (e.g., slopes), and is subject to variations in how the test is conducted (e.g., sensor placement and read time).

Recent studies showcasing the ability of aircraft and satellites to detect and quantify site-scale emissions have increased interest and research in using aerial technologies to identify and subsequently mitigate landfill methane emissions. EPA is interested in evaluating whether aerial technologies could be used within the NSPS/EG as a tool to further reduce landfill methane emissions.

Aerial technologies for detecting and quantifying methane emissions are currently used in other industries including crude oil and natural gas, mining, and agriculture. For example, in 2023, EPA finalized a program that would potentially allow satellite detection and remote-sensing aircraft technologies for identifying "super-emitter events" for crude oil and natural gas facilities (40 CFR part 60, subpart OOOOb,c).[1]

Investigation and Results

Review of Aerial Technologies and Approaches

Several technologies and approaches have been used for aerial monitoring of landfill methane emissions. These can be divided into two categories based on how methane measurements are taken:

- **Remote sensing:**[2] Remote sensors measure reflected and scattered radiation from the Earth's surface to determine the concentration of methane (column-based concentration) without direct sampling of atmospheric gases. This category can be further divided into approaches that use remote sensors on 1) aircraft or 2) satellites.
- **Direct sampling:**[3] Aircraft are used to directly sample "in-situ" atmospheric gases and measure methane using an onboard sensor (e.g., cavity ring down spectrometer (CRDS)).

Remote sensing uses sensors to measure reflected or scattered radiation between the Earth's surface and the sensor, which is then correlated to a concentration. Using weather data (e.g., wind speed, wind direction), additional site information (e.g., background atmospheric measurements and solar albedo), and data processing, these concentrations can be used to determine methane flux or estimate an emission rate. For remote sensing methods, sensors are attached to aircraft and satellites to measure methane concentrations and estimate emissions remotely and do not require physically sampling and measuring methane concentrations in the atmosphere.

Alternatively, direct sampling methods use gas measuring sensors attached to aircraft that can fly directly through methane plumes to take measurements of the plume at discrete points. Methane concentrations along with real-time weather data collected during the flight such as wind speed and direction can be used to estimate methane emissions and plumes. These approaches for landfill methane detection and emission estimation are examined in the following subsections.

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[1] Notifiers of super-emitter events must use an alternative test method approved by EPA. At the time of this paper, EPA has not yet approved an alternative test method for methane detection technology.
[2] This category is also often referred to as spectral imaging.
[3] This category is encompassed in "mass balance" methodologies for estimating methane emissions when paired with weather data (i.e., wind speed/direction).

Remote Sensing Approaches – Aircraft

Remoting sensing via aircraft has been used in several recent studies to detect and quantify landfill methane emissions (Krautwurst et al., 2017; Duren et al, 2020; 2022; Pennsylvania DEP, 2022; Cusworth et al., 2024). These aircraft studies have used spectrometer sensing technologies including:

- Next Generation Airborne Visible/Infrared Imaging Spectrometer (AVIRIS-NG) operated by the National Aeronautics and Space Administration (NASA) Jet Propulsion Laboratory (JPL) (Krautwurst et al., 2017; Duren et al., 2019; Duren et al, 2020; Cusworth et al., 2020; 2024).
- Methane Airborne MAPper (MaMAP) operated by the University of Bremen (Krautwurst et al., 2017).
- Global Airborne Observatory (GAO) operated by Arizona State University (Duren et al., 2022; Pennsylvania DEP, 2022; Cusworth et al., 2024).

These spectrometers measure the solar radiation reflected and scattered from the Earth's surface to determine column-based[4] methane concentrations between the surface and the sensor (aircraft) that are processed to estimate emissions over time. Both AVIRIS-NG and GAO measure ground-reflected solar radiation from the visible to infrared spectral ranges (~350 to 2,500 nanometers (nm)) with 5-nm spectral sampling, while MaMAP focuses on the near infrared (NIR)/short wave infrared (SWIR) spectral range at wavelengths around 1,600 nm, 1,660 nm, and 760 nm, which allows for high sensitivity for small changes in methane and carbon dioxide concentrations (University of Bremen, n.d.).

The AVIRIS-NG and GAO instruments are both push-broom instruments[5] with a 34-degree field of view. Field of view length and pixel resolution varies depending on flight altitude, with a 1.8-kilometer (km) field of view and a 3-meter (m) pixel resolution at a typical survey altitude of 3 km (Duren et al., 2019; 2022). Additionally, both AVIRIS-NG and GAO allow for imaging capabilities to identify potential source positions for methane, which is not possible with MaMAP (Krautwurst et al., 2017). MaMAP can, at a flight altitude of 3 km and a ground speed of 300 kilometers per hour (km/hour), generate a ground scene size of 50 m x 100 m (cross track x along track) over land (University of Bremen, n.d.). Krautwurst et al. (2017) estimated methane plume positions based on MaMAP spatial concentration data and the visualized plume developed using AVIRIS-NG data and found good agreement between the two spectrometers; no other comparison on detection sensitivity or variability was made.

The California Methane Survey (Duren et al., 2019; Duren et al, 2020; Cusworth et al., 2020) performed from 2016 to 2017 used AVIRIS-NG, while the GAO was deployed by Carbon Mapper in a 2020 follow-up study (Duren et al., 2022) to the California Methane Survey and a Pennsylvania Department of Environmental Protection (DEP) study (Pennsylvania DEP, 2022).

During the initial California Methane Survey, methane plumes were detected at only 32 of the 437 landfills and composting facilities surveyed.[6] This survey noted, using imagery of landfills with identified plumes, that these sites were often associated with construction activities (e.g., installing new gas wells,

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[4] i.e., the amount of methane between the sensor and Earth's surface.

[5] Push-broom instruments refer to a class of remote sensors that use detectors positioned perpendicularly to the flight direction of an aircraft or satellite, which allows the swath (image) to be collected one line at a time with all pixels in that line being measured simultaneously. This process results in stronger signals than whisk-broom sensors, which have been used in aerial/satellite imaging in the past.

[6] This survey also examined methane emissions from other industries such as crude oil and natural gas and agriculture, but this paper focuses on landfill methane sources.

excavations into existing waste), gas from intermediate cover, and leaking gas capture wells. Plumes were not detected from a large population of small methane point sources across the landfill sector, despite the AVIRIS-NG having a reported detection limit of roughly 10 kilograms per hour (kg/hr) methane at a variety of flight altitudes and wind speeds. This finding suggests that those facilities emit methane as diffuse, area sources that are not detectable with the AVIRIS-NG.

The follow-up study (Duren et al., 2022) in 2020 revisited some of these previously monitored landfills plus 11 additional facilities using GAO, which had similar detection capabilities and used analogous methods and assumptions for data processing and emission estimation, including detecting only larger point sources from landfills exceeding the detection limit (~10 kg/hr methane). Overall, both surveys revealed the same number of plumes (17) and a similar number of facilities with plumes (16 in the initial survey and 17 in the second survey).

In 2021, Pennsylvania DEP commissioned a survey of methane emissions from industries including crude oil and natural gas, mining, and landfills (Pennsylvania DEP, 2022).[7] GAO used by Carbon Mapper for this study had a minimum detection limit of 10 kg/hr methane and identified nine landfill sites that had estimated emission rates above 100 kg/hr methane.[8] These observations were used by Pennsylvania DEP to send notices to these specific facilities to address these elevated emissions. For eight of these sites, owners/operators performed corrective actions on specific sources of emissions that reduced methane emissions by 39.5 percent.

Cusworth et al. (2024) examined other flights flown over landfills across the continental United States using AVIRIS-NG and GAO from 2016–2022 aside from California and Pennsylvania. Altogether, 250 open landfills across 18 states were surveyed, representing roughly 21 percent of the approximately 1,200 reported open landfills in the United States (Cusworth et al., 2024). Flights were typically flown at altitudes ranging from 3 to 5 km above ground level, which resulted in methane plume concentration pixels with 3- to 5-m spatial resolution. Methane plumes were detected at 52 percent of landfills surveyed. Additionally, Cusworth et al. (2024) estimated emissions persistence for each landfill in the study based on the number of days it was flown over and the number of emissions observed during this study period (2016–2022). This analysis revealed that a subset of the landfills with observed plumes had observed emissions nearly every time they were flown over. This subset represented more than 60 percent of the landfills with observed plumes and 87 percent of all quantified emissions in this study. This finding suggests that focusing on resolving issues at landfills with persistent emissions could significantly reduce LFG emissions across the landfill sector.

Remote Sensing Approaches – Satellites

EPA is actively exploring the integration of satellite remote sensing technologies, such as NASA's Earth Surface Mineral Dust Source Investigation (EMIT), MethaneSAT, and Planet's Tanager Constellation, to enhance landfill emission monitoring. These advanced satellite systems offer the potential for more comprehensive and near real-time detection of methane and other greenhouse gases over large areas, providing a broader scope of data collection than traditional ground-based methods. By leveraging these technologies, EPA could improve the accuracy of emissions quantification and identify hotspots of high methane release, ultimately informing mitigation strategies for reducing landfill gas emissions. The

[7] Like the California Methane Survey, only results pertaining to landfills are discussed in this paper.

[8] However, for this specific study, sites that did not have emissions of 100 kg/hr methane or greater were not quantified or analyzed and were deemed beyond the scope of this investigation.

combination of satellite data with existing monitoring approaches could lead to more efficient and cost-effective oversight of landfill operations across the country.

Several studies (Maasakkers et al., 2022; Balasus et al., 2024; Nesser et al., 2024; Roger et al., 2024) have examined satellite remote sensing and its possible use for detecting and quantifying methane emissions from landfills. One satellite, the Tropospheric Monitoring Instrument (TROPOMI), can measure methane in a column-based measurement and quantify total emissions over the landfill area (Balasus et al., 2024). It is on board the European Space Agency (ESA) Sentinel-5 Precursor low-Earth orbiting satellite and observes atmospheric methane concentrations with continuous global daily coverage and 5.5 x 7 km^2 nadir spatial resolution per pixel. This spatial resolution can be effectively increased to 1 x 1 km^2 by conducting multiple days of observations (Maasakkers et al., 2022; Balasus et al., 2024). TROPOMI, and satellites in general, can provide regular mapping of specific sites as frequently as daily, which is a benefit when compared to aerial flyovers that must be scheduled and performed and often provide a "snapshot" in time.

However, while it is possible to detect methane emissions from landfills using satellites, it can be challenging if the emissions are not significant enough and because of the large spatial resolutions used by global surveying satellites such as TROPOMI (Maasakkers et al., 2022; Roger et al., 2024). For this reason, Maasakkers et al. (2022) proposed using the global surveying TROPOMI to identify large regional emission "hot spots" and use this information to employ the use of high-resolution target-mode observations with satellites with a lower spatial resolution and higher sensitivity per pixel, such as the GHGSat instrument suite to identify facilities and characterize emissions for very high emitters.

This strategy uses complementary satellites to enable global detection, identification, and monitoring of landfills with methane emissions. The GHGSat-D, GHGSat-C1, and GHGSat-C2 satellites were launched in 2016, 2020, and 2021, respectively, and use Fabry-Pérot spectrometry to measure solar backscatter in the 1630-1675 nm short wave-infrared (SWIR) portion of the spectrum. GHGSat-D has a targeted field of view of ~10 x 10 km^2 with a pixel resolution of 50 x 50 m^2, while GHGSat-C1 and GHGSat-C2 have an improved detection limit with pixel resolution of approximately 25 x 25 m^2 and a targeted field of view greater than ~10 x 15 km^2. These targeted satellites can detect methane point sources down to a rate of 100 kg/hr.

Airborne Direct Sampling Approaches

As mentioned earlier, airborne direct sampling involves taking in-situ methane measurements using a sensor attached to an aircraft that also has on-board instruments for measuring wind speed and atmospheric conditions to estimate methane flux from a site. Scientific Aviation (Champion X) applies this approach and uses a modified mass balance calculation based on Gauss' Law. This approach involves flying multiple closed-loop patterns around a site at increasing altitudes to fully sample upwind and downwind of a source and within the full vertical extent of a plume.

The flight altitude begins at about 200-500 feet (ft) above ground level and climbs until on-board methane measurement readings indicate that the aircraft is above the methane plume. Based on this sampling approach and using on-board instruments, a methane emission rate is determined. Scientific Aviation's methodology can detect methane emissions as low as 5 kg/hr and uses a CRDS to determine in-situ concentrations of methane with 1-second precision at 1 part per billion by volume (ppbv) (Smith, 2021). From 2019 to 2021, Scientific Aviation conducted a study of methane emissions in California from

53 landfills (130 total measurements) that ranged from below detection limit (5 kg/hr) to 2,976 ± 624 kg/hr with an average methane emission rate over all landfill measurements of 1,026 ± 713 kg/hr.

This mass balance approach using in-situ samples of atmospheric gases has been compared to remote sensing approaches in a couple of studies (Krautwurst et al., 2017; Cusworth et al., 2024). In Krautwurst et al. (2017) the estimated emission rates between remote sensing and the in-situ based method revealed good agreement and the results were similar to one another in Cusworth et al. (2024) as well. Cusworth et al. (2024) noted that in general, in-situ estimates based on sampling atmospheric methane were higher than estimates using remote sensing by the AVIRIS-NG technology. This observation is the result of the in-situ method also detecting and measuring the lower concentration, diffuse area sources of methane in the atmosphere in addition to the higher concentration point sources of methane. Remote sensing technologies like AVIRIS-NG and GAO are tuned to detect larger point sources and typically cannot detect the lower concentration, diffuse area sources; thus, remote sensing technologies typically do not encapsulate those diffuse emissions into their emission estimates from a site.

Advantages and Challenges with Aerial Monitoring Approaches

The studies identified several advantages and challenges with using aerial monitoring techniques to detect and quantify methane emissions from landfills. Here, these advantages and challenges are identified and discussed by technology.

Remote Sensing Technologies (Satellite or Aircraft)

The benefits and drawbacks from using remote sensing technologies, whether using satellites or aircraft, to detect methane include:

- Benefits:
    - Remote sensing technologies can detect and quantify methane emissions from point sources quicker than direct sampling methods, often requiring fewer flyovers per site, which allows for additional sites to be covered during a flight day.
    - Technologies like AVIRIS-NG and GAO can map plumes visually.
    - The spatial resolution of remote sensing highlights large point source emissions making these sources more identifiable.[9]
- Drawbacks:
    - Spatial scales of some satellite-based measurements, like TROPOMI, may be too large for accurate detection of specific point sources (e.g., wells, flares) from landfill sites. The ability of satellites such as TROPOMI to detect and quantify emissions from point sources is still limited to relatively coarse pixel resolutions (5.5-km by 7-km). Smaller, targeted satellites such as the GHGSat series can capture a smaller pixel resolution (e.g.,50 x 50 m^2) and may be better suited to detecting point sources at landfills, but they still require fairly high (~100 kg/hr methane) emission rates before methane is detectable (Maasakkers et al., 2022).
    - Remote sensing approaches have limited ability to capture diffuse areas sources due to low concentration emissions.

[9] These large point sources of emissions are also typically more straightforward to identify on-site once detected for the overall site (e.g., a malfunction/non-functioning flare).

- Successful measurements are limited by cloud cover and surface reflectivity anomalies. These methods are heavily influenced by local weather conditions, and, in the case of aircraft, wind speed and direction can prevent data capture. Additionally, other factors include how the data are processed and the background atmospheric data that are used to compare the emission data.
- For aircraft, how flights are performed can have a major impact on the accuracy of results. Flights need to be carefully planned and operated to capture plumes accurately (Krautwurst et al., 2017).
- The cost implications of remote sensing monitoring solutions may be significant considering the geographical spread and number of landfills to be monitored.

Direct In-Situ Sampling (Aircraft)

The benefits and drawbacks from using a direct sampling method (in-situ) using aircraft to detect and quantify methane emissions are:

- Benefits:
    - Less susceptible to cloud cover/solar reflectance conditions.
    - In-situ methane measurements can capture both point sources and diffuse area sources of methane, allowing for a more accurate representation of overall methane emissions from a site.
- Drawbacks:
    - Similar to remote sensing, the cost of aerial monitoring depends on the number and location of sites being monitored. It is more cost-effective when multiple sites are close together, allowing them to be covered in a single flight. However, for industries with fewer, widely spaced sites, the cost increases, as a single flight may only cover one or two locations. In these cases, frequent monitoring can make it difficult to justify the expense unless there are improvements in efficiency or reductions in cost.
    - Taking in-situ measurements is a more time-consuming process than remote sensing and must be completed in a single attempt (i.e., a sufficient number of captures, rotations around a site) or else data capture may be insufficient for estimating emission rates.[10]
    - This method is highly susceptible to flight and sampling conditions.
        - Favorable wind conditions and sufficient vertical mixing are important. Ideal wind conditions are moderate and steady with speed and direction. Completely calm, high speeds, or rapidly varying wind directions are not suitable.
        - Weather conditions (e.g., turbulence, precipitation) can limit or cancel scheduled flights.[11]
        - For the greatest accuracy, flights need to be near ground level or utilize near-ground data. Flights would need to follow federal aviation regulations and safety procedures.

[10] The spectrometers used throughout these reviewed studies measure methane concentrations. Using this measured concentration along with weather data (e.g., wind speeds, direction), background corrections (e.g., surface albedo), and other built-in assumptions based on their methodologies, an emission rate can be estimated with some level of uncertainty.
[11] Poor weather conditions can also affect using aircraft for remote sensing applications as well.

    - Trained expertise is required to understand plume sources to know how and where to fly to capture the majority of the plume. Otherwise, results may be inaccurate.
  - Results obtained from this method could possibly be skewed by other emission sources upwind of the target site if present in proximity.
    - Other emission sources can obscure whether emissions are coming from within the target site or are traveling into the closed-loop boundary (i.e., the boundary around the target site).
    - This skewing of results is particularly an issue if the upwind source is similar in magnitude or larger than the target source.
    - Often, an estimate of target emissions can still be made but will have a larger uncertainty associated with it.

How Aerial Monitoring Could Be Integrated into the NSPS/EG

Understanding the strengths and weaknesses of these aerial monitoring approaches is necessary to identify how these tools could be integrated into the upcoming NSPS/EG rulemaking. Based on the review in the previous section, some applications for using aerial monitoring for methane emissions from landfills could include:

- Use in determining applicability threshold for the NSPS for landfills, similar to how design capacity and emission thresholds are currently applied.
- Use as a monitoring tool to evaluate concentrations and/or emissions on a site-wide basis, either as a screening tool or tiered approach to identify sites that may not be operated in a manner to minimize emissions.

NSPS Applicability: Aerial monitoring could be used to help determine whether a site must comply with the NSPS/EG to control its emissions in lieu of or in addition to current size/design capacity thresholds. For example, aerial technologies could be used to develop methane emission rate criteria that could be used as an applicability requirement (e.g., sites emitting more than XX Mg in a specific time period methane must comply with the NSPS/EG). How this application could affect changes in rule language and structure is discussed further in the Potential Regulation Changes section.

Routine Monitoring: Using aerial technologies for regular landfill monitoring could involve either using the technologies to determine surface concentrations of methane or using them to estimate emissions to determine whether a site is operating its GCCS in compliance with the requirement to control emissions. As noted in the previous section, a challenge with using aerial technologies to detect diffuse area surface emissions is the relatively low surface concentrations that can vary daily and seasonally and be difficult to discern below certain thresholds.

Aerial technologies could be used as a screening tool or tiered approach to identify sites that appear to have significant sources of methane emissions that merit a closer examination of on-site emissions using additional tools such as surface emission monitoring (Method 21) and/or possibly Unmanned Aircraft System (UAS)/drone technologies to identify emission "hot spot" areas.[12] Alternatively, this strategy can be used with Method 21 to either 1) confirm that this method is not missing significant point sources

[12] See additional details on how UAS/drone technologies may be used in identifying emission hot spots and monitoring landfills in the UAS/Drone Monitoring white paper.

that could be missed during quarterly scans or 2) confirm that observed surface exceedances during these quarterly scans are resulting in detectable methane plumes or emissions.

Challenges: Three questions that must be answered that are central to each of these potential uses of aerial technologies in the NSPS/EG are:

1) **What level of accuracy is expected or reasonable to be enforceable for an applicability and/or compliance requirement?** For example, what is the appropriate approach if a limit for regulatory applicability or compliance is 100 kg/hr and an estimated emission rate has an uncertainty that could cause it to exceed this threshold (e.g., 35 ± 70 kg/hr methane). It is important to recognize that current technology might not be sufficient to establish a strict quantification limit. The uncertainty in flux measurements, particularly from dispersed sources, can be large due to influences such as local weather conditions, sensor noise, measurement parameters, and site topography. Given these limitations, EPA considers the implementation of a detection program based on the probability of identifying emissions above a set threshold. For example, rather than relying on absolute measurements, a detection approach could be based on achieving a 90% probability of detecting emissions greater than a specified rate (e.g., "X" kg/hr).
2) **How should aerial monitoring and a compliance limit consider the temporal aspect of landfill emissions?** Should limits be based on a one-time exceedance, an annualized exceedance, or an averaged exceedance over a specific time-period? How often would monitoring events be required to make these determinations if not based on a one-time exceedance? Some examples include:
    a. If the landfill exceeds XX kg/hr methane during a single observation, then does the landfill need closer examination? Or if the landfill exceeds an average of XXX kg/hr of methane over a 1-year period? Or if the landfill releases more than XX kg of methane during the year based on the emission rates determined at specific monitoring events (e.g., quarterly)?
    b. An ongoing research question is how emissions are affected by meteorological and diurnal/nocturnal fluctuations. The remote sensing technologies reviewed in this paper typically rely on solar backscatter to measure methane concentrations and are only collected during daytime hours and periodically (i.e., not continuously); this makes accurate estimates of total emissions over a daily or even yearly period challenging.
3) **Should regulatory limits and/or monitoring frequencies be site-specific or based on a specific landfill type or characteristic(s)?** Landfill characteristics such as size, age, or specific operations (e.g., construction, well drilling, working face) can potentially affect the emissions from these sites and their variability over time. As described earlier, emissions from landfills can be defined as "area" or "point;" the former consisting of diffuse emissions that are expected of typical landfill operation while the latter suggests poor landfill operations such as poorly operating GCCS or leaking cover penetrations, which can be intermittent in nature. However, the current understanding of how specific operational issues such as these affect observed methane emissions as well as what is "typical" emissions expected of a well-operated GCCS merit additional work and analysis; thus, mandating a required emission limit for applicability or compliance may be premature.

Potential Regulation Changes

As described in the previous section, revising the NSPS/EG to include aerial technologies for methane monitoring could involve allowing its use for different types of applications, including:

- NSPS/EG applicability.
- Routine monitoring.

If EPA chooses to adopt aerial technologies, this could require EPA to develop rule language that references a methodology and required specifications for the aerial monitoring equipment (e.g., methane detection payload device and cameras, measurement uncertainty thresholds) or to describe these requirements in the rule itself. For example, the NSPS (40 CFR 60.765(c)(3)) refers to performing SEM in accordance with Method 21 along with additional requirements that include:

- Probe inlet must be placed within 5 to 10 cm of the ground.
- Monitoring must be performed during typical meteorological conditions.

Alternatively, EPA could vet specific vendors of these technologies to confirm if these services meet the requirements of the NSPS/EG.

NSPS/EG Applicability: Potential rule changes could be either in addition to or a replacement of the existing NSPS/EG applicability standards for the installation of a landfill gas collection and control system. One scenario could be if a landfill site exceeds the design capacity threshold but has a modeled NMOC emission threshold of under 34 Mg/yr NMOC, it would not be required to install a GCCS; however, if this site had an observed monitored methane emission rate exceeding a predetermined threshold, either once, or over an accepted frequency, then it would be subject to NSPS/EG requirements for LFG collection and monitoring. Alternatively, revised rules could subject sites to the NSPS/EG based on this monitored methane emission rate exceedance alone.

Routine Monitoring: If aerial technologies were implemented as part of requirements in the NSPS (40 CFR 60.765) or EG (40 CFR 60.36f), it is likely that revisions to these sections would be necessary. Using aerial technologies may have challenges detecting diffuse, area sources of emissions from landfill surfaces as indicated in the reviewed studies (Duren et al., 2019; Cusworth et al., 2024) discussed in the previous section. Aerial technologies may be better suited for capturing large point sources that clearly indicate poor operation (e.g., insufficient cover, malfunctioning GCCS). Potential use in regulation could require establishing a concentration or emission rate threshold as a requirement as well as possibly new monitoring frequencies and requirements if exceedances are detected (i.e., a “follow-up” scan within a specified time period).

Currently, landfills must perform quarterly SEM using Method 21 and take corrective actions for surface emissions that exceed 500 ppmv. The use of aerial technologies could provide an alternative to Method 21, possibly allowing for its use to confirm observed exceedances instead of requiring manual scans quarterly, which could have benefits for site operation efficiencies and cost reductions depending on the overall cost and efforts required for aerial monitoring approaches. This approach could require addressing the challenges mentioned in the previous section with respect to dealing with uncertainties with measurements, considering the temporal aspect of landfill emissions, and considering appropriate limits based on landfill characteristics (e.g., waste age, site-specific operations). Alternatively, aerial monitoring approaches could also be used as a tool to confirm that routine on-site monitoring from Method 21 does not miss significant point sources that could be missed based on quarterly testing frequency and spacing between sample points on a landfill surface or that these measured surface exceedances are resulting in detectable emissions.

Implementation and Possible Impacts

Revising the NSPS/EG to include aerial technologies for methane monitoring could result in a range of effects, additional efforts, and financial impacts within the landfill industry.

Depending on how aerial technologies are implemented, some potential impacts could include:

- ***Using aerial technologies and observed emissions as an applicability criterion for NSPS:*** If taken, this action could increase the number of facilities affected by the NSPS, which could increase reporting efforts and resources for those facilities as well as recordkeeping efforts for regulatory agencies. However, this change could also increase the amount of methane captured and controlled overall, especially if it results in GCCS installation and operation earlier. Earlier GCCS installation and operation would result in costs for landfill owners and operators sooner than would be expected under the current NSPS/EG.
- ***Routine monitoring as a screening tool or tiered approach:*** If aerial technologies could be used as a replacement for, or as a tool to reduce the frequency of manual (ground-level) surface monitoring events, they could result in lower labor costs and increased efficiencies. The current ground-based SEM is a labor-intensive process that requires personnel time and exposure to potentially hazardous conditions (e.g., slopes, inclement weather, animals, and pests). Using aerial technologies could reduce labor costs and reduce the hazards for personnel. The potential costs for using aerial technologies could be higher, at least initially, for landfill owners and operators purchasing access to aerial surveys; however, these costs could be offset if reductions in manual monitoring (i.e., Method 21) could be achieved as well as overall reduced costs (e.g., labor) while simultaneously reducing site methane emissions. Being able to rapidly detect methane emissions could allow for quicker responses to landfill methane leaks and ability to take remedial actions. Current monitoring of landfill surfaces occurs on a quarterly basis; a more frequent assessment of methane emissions could allow for quicker remediation to avoid excessive methane emissions. From the previously reviewed surveys (Duren et al., 2020; Pennsylvania DEP, 2022), aerial monitoring is likely to reveal sources of emissions from facilities that were not apparent from routine SEM events. This strategy is likely to result in further methane emission reductions from identifying and resolving these additional methane sources. The amount of these additional reductions merits further analysis to evaluate the cost-effectiveness of this strategy.

Economics is an important consideration for implementing these technologies, as well as building systems to obtain reliable data on a frequent basis that can be used to improve site operations. It is important to identify to what degree monitoring may be provided by a regulatory agency versus what would need to be provided by the landfill owner/operator and how those services can be procured. Additionally, whether this technology will be a requirement or an option in the NSPS/EG will have a major impact on overall costs for landfill owners and operators and regulatory agencies.

The California Air Resources Board (CARB) has built upon its previous studies to partner with vendors to consistently retrieve satellite data for methane emissions from facilities throughout the state, including landfills. This approach involves working with these vendors to develop and deploy additional satellites.

California implemented a state act (California State Budget Act of 2022) that allocated $100 million for purchasing methane plume data from a commercial satellite company. For other entities (e.g., municipalities, private businesses), the more practical approach is to purchase satellite/aerial data from existing satellites or aerial studies. Additionally, depending on how requirements are developed, it is possible that certain landfills (e.g., larger landfills) may be required to monitor more often, which could result in greater costs and required resources and would need to be considered for those facilities.

It is possible that new methods for aerial technologies would have to be developed to implement the proposed applications discussed, which would require a significant investment in time and resources on the part of technology vendors, as well as substantial interaction with the industry to confirm that the technologies work as expected in the landfill sector. Alternatively, approaches used by current providers of these technologies could be vetted by EPA to confirm they meet the desired needs of an aerial monitoring program.

Summary and Next Steps

This paper reviewed and discussed recent studies on aerial monitoring technologies, approaches for detecting and estimating methane concentrations and emissions from landfills, and how these technologies could be included in the upcoming NSPS/EG rulemaking. As described in this paper, aerial monitoring has benefits and drawbacks:

- Benefits:
    - Can detect and estimate large point sources of methane emissions from landfills, which may be indicative of malfunctioning equipment or deviation from site best practices.
    - May enable more rapid site-wide methane emission estimations, as well as estimates from multiple sites (e.g., regional analysis).
- Drawbacks:
    - Requires extensive expertise for data acquisition and processing.
    - Can be sensitive to local weather conditions and flight operations.
    - Challenging to identify/quantify diffuse, area sources of emissions from landfills.

Implementing aerial monitoring technologies to measure and monitor methane emissions in the NSPS/EG would likely require extensive efforts to develop regulatory language and methodologies to ensure that the proper results and intended goals for using this type of monitoring technology are achieved. Landfill owners and operators and local and state regulatory agencies could incur costs for additional recordkeeping, testing, analyses, and technology purchases and/or service subscriptions. However, aerial monitoring could be effective at identifying major releases of methane from landfills and allow for quicker identification and resolution of those emissions to maximize the efficient use of time and resources to minimize methane emissions within the solid waste industry.

These technologies are also likely to detect additional methane emissions as indicated in reviewed studies; however, quantifying those emissions would require additional analysis that is outside the scope of this white paper.

Potential next steps and analyses for determining feasibility of aerial monitoring include:

- Determine approaches and technologies that would satisfy the functions that EPA wants aerial monitoring to fulfill, such as identifying facilities emitting more than a pre-determined emission rate, and develop and/or vet and approve protocols and methodologies for these approaches.
- Perform analyses that examine the potential costs for industry resulting from the use of aerial monitoring compared to the potential methane emission reductions.
- Examine potential funding mechanisms for facilities to implement aerial monitoring programs and/or data acquisition from existing programs, such as grants and loan opportunities.

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