METHANE EMISSIONS

Quantifying methane emissions from United States landfills

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Methane emissions from solid waste may represent a substantial fraction of the global anthropogenic budget, but few comprehensive studies exist to assess inventory assumptions. We quantified emissions at hundreds of large landfills across 18 states in the United States between 2016 and 2022 using airborne imaging spectrometers. Spanning 20% of open United States landfills, this represents the most systematic measurement-based study of methane point sources of the waste sector. We detected significant point source emissions at a majority (52%) of these sites, many with emissions persisting over multiple revisits (weeks to years). We compared these against independent contemporaneous in situ airborne observations at 15 landfills and established good agreement. Our findings indicate a need for long-term, synoptic-scale monitoring of landfill emissions in the context of climate change mitigation policy.

Landfill methane (CH_4) emissions are estimated to make up nearly 20% of global anthropogenic CH_4 emissions (years 2000 to 2017) (*1*) and 17% of US anthropogenic CH_4 emissions (years 1990 to 2020) (*2*). However, these estimates are almost entirely driven by bottom-up process models that have not been comprehensively validated by direct measurement across a broad population of global landfills and dumpsites. Landfill gas emission models generally rely on waste tonnage, decay parameterizations, and some estimate of gas capture, if applicable (75% is commonly used in US), to estimate annual CH_4 emissions (*3*, *4*) These parameters are difficult to generalize because they rely on factors intrinsic to a particular landfill, regional waste stream (e.g., proportion of organic material), operator practices, and jurisdictional oversight. To the best of our knowledge, direct measurements of CH_4 emissions at landfills to date using surface or aircraft instruments have largely been limited to a small number of facilities due primarily to cost, which has resulted in incomplete spatial and temporal sampling. Given the diversity of operational and environmental factors driving landfill emissions, these observational limitations lead to continued uncertainty in this sector's contribution to regional, national, and global CH_4 emission inventories, which can complicate assessing the efficacy of emission mitigation efforts.

CH_4 emissions at solid waste sites result from several processes. Nearly every location with buried organic waste will generate CH_4 gas at some time scale (*5*, *6*). A fraction of that generated gas may escape to the atmosphere through transport or diffusion through soil layers by taking the path of least resistance (*7*). Therefore, changes in barometric pressure have been shown to influence emission variability (*8*–*10*). However, current datasets are insufficient to represent pressure-emission relationships at typical landfills with variable topography, landfill design and operation, waste composition and quantity, gas capture and collection, water management, and daily working face design and operation (*10*). Fugitive emissions of landfill gas can be caused by undersized air pollution control equipment, cracks in cover due to drought, side slope erosion, and how the working face is operated. Emissions can also result from extreme precipitation events, because landfill gas wells can be disconnected from landfill gas header pipes because of the high level of liquids. These emissions may manifest as a distributed diffuse "area source" over a wide area of the waste site or as a "point source" localized to a certain region or hot spot of the site. Waste sites may also contain multiple point or area sources (or both) at any given time. Area source emissions are constrained by the CH_4 generation potential at a landfill, but point sources are more likely related to the dynamic operational nature of a landfill. For example, planned maintenance or construction at a landfill or equipment failures can result in highly concentrated CH_4 point sources that can persist for periods ranging from hours to months. For safety reasons, operators may also "underpull" or apply less vacuum to a gas collection system to avoid excess oxygen from entering the soil.

In the US, CH_4 is most frequently measured at landfills through surface emission monitoring (SEM) walking surveys. These generally involve a person equipped with a low-sensitivity CH_4 detector (e.g., a flame ionization detector) walking along a serpentine path across portions of the landfill and logging the coordinates of any exceptionally high detected surface concentrations >500 ppm [40 CFR 63.1958(d); 40 CFR 63.1960(c) and (d)]. Walking surveys are complicated by the fact that many locations on an active landfill are unsafe to measure (e.g., walking along face areas where new trash is deposited or steep side slopes). SEM surveys are federally required only four times per year for most landfills, which limits their ability to capture any dynamics in emissions. SEM survey accuracy is also highly dependent on the human operator and exact choice of measurement locations, with the result that high-emission locations potentially can be missed entirely. Additionally, SEM measurements do not explicitly represent an emission rate, but instead are designed to flag CH_4 concentration "hot spots" that may indicate a potential regulatory exceedance. Actual quantification of landfill emission fluxes requires the concurrent observation of CH_4 concentration fields and surface wind speed, which often requires the use of sophisticated atmospheric transport modeling. Other studies have leveraged various ground- and aerial-based technologies to measure landfill gas emissions using technologies such as eddy covariance, radial plume mapping, tracer correlation, and flux chambers, among others (*11*, *12*). However, because of the complexity involved in operating these measurement systems, these studies are often limited to a small sample of landfills, making extrapolation to larger waste sector dynamics difficult.

Although strategies to compare, design, and scale emission quantification technologies tailored for landfill CH_4 quantification continue to be developed, there is an immediate need to make a baseline observational assessment of CH_4 emissions across a large swath of waste sites. Remote sensing offers an efficient method for surveying widely dispersed waste sites without costly and time-consuming efforts to gain access to facilities with surface-based observations. In 2016 and 2017, airborne imaging spectroscopy was used to observe >400 active and closed landfills and waste diversion sites in California as part of the California Methane Survey (*13*). This observational approach is sensitive to high-emission CH_4 point sources (typically >10 kg h^{-1} for typical wind speeds and surface albedo), produces high spatial resolution plume maps of emission hot spots, and can quantify emissions of those hot spots under adequate observing conditions. Here, "plume" refers to a region of contiguous pixels of elevated CH_4 concentrations that is observed by an imaging spectrometer and attributable to landfill gas emissions. These plume maps have in turn been used to guide operators

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in locating emission sources at landfills and have prompted mitigation (*14*).

Patterns of high-emission point sources at landfills revealed by the California Methane Survey suggest that persistent super-emitter activity could be prevalent more broadly across the solid waste management sector in the US. To test this hypothesis, we generated an observationally based CH_4 dataset spanning a diversity of US climate zones and jurisdictions, including repeat observations over multiple seasons and, in some cases, years. The sites surveyed in this study represent the largest airborne or ground-based survey of US landfills to date, totaling 250 US Environmental Protection Agency (EPA) Greenhouse Gas Reporting Program (GHGRP) landfills in 18 US states surveyed between 2018 and 2022. We analyzed this statistically robust dataset to assess at what rate point source emissions are prevalent at large (i.e., GHGRP reporting) managed landfills, how long they persist, and whether the magnitude of quantified emission rates is consistent with reported values. This dataset is key for future comparison with other non-US jurisdictions, especially for regions that lack waste management but are looking to incorporate more recommended practices for emission mitigation and public health improvement. In this study, significant point source emissions were detected at a majority of landfills, many with emissions persisting over multiple revisits spanning several months and, in some cases, over multiple years. These results show the need for sustained measurements at landfills to provide operator guidance and to better constrain emission variability.

Results

Landfills surveyed between 2018 and 2022 across the US, as well as landfills surveyed between 2016 and 2017 during the California Methane Survey (*6*), are summarized in Fig. 1A. These surveys deployed either the Next-Generation Airborne Visible/Infrared Imaging Spectrometer (AVIRIS-NG) operated by the NASA Jet Propulsion Laboratory or the equivalent imaging spectrometer onboard the Global Airborne Observatory (GAO) operated by Arizona State University. Both spectrometers measure solar backscattered radiance from 380 to 2500 nm with 5-nm spectral sampling, enabling the estimation of atmospheric column CH_4 concentrations using a retrieval algorithm. We used the columnwise matched filter retrieval tuned to the CH_4-absorbing wavelengths between 2200 and 2400 nm (*15*), consistent with the California Methane Survey. Typical flight altitudes ranged between 3 and 5 km above ground level, resulting in CH_4 plume concentration maps with 3- to 5-m spatial resolution. Surveys were designed to require a minimum of three overpasses on different days

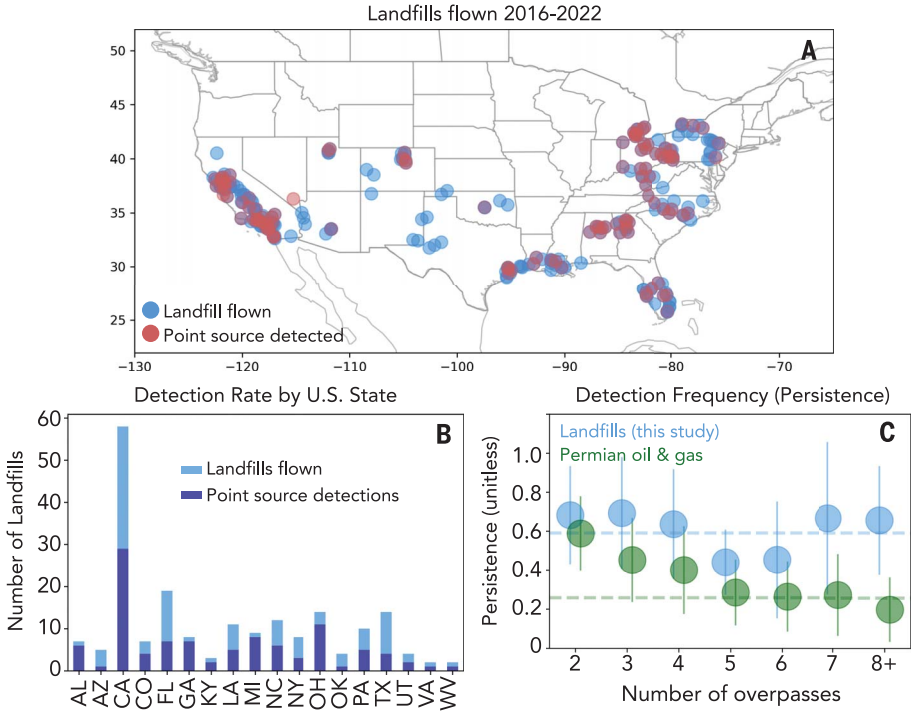

Fig. 1. Landfills flown between 2016 and 2022 using the AVIRIS-NG or the GAO. (**A**) Spatial extent of US surveys. Blue dots represent all landfills with flyovers, and red dots represent landfills where point sources were detected on at least one overpass. (**B**) Total number of large (>20,000 $MtCO_2e$ reported to GHGRP) landfills surveyed by state (light blue) and the number of landfills where we detected point sources in at least one overpass (dark blue). (**C**) Average and SD of detection frequency, also known as persistence (number of detections/number of overpasses), across all surveyed landfills as a function of the number of overpasses. Dashed lines represent the average persistence for facilities flown at least three times on three different days.

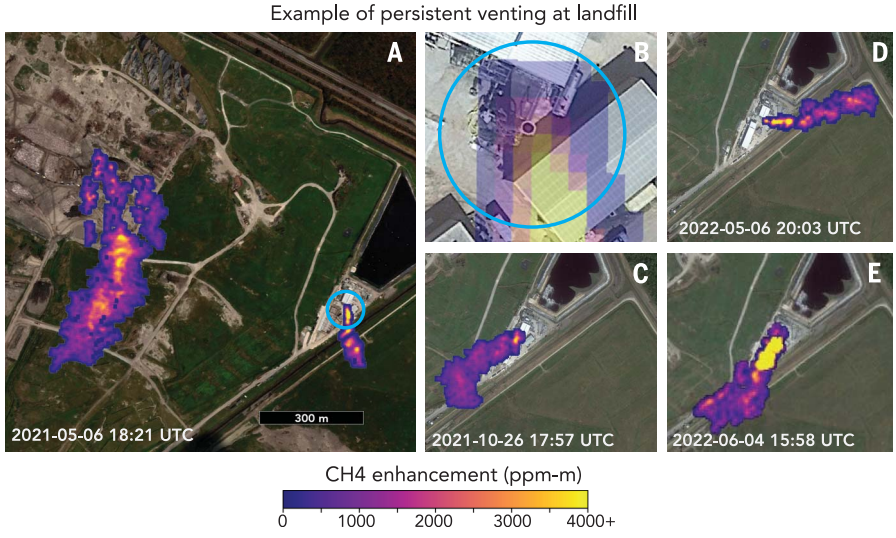

Fig. 2. Example of multiple persistent point sources at a landfill. (**A**) At least two plumes can be seen detected from a single overflight in May 2021. (**B**) The plume emanating from the blue circled region potentially corresponds to a vent or unlit flare. (**C** to **E**) Emission from this vent persisted across all other overflights between May 2021 and June 2022. Visible basemaps are provided by Google Earth.

(average 5.5) to provide a basic constraint on emission persistence (number of detections/number of overpasses) and variability. Information on emission quantification can be found in the materials and methods section of the supplementary materials.

The California Methane Survey performed a landscape assessment of 436 facilities across

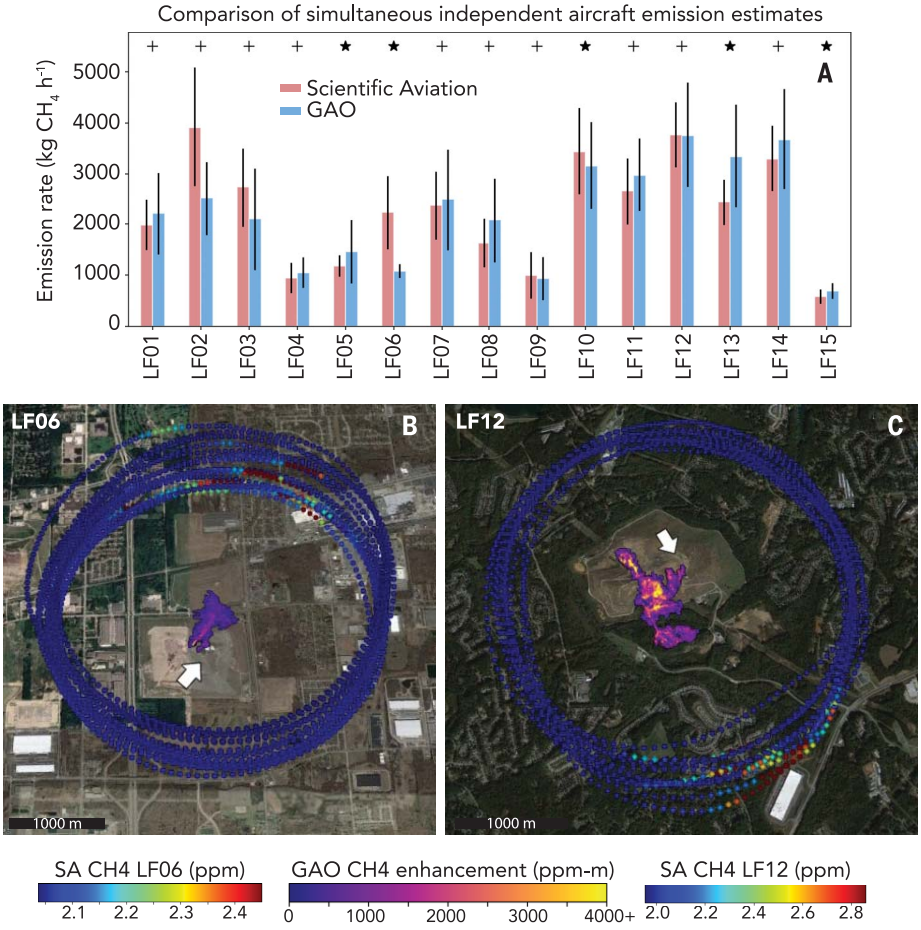

Fig. 3. Comparison of emission rates at landfills derived using the SA mass-balance approach and the GAO imaging spectrometer. (**A**) Fifteen landfill overpasses where comparison between emissions was possible. The plus symbol indicates simultaneous data acquisition. The asterisk indicates asynchronous but same-day observations within 2 hours of one another. Error bars represent 1 SD uncertainties on emission rates. (**B** and **C**) CH_4 observations at LF06 and LF12, respectively, from (A). The white arrow indicates wind direction.

the waste sector in California, including active landfills, closed landfills, dry digestion facilities, and composting facilities (*13*). The study only detected large point source emissions at 32 of those facilities, although emissions from just those facilities made up a disproportionate sector contribution compared with all aggregated sector emissions quantified in the survey (oil and gas, livestock, energy, and wastewater treatment sectors). Of those 32 facilities, 21 (66%) were open landfills that reported CH_4 emissions of at least 50,000 metric tons of carbon dioxide equivalents ($MtCO_2e$) to the GHGRP and 12 (38%) reported at least 100,000 $MtCO_2e$. Given the observed prevalence of high point-source emission rates at large open landfills in California [i.e., landfills that accept large quantities of waste on an annual basis (*4*)] and in an effort to expand coverage across diverse climatic zones and jurisdictions, this study focused on similarly classified facilities based on emissions reported to the GHGRP, generally >50,000 $MtCO_2e$. Although they make up only a fraction of each state's waste facilities, together these facilities represent on average 36% (range 3.8 to 81%) of each state's anticipated landfill emissions according to the GHGRP. The 18 states in this survey made up 67% of the US municipal landfill emissions in the GHGRP (2019 reporting year). To our knowledge, this study represents the most systematic measurement-based study to date of CH_4 point sources from the high-emission solid waste sector, spanning 20% of ~1200 reported open landfills in the US.

We detected plumes at 52% of the landfills that we surveyed (Fig. 1B), far exceeding the point-source detection rate in other CH_4 emission sectors. For example, airborne surveys in California and the Permian Basin showed that ~0.2% and 1% of infrastructure had detectable plumes, respectively (*13*, *16*). However, landfills are complex facilities with anticipated continuous emissions and are fundamentally different from other anthropogenic emission sectors. For example, in the oil and gas sector, point sources detected by imaging spectrometers are usually clearly associated with intermittent but expected operations (maintenance, venting, and flaring) or fugitive emissions (leaks). The higher detection rate of point sources at large landfills confounds any clear separation between operational and anomalous emission behavior because some continuous CH_4 emissions are always to be expected at landfills. To underscore this point, Fig. 1C shows the persistence (i.e., CH_4 detection frequency, where persistence equals the number of detections divided by number of overflights) of CH_4 at surveyed landfills compared with the persistence of oil and gas infrastructure in the Permian Basin (*16*). As evidenced by the US Environmental Protection Agency's recently finalized Super Emitter Program for oil and gas production and proposed changes to the Greenhouse Gas Reporting Program, high-emission point sources (>100 kg h^{-1}), regardless of persistence, are important to identify given their contribution to net emissions. Additionally, any such sources that persist over time may indicate anomalous behavior (e.g., leaks, malfunction) that warrant expedited repair. For the Permian, the average persistence for facilities with at least three overflights is 0.26, whereas for landfills, the persistence is a higher 0.60.

Related to persistence, we calculated the timescale or duration of point source activity for each landfill during its period of observation (*17*). This metric is calculated as the length of time that point sources were detected at a landfill divided by the length of time the landfill was observed. We found a bimodal distribution across landfills (see the supplementary materials, section S2), meaning that there exists a population of landfills where point source activity only was observed for a short period of time and another distinct population of landfills where point source activity apparently persisted across nearly the entire observing record. This long-duration population represents >60% of all landfills and 87% of all quantified emissions. These results highlight the distinct nature of point sources at landfills compared with other sectors. Within the oil and gas sector, point source duration time scales are also bimodally distributed, but long-duration sources make up a smaller fraction of all point sources (*17*), whereas the majority of landfills with point source detections show more persistent and long-lasting emission activity, highlighting the fundamentally different activities, equipment, and dynamics of these sectors. In particular, mitigating persistent landfill sources potentially poses a greater climate benefit because they make up an outsized contribution of total emissions from that sector and are more readily attributable and

verifiable with on-site leak detection and repair protocols.

Point source CH_4 emissions at landfills may result from complex operational dynamics, including the constant movement of the active or working face, maintenance of the gas capture system, delays between waste burial and gas collection installation, construction of new waste cells, etc. There may also be operational inefficiencies or exceptional circumstances that lead to emissions (e.g., poor maintenance of cover material, insufficient vacuum applied to wells, flooded wells, droughts creating cracks in cover). This dynamic environment where multiple factors could lead to point source emissions may explain the higher detection rate and persistence of CH_4 point sources. High-resolution plume maps can aid in uncovering information about processes that lead to point sources. However, ground information from landfill inspections is also vital to connecting observations to processes, because causes of emissions may be due to subsurface processes or small surface features that are difficult to discern even with high-resolution aerial imagery. During these surveys, data were shared with several operators and feedback solicited regarding potential causes of the detected point sources. Although we only received limited responses, many plumes were confirmed to be near the active working face, near compromised wellheads, or in areas where wells were being drilled. Sustained efforts are needed to connect detections and quantification to specific practices so that a better database of emission factors can be developed to help improve management practices and understand the causes of landfill CH_4 emissions.

We observed many plumes where source attribution was much clearer when compared with high-resolution visible imagery. These cases usually corresponded to easily distinguishable gas capture infrastructure. For example, we surveyed a landfill in the southern US in May 2021, October 2021, May 2022, and June 2022 (Fig. 2, A to E). We observed exceptionally large (2000 to 6000 kg CH_4 h^{-1}) plumes emanating from multiple points across the face of the landfill at every airborne overpass. However, to the east of these massive plumes is a smaller, though still significant, plume emanating from gas capture infrastructure. Figure 2B shows a close-up of this facility. The origin of the plume appears to be from an unlit flare or vent stack, and plumes are detected at every overpass between 2021 and 2022. Although the massive landfill plumes to the west are larger in magnitude, the persistent emissions from the unlit flare are still concerning because these are emissions that are not expected with a functioning gas capture and control system. At a minimum, these excess emissions are normally expected to be flared instead of vented. To detemine whether any flaring occurred at this site in between our overflights, we queried satellite fire detections using MODIS and VIIRS day and nighttime overpasses (*18*). The satellites did not discover any thermal signatures indicative of flaring in the vicinity of this site. When we take the average emission rate from all overpasses of this flare stack (1470 ± 720 kg CH_4 h^{-1}) and integrate across the ~12 months of observations, the total emissions are 12,900 metric tons CH_4 or 322,000 $MtCO_2e$. For reference, GHGRP reports CH_4 emissions of 2,920,000 $MtCO_2e$ for this state's total landfill sector, so this single large point source is equivalent to 11% of that portion of the state's inventory. Therefore, as we continue to use observations to uncover process-level complexities at landfills, there is a population of CH_4 mitigation candidates in which timely repairs could have a significant impact.

Emission estimates derived from imaging spectrometers using the Integrated Mass Enhancement method have been evaluated in multiple controlled-release experiments and independent measurements (*19*–*21*). However, given the aforementioned complexities with landfills, including topography, meteorology, and multiple plume origin locations, we performed extensive intercomparison with contemporaneous airborne surveys using Scientific Aviation's (SA's) mass balance approach (*20*). This measurement technique uses low-altitude aircraft equipped with cavity-ring down spectrometers and a wind measurement system to conduct spiral surveys around a facility at various altitudes (generally 500 to 1500 m). The emission rate is calculated by applying Gauss's theorem to observed concentrations and wind speeds. Unlike the imaging spectrometers used in this study, which only detect strong point sources, SA measures the net emission flux from a landfill, including the sum of diffuse area source fluxes and point source fluxes. Therefore, in comparing imaging spectrometer-derived emissions with SA, we would expect the former to produce lower emission estimates than SA if at the time of overpass there are significant contributions from area sources. However, if the net landfill flux at the time of overpass was dominated by strong point source emissions, then we would expect SA and imaging spectrometer–derived emissions to be comparable. SA generally requires 30 to 40 min of spiral observations to quantify emissions from a facility the size of a landfill. This enables as many as three to six overpasses with the airborne imaging spectrometer. This approach was initially demonstrated with landfills in California in 2017, but only a small number involved simultaneous overflights, and intercomparison of measurements separated by days to months was affected by source variability (*13*). In this study, most of the intercomparison flights were conducted simultaneously, as well as a few flights that occurred on the same day but were separated by up to 2 hours.

Figure 3 shows a comparison between SA- and GAO-derived emission rates that passed quality control protocols at 15 landfill overpasses in several midwestern and southern US states (landfill names redacted). GAO emissions represent the average of all imaging spectrometer observations acquired during an SA observation window. The results are generally consistent (R^2 = 0.69; fig. S7). Figure 3, B and C, shows a visual example of a landfill in which the GAO-derived emission rate was smaller than the SA-derived rate (Landfill 06) and an example in which GAO and SA showed comparable emission rates (Landfill 12). In

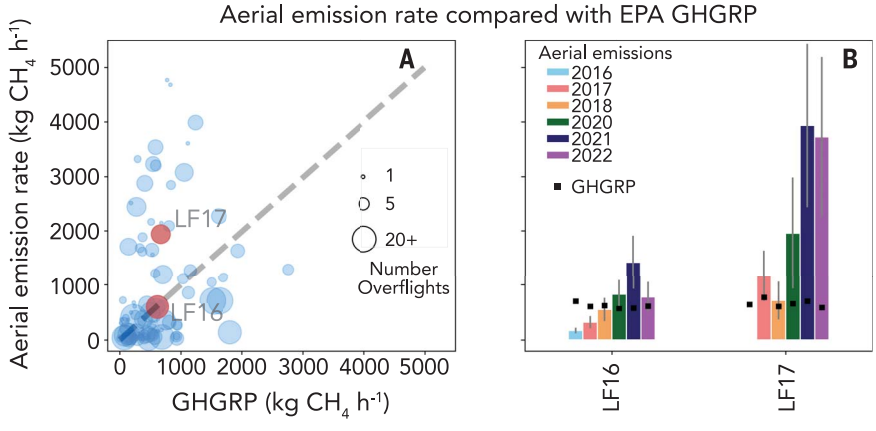

Fig. 4. Comparison of aerial emission rates with EPA GHGRP for landfills where point sources were detected at least once. (**A**) Mean CH_4 emission rates across all aerial overpasses compared with average GHGRP emissions. The gray line represents the one-to-one line. The size of the dots corresponds to number of overflights. Two red-colored dots in (A) correspond to landfills with 5+ years of observations in which the observed emission trends are significant ($P < 0.05$). (**B**) Trends for these landfills. Black squares represent GHGRP reporting for that year. Error bars represent 1 SD uncertainties on emission rates.

both cases, the CH_4 plumes observed by GAO correspond closely with observed downwind high CH_4 concentrations observed by SA. The generally good agreement between GAO and SA builds confidence in the broader application of the remote sensing method to the larger population of landfills. Because remote observations are increasingly being considered as contributors to routine CH_4 emission monitoring over large areas, confidence in emission quantification is essential for their adoption.

Figure 4A shows a comparison between the imaging spectrometer–quantified average emission rates and those emissions reported to the GHGRP for those facilities. In the US, landfills report emissions according to the Code of Federal Regulations (40 CFR Part 98 Subpart HH) either by modeling generated emission from reported annual waste disposed (HH1/HH6) or, for landfills with gas capture and collection systems, from back-calculations based on reported annual gas captured and assumed collection efficiency (HH7/HH8). For landfills where multiple years of observations are available through Carbon Mapper flights, we took the average GHGRP across those years. Poor correlation exists between aerial emission rates and GHGRP (R^2 = 0.07), which could be expected under sparse sampling. However, even for landfills where we surveyed 10+ times (20 landfills total), we still found little agreement between emission estimates (R^2 = 0.02). This discrepancy appears equally in both directions; there is a population of landfills (47% of all sites) with aerial emissions that are higher than GHGRP and a population (53%) in which they are lower or did not show evidence of any point source emissions. On average, aerial emission rates were a factor 2.7 higher than GHGRP for all landfills and a factor 1.4 higher for landfills with 10+ unique overpasses. Consistent with this study, independent assessments of US emission inventories have indicated a needed 1.25 to 1.5 scaling of waste emissions to reconcile inventories with in situ ground-based measurements and coarse-resolution satellite observations (*22*, *23*). Furthermore, in some cases, coarse-resolution satellite instruments (e.g., TROPOMI) can quantify annualized emissions from individual landfills that are isolated from other emission sources (*23*). These annualized satellite observations show better correlation with our airborne datasets (15 landfills total) than with GHGRP (for details, see the supplementary materials, section S2). We also found no significant aggregate bias in airborne results from seasonal and/or diurnal barometric pressure variability (for details, see the supplementary materials, section S3). Therefore, our airborne data, although not continuous, are still in aggregate likely indicative of general trends of discrepancy with national inventories.

Figure 4B shows yearly averaged aerial emission estimates from two landfills with 5+ years of aerial sampling in which trends in emission rates are significant ($P < 0.05$) based on an ordinary least-squares fit to the data. For both of these landfills, EPA GHGRP indicates an insignificant trend in emission rates. In the case of Landfill 17 (LF 17), airborne observations also suggest at least a factor of 2.5 underestimate compared with GHGRP. There could be some significant operational issues at that landfill leading to larger than predicted emissions. Figure 4B therefore shows an example of how one could use top-down information as a check against reporting or enforcement protocols. When a significant number of atmospheric observations sustained over many months to years show persistent discrepancies and diverging trends with bottom-up process-based emission estimates, it highlights areas for attention and action. Additionally, when coupled with nimble application of emerging onsite emission assessment approaches, a single CH_4 plume image with sufficient clarity could trigger an expedited response to guide follow-up root-cause analysis, improve general practices, and potentially reduce emissions.

Landfill emissions are composed of some fraction of spatially dispersed area and localized point sources, but a typical ratio of area to point source emissions for a given landfill in most cases remains unknown and may vary with site operations and environmental conditions. These conditions may affect emission pathways and gas collection system efficacy in complex ways. The comparison of GAO and SA suggests that for landfills with detectable point sources, these emissions may make up an outsized contribution against the total CH_4 contribution. Airborne and satellite remote sensing observations can provide some initial indications regarding the distribution of physical emission types for landfills through relatively frequent, wide-area monitoring of high-emission point sources. In a tiered observing strategy, the remote sensing data can be combined with net facility emission estimates from mass balance aircraft (Fig. 3) and more widespread deployment of continuous surface monitoring to quantify the contribution of point sources relative to the net landfill emission flux and to better understand variability.

Discussion

There are at least two use cases for plume-scale remote sensing of landfill CH_4 point sources. The first is quick detection and precise geolocation of emission hot spots at a landfill. After communicating with some facility operators, we attributed a few of our detected plumes to specific operations (e.g., working face, well drilling, construction). More effort is needed to connect the detected emission hot spots to operations to better understand the carbon impact of certain management practices and to help guide operators to areas on landfills where remediation may be needed. The EPA Inspector General issued a report in 2020 finding that EPA needs to improve oversight of how states implement air emissions regulations for municipal solid-waste landfills (*14*, *24*). Much more attention toward Clean Air Act Compliance is anticipated because of the ongoing landfill inspections by both federal and state governments and the interest in CH_4 reduction.

The second use case is quantifying emission rates to support evaluation of emission factors used in reporting programs and inventories. At this stage, we find a large discrepancy and generally poor correlation between EPA GHGRP bottom-up emission estimates and what we observed from airborne platforms. This discrepancy may be partially explained by sampling, but there could also be systematic issues with the models that underpin reporting programs. Ultimately, informed comparison of emission rates derived from atmospheric measurements with bottom-up calculations requires an improved understanding of the site processes that these airborne platforms detect. However, regardless of root cause, the detection rate and persistence of point source emissions at landfills and the large magnitude of aerial emission rates found in this study point to potential gaps in landfill models and/or calculation of emissions reported to the GHGRP.

Reconciling top-down and bottom-up estimates requires improved accounting for potential point source emissions in inventories in the context of current regulatory structures. Unplanned emissions such as unlit flares or large leaks from gas collection fields (particularly ones detectable by SEM) may not be reflected in inventory estimates. Planned maintenance activities of limited temporal extent could be represented at some level. Working face emission potential is largely unknown. In the future, in situ measurements and new site metadata, such as changes in time-resolved gas collection and maintenance event temporal tracking, would complement the top-down data, improving inventories and reducing unnecessary emissions. Additional multisensor field studies are needed to conclusively determine whether there are systematic biases in landfill emission models used in CH_4 inventories.

Airborne remote sensing platforms have proven extremely valuable for initial surveys and baseline assessments of CH_4 emissions across multiple sectors. However, the sustained sampling of landfills recommended by this study requires systems in which routine observation is logistically more feasible. Especially outside of the US, where many waste sites in developing countries lack any form

of management or monitoring, emissions may be disproportionately large compared with other sectors and bottom-up models. As countries move toward incorporating best management practices for waste, using atmospheric measurements that can be deployed at scale to verify emission reductions will be critical. Satellites could provide a solution to sampling when they are configured or capable of scanning large areas frequently and have sufficient sensitivity to point source emissions (*25*). Preliminary studies with the TROPOMI, GHGSat, and EMIT satellite instruments have identified large point sources at a small subset of global waste sites, many of which lack management practices geared toward reducing CH_4 emissions (*26*, *27*). The Carbon Mapper Coalition plans to launch two Planet Tanager satellites in 2024, which are optimized for CH_4 and CO_2 point source monitoring from space and build on advances from NASA's EMIT mission (*28*). This system will provide wide-area coverage and frequent sampling to quantify CH_4 emissions from a large population of managed and unmanaged waste sites around the world. Satellites offer the ability to monitor CH_4 emissions from landfills and unmanaged dumps across regions that are largely inaccessible because of workforce and resource limitations. Satellites also offer more complete coverage than aircraft in many regions given high costs, logistics, and airspace restrictions. Although not a complete solution to waste emission quantification, the ability to quantify and precisely geolocate point source emissions routinely at global scale with a combination of these remote sensing platforms represents an important contribution to this sector. This information, combined with multiscale information from a tiered observing system, can be effective in accelerating mitigation if efforts to connect observations with operators and regulators are sustained.

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SUPPLEMENTARY MATERIALS

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Materials and Methods
Supplementary Text
Figs. S1 to S8
References (*31*, *32*)
Carbon Mapper Emission Data
SA Data

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