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Using remote sensing to detect, validate, and quantify methane emissions from California solid waste operations

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Abstract

Solid waste management represents one of the largest anthropogenic methane emission sources. However, precise quantification of landfill and composting emissions remains difficult due to variety of site-specific factors that contribute to landfill gas generation and effective capture. Remote sensing is an avenue to quantify process-level emissions from waste management facilities. The California Methane Survey flew the Next Generation Airborne Visible/Infrared Imaging Spectrometer (AVIRIS-NG) over 270 landfills and 166 organic waste facilities repeatedly during 2016–2018 to quantify their contribution to the statewide methane budget. We use representative methane retrievals from this campaign to present three specific findings where remote sensing enabled better landfill and composting methane monitoring: (1) Quantification of strong point source emissions from the active face landfills that are difficult to capture by *in situ* monitoring or landfill models, (2) emissions that result from changes in landfill infrastructure (design, construction, and operations), and (3) unexpected large emissions from two organic waste management methods (composting and digesting) that were originally intended to help mitigate solid waste emissions. Our results show that remotely-sensed emission estimates reveal processes that are difficult to capture in biogas generation models. Furthermore, we find that airborne remote sensing provides an effective avenue to study the temporally changing dynamics of landfills. This capability will be further improved with future spaceborne imaging spectrometers set to launch in the 2020s.

1. Introduction

Methane is a powerful greenhouse gas (GHG) that is emitted from a variety of natural and anthropogenic sources (e.g. agriculture, oil/gas systems, waste, and coal mines; EPA 2019). The State of California set legislative requirements to limit GHG emissions for solid waste infrastructure to combat climate change (AB 32, SB 1826, SB 1383). Landfills represent a potentially huge source of methane, as decomposition of organic material in anaerobic conditions promotes methane production. The United States Environmental Protection Agency (EPA) estimates that solid waste accounted for 18% of all anthropogenic methane emissions in 2017

(EPA 2019). However, quantifying the total methane emission for any given landfill is challenging as operations, meteorology, topography, and infrastructure change constantly. Remote sensing of methane emissions with high spatial resolution is now a possibility with advances in airborne and satellite instrument technology (Frankenberg *et al* 2016, Thompson *et al* 2016, Cusworth *et al* 2019). Previous studies have shown that methane emissions from individual landfills are detectable by airborne imaging spectrometers (Krautwurst *et al* 2017; Duren *et al* 2019). This new observing capability opens up the possibility to quantify and validate methane emissions that result from landfill management practices.

Municipal solid waste landfills that generate above 25,000 metric tons of carbon dioxide equivalent methane per year ($\sim 114 \text{ kg h}^{-1}$ average methane emission rate) are required to report their GHG emissions to EPA as part of the Greenhouse Gas Reporting Program (GHGRP; 40 CFR Part 98 Subpart HH). EPA reporting requires landfill operators to calculate emissions using the LANDGEM model. This model is based on a first-order biogas generation model that estimates emission rates for each landfill depending on the annual reported tonnage of waste (waste-in-place), a default biogas yield per unit waste constant, and a kinetic decay constant (LANDGEM; Alexander *et al* 2005). This approach produces the landfill's expected annual biogas generation quantity. If biogas recovery efficiency and annual soil oxidation constants are used (generally 75% and 10%, respectively), then any non-recovered biogas is assumed to be emitted to the atmosphere. However, few field measurements were taken during development of this model, and subsequent field studies have shown LANDGEM can underestimate landfill gas (LFG) generation by as much as 80% (Thompson *et al* 2009 ; Amini *et al* 2013).

Landfill cover type, thickness, and material heterogeneity are not included in LANDGEM, though variations in these parameters are known to drive methane emissions (Bogner *et al* 2011). The California Landfill Methane Emissions Model (CALMIM) was developed to account for these parameters, and simulates landfill methane emissions as a function of waste-in-place, landcover type, landcover thickness, biogas recovery efficiency, precipitation, and ambient temperature (Spokas *et al* 2015). A CALMIM modeling study of California landfills estimated higher methane emissions for landfills with low oxidizing intermediate cover instead of just high waste mass (Spokas *et al* 2015). However, even with improved modeling capability, accurate estimation of emissions remains difficult because of the dynamic topographic nature of landfills—the spatial extent and composition of landfill cover change frequently. Also, model simulations are currently unable to capture fugitive emissions that result from equipment malfunction or poor management practices.

Atmospheric observations provide top-down constraints to methane emissions from landfills and critical checks on the models like CALMIM and LANDGEM used to estimate emissions. The AVIRIS-NG instrument measures solar backscatter, so it retrieves column-averaged methane concentrations along the slant column between the sun and the instrument. When AVIRIS-NG is flown 3–4 km above ground, it provides methane observations at 3–4 m spatial resolution, and is sensitive to methane emission point sources down to $5\text{--}10 \text{ kg h}^{-1}$ (Thompson *et al* 2016, Frankenberg *et al* 2016). AVIRIS-NG only provides snapshots of methane emissions in space and time. Solid waste operations at landfills and

composting facilities are dynamic, so frequent revisit is the ultimate goal in precise top-down quantification of methane emissions.

The California Methane Survey flew AVIRIS-NG over 436 Californian landfills and composting facilities and found persistent methane plumes at 32 sites (Duren *et al* 2019). Methane emissions from these 32 landfills constituted 41.3% of the total state-wide methane point source population that was quantified during the study, making solid waste (IPCC designation 4A) the largest point source emission sector. Since AVIRIS-NG observes at meter-scale spatial resolution, confident source attribution for detected methane plumes is possible, especially when combined with operator/regulator-specific knowledge of a landfill's specific characteristics. Extensive airborne measurements were also made with the Scientific Aviation aircraft using airborne *in situ* mass balance sampling over several Californian landfills during the same time period as the California Methane Survey (Guha *et al* 2018). These mass balance measurements quantified the total methane emission rate from the landfill by flying concentric circles of various altitudes around the site and sampling *in situ* methane concentrations. Using mass balance, a total area methane emission rate was estimated. As expected, the AVIRIS-NG estimates emission rates were in sum 19% lower than the corresponding Scientific Aviation estimates (Duren *et al* 2019). This is because the mass balance approach is sensitive to all methane emissions within its sampling domain, including emissions from very small and diffuse sources, whereas AVIRIS-NG imagery only detected point sources with emissions rates larger than approximately $5\text{--}10 \text{ kg h}^{-1}$ (Duren *et al* 2019).

In this study we present three results where remote sensing with the AVIRIS-NG instrument enhanced the capability of monitoring process-level landfill methane emissions: (1) quantification of strong point source emissions from the active face landfills that are difficult to capture by *in situ* monitoring or landfill models, (2) emissions that result from changes in landfill infrastructure (design, construction, and operations), and (3) unexpected large emissions from two organic waste management methods (composting and digesting) that were originally intended to help mitigate solid waste emissions. We focus on a handful of landfills and composting facilities that were imaged during the California Methane Survey, and where open communication exists with landfill operators and/or the local enforcement agency.

2. California's large landfills and composting facilities

Federal regulations require landfills with annual methane emissions of 1000 metric tons per year (114 kg h^{-1}) to report to the Greenhouse Gas

Reporting Program (40 CFR Part 98 Subpart HH). Landfills operate under positive pressure, meaning that landfill gas (LFG) can be captured by installing collection wells and applying a moderate vacuum at various points along the landfill. However, if too much of a vacuum system is deployed, excess oxygen may be sucked into the landfill, potentially leading to unwanted combustion. Landfill methane emissions are often reported following the LANDGEM methodology, which parameterizes methane emissions as a function of tonnage of disposed waste, an assumed kinetic decay constant, a gas recovery efficiency estimate, and a soil oxidation percentage. We analyze several landfills for which emissions observed during the California Methane Survey exceeded their reported 2017 values, and where we have access to process level understanding of operational practices.

Solid waste disposal policies intended to enhance sustainability may have unintended consequences with respect to methane emissions. Composting is seen as one avenue to reduce greenhouse gas emissions by diverting organic material from municipal waste streams, so California has set a legislative goal of a 50% reduction of statewide disposal of organic waste to landfills (SB 1383). This bill supports broader legislative efforts requiring 75% of the State's solid waste to be reduced, recycled, or composted by 2020 (AB 341). SB 1383 also strengthens the implementation requirements and expands the targeted materials of AB 1826, which requires businesses that produce a specified amount of organic waste to arrange for recycling services for that waste (AB 1826). These bills are designed to help California to meet its 2020 goal of reducing GHG emissions to 1990 levels (AB 32). However, organic diversion facilities are not currently required to report their methane emissions to the State of California or the GHGRP. We first consider an anaerobic high solids dry digestion facility that is permitted to accept 590 metric tons per day of organic waste materials (CalRecycle 2020a). Second, we consider a composting facility that receives approximately 1360 metric tons per day of yard trimmings and municipal solid waste that is composted and sold to farmers and the landscaping industry (CalRecycle 2020b). Given these large quantities of accepted waste and coincident AVIRIS-NG overpasses during the California Methane Survey, we quantify methane emissions at these facilities.

3. Methane emission estimates from airborne remote sensing

The AVIRIS-NG instrument measures solar backscatter between 380–2500 nm at 5 nm spectral resolution. Though coarser resolution than other methane remote sensing systems (0.25 nm for the TROPospheric Monitoring Instrument; TROPOMI; Hu *et al* 2018), the 5 nm resolution of AVIRIS-NG coupled with its high signal to noise ratio (>1000 at

2200 nm; Thenkabail *et al* 2019) provides detection of atmospheric methane plumes using absorption features in the 2215–2415 nm shortwave infrared wavelength range (Frankenberg *et al* 2016, Thorpe *et al* 2017). Meter-scale spatial resolution is a distinct advantage of the AVIRIS-NG instrument. For example, AVIRIS-NG flew 3–4 km above ground level during the California Methane Survey, allowing for a ground sampling distance of 3–4 m (Duren *et al* 2019). This spatial resolution enabled mapping and quantification of individual plume structures associated with methane emitting facilities. We used the linearized matched filter algorithm to infer methane slant column concentrations (units ppm m) from AVIRIS-NG radiance spectra (Thompson *et al* 2016, Duren *et al* 2019).

We determine the structure of methane plumes from landfills by isolating high methane concentration regions from AVIRIS-NG scenes, and call these isolated regions plume masks. We follow the methods described in previous studies to remove spurious signals by applying median and Gaussian filters to pixels above a critical methane concentration threshold within each scene (Varon *et al* 2018, Cusworth *et al* 2019). These filters result in a mask that maps the spatial extent of the plume. We integrate the methane concentrations above the background within this plume mask, and call the quantity the integrated mass enhancement (IME; Frankenberg *et al* 2016, Varon *et al* 2018). The IME represents the excess methane that was generated by the emission source. The IME is calculated as:

$$\text{IME} = \sum_{i=1}^N \Delta\Omega_i \Lambda_i \quad (1)$$

where $\Delta\Omega_i$ is the plume mass enhancement in pixel i relative to background (kg m^{-2}), Λ_i is the area of the pixel, and N is the number of pixels in the plume mask. We define the background as a percentile of retrieved methane concentrations within the scene. The emission rate Q is then inferred from the IME as (Varon *et al* 2018)

$$Q = \frac{U_{\text{eff}}}{L} \text{IME}. \quad (2)$$

where $L = \sqrt{\sum_{i=1}^N \Lambda_i}$ is a characteristic plume size and U_{eff} is an effective wind speed that accounts for turbulent dissipation. We use the empirical relationship described in Varon *et al* (2018) to relate U_{eff} to U_{10} :

$$U_{\text{eff}} = 1.1 \log U_{10} + 0.6. \quad (3)$$

where U_{eff} and U_{10} are in units of $[\text{m s}^{-1}]$. For the Sunshine Canyon Landfill, U_{10} is available from *in situ* towers. For other sites, we use DarkSky historical weather archive (DarkSky 2020). To create uncertainty estimates, we generate several emission rates by sampling different background levels between

the 75 to 85th percentile of retrieved scene methane, and by sampling various reported wind speeds within the hour before and after the AVIRIS-NG overpass. The choice of background percentile is somewhat arbitrary, but we choose high percentile values so that our resulting emission estimates are conservative.

4. Remote sensing use cases for monitoring of landfill emissions

Here we describe three examples for monitoring of landfill methane emissions using remote sensing: (1) Quantification of strong point source emissions from the active face landfills that are difficult to capture by *in situ* monitoring or landfill models, (2) emissions that result from changes in landfill infrastructure (design, construction, and operations), and (3) unexpected large emissions from two organic waste management methods (composting and digesting) that were originally intended to help mitigate solid waste emissions. We focus on a few examples of landfills and facilities that were imaged during the California Methane Survey (Duren *et al* 2019). Additional AVIRIS-NG methane plumes from a wider array of landfills and other methane emission sources can be visualized on the Methane Source Finder data portal (MSF 2020).

4.1. Strong point source emissions from the landfill active face

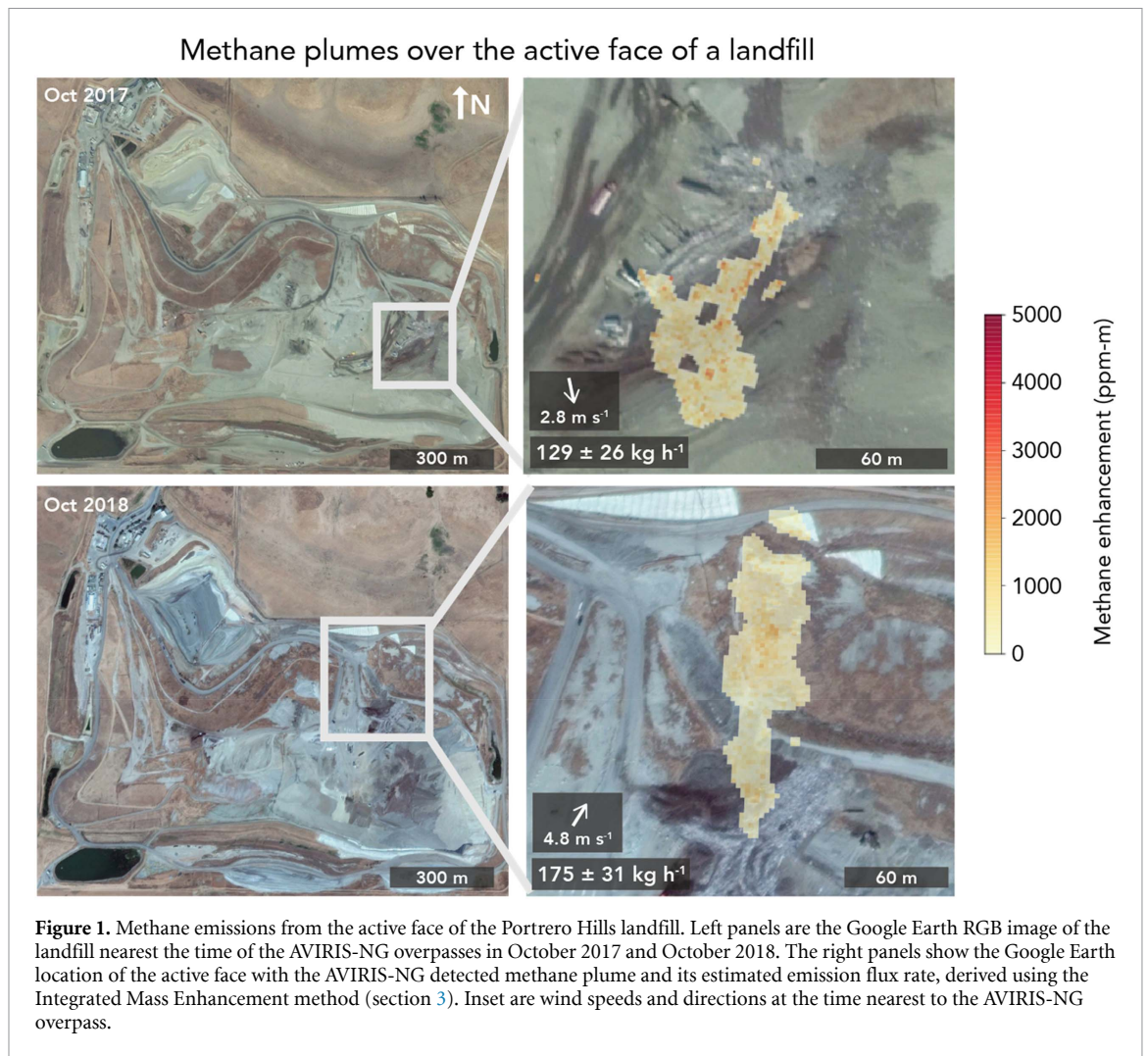
The active or working face of a landfill is the location where incoming waste is deposited. Federal regulations require the active face to be covered by at least a six inch layer of earthen materials at night, known as daily cover (CFR 40 § 258.21). Daily cover acts to prevent propagation of flies, reduce odor, litter, and scavenging. *In situ* monitoring of methane emissions on the active face is difficult due heavy operator traffic in that area. The active face location varies daily, making a fixed deployment of an *in situ* tower ill-equipped to provide consistent direct monitoring. Landfill operators are required to monitor methane concentrations on the landfill and along the perimeter of the landfill's footprint. If there is an exceedance of a regulatory standard (>200 ppm; 17 CCR § 95470), the location is recorded, and maintenance is required within a specified time. Remote sensing can improve on this monitoring capacity by providing a top-down view of a continuous column methane concentration field.

Figure 1 shows two overpasses of the AVIRIS-NG instrument over the Portrero Hills Landfill during 2017–18. The top panels show that the active face was located on the eastern edge of the landfill in October 2017. Using the IME flux quantification method (section 3), we derive a methane emission rate of 129 ± 26 kg h⁻¹ for just the active face. By October 2018 (bottom panels in figure 1), the active face had moved slightly northwestward. For this overpass

we derive an emission rate of 175 ± 31 kg h⁻¹. The consistency in emission rates between years hints that the composition of the active face waste was consistent between overpasses, possibly with a large share of organic or septic material. Emissions may also be the result of the active face being placed over an older trash cell. When the daily cover is peeled back, it potentially allows for methane generated from older and deeper waste to escape.

These emission rates from the active face may not be captured in a reporting model like LANDGEM. Here we see that large emissions emanating from the active face, before any such recovery has taken place. If we expand the domain of figure 1 to include the entire landfill (not pictured), we derive an emission rate of 1170 ± 219 kg h⁻¹ for October 2017 and 818 ± 155 kg h⁻¹ for October 2018. This means that active face emissions represented 11%–21% of the total landfill emission during the study period. For reference, the 2017 EPA reported emission rate for Portrero Hills is 394 kg h⁻¹, which is 2–3 times lower than what AVIRIS-NG quantified during its overpasses, and consistent with previous studies finding LANDGEM to overestimate biogas recovery (Thompson *et al* 2009, Amini *et al* 2013). However, this underestimate may actually be conservative, as AVIRIS-NG is only sensitive to methane point sources and not diffuse area sources. The challenge of detecting area sources with AVIRIS-NG was previously noted at landfills during the California Methane Survey, where coincident flights of the Scientific Aviation *in situ* airborne mass balance measurements, which are sensitive to all emissions within a domain, tended to generally infer larger emission rates than AVIRIS-NG. For the Portrero Hills, Scientific Aviation estimated an average emission rate of 2030 ± 445 kg h⁻¹ over the same study period (Guha *et al* 2018, Duren *et al* 2019).

Previous work quantified active face emissions using vertical radial plume mapping with tunable diode lasers on top of towers. In a survey of several landfills across the United States, Goldsmith *et al* (2012) found active face emissions ranged from 2.02–4.97 kg m⁻² h⁻¹. We normalize our active face emission estimates from Potrero Hills using the plume mask area, and find active face emissions of 39.2 ± 7.9 kg m⁻² h⁻¹ for October 2017 and 19.0 ± 3.4 kg m⁻² h⁻¹ for October 2018. These emissions are much larger than the results of Goldsmith *et al* (2012), which may be attributed to different operational practices and climate conditions at Potrero Hills. In the broader California Methane Survey, most of the landfills' active face emissions across the state were below the AVIRIS-NG detection limit (Duren *et al* 2019). The fact that we detect methane plumes on the active face at Potrero Hills indicates higher active face emissions than those surveyed elsewhere in California and measured in previous work (e.g. Goldsmith *et al* 2012).

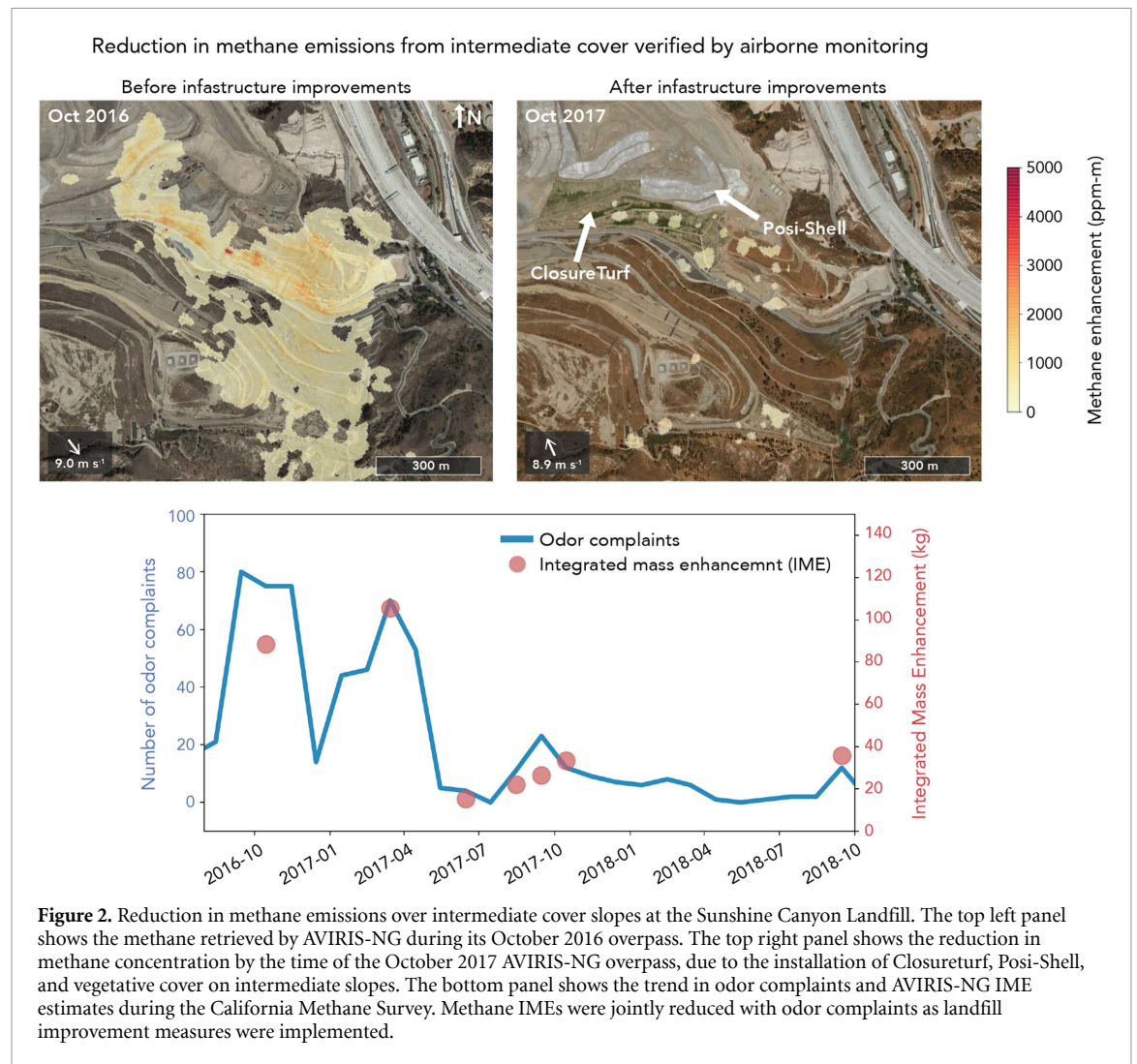


4.2. Emissions that result from changes in landfill infrastructure

Landfill topography and operational practices are dynamic, which impacts methane emissions. For example, during the Fall of 2016, AVIRIS-NG flew over Sunshine Canyon Landfill and noticed massive methane plumes emanating from its intermediate cover slopes (figure 2). Contact was made with the Sunshine Canyon Landfill Local Enforcement Agency (SCL LEA). Sunshine Canyon Landfill had been receiving an increase in residential odor complaints since 2009. Due to their close familiarity with the history of management practices at Sunshine Canyon, the SCL LEA determined that antecedent poor practices by the preceding owner/operator was the one of the primary causes for the increased odor complaints. In 2010, as an attempt to reduce odor, a non-standard industry practice of requirement of a minimum of 9" of compacted daily cover without peel-back was instituted (CUP 00-194-5, Amendment 45.N-2). Peel-back is the process of removing daily cover from the active face before new waste is added. This new practice of not peeling back meant that the daily cover unintentionally acted as

an impermeable barrier by not allowing leachate from the layer above to percolate to the bottom of the cell and it also restricted the movement of LFG. As the new cell was built up, methane was generated nearer to the surface, leading to pressure buildup within the landfill and persistent blowouts (referred to as puffing or burping) of LFG. The LFG carried odorous compounds into the local neighborhood, resulting in increased complaints. These consequences of not stripping daily cover had previously been studied (Bolton 1995), hence the industry standard practice of daily cover removal during the next day's disposal operations.

Odor complaints resulted in an Abatement Order (SCAQMD v. REPUBLIC, Case No. 3448-14) which included SCL LEA recommended mitigation measures that included a comprehensive combination of best management practices, including the utilization of an Alternative Daily Cover (ADC) and the discontinuation of the compacted soil cover without peel-back. The mitigation measure focused on improving the effectiveness of the LFG collection system and also included short term remedial measures to reduce the surface emissions of LFG. Between



March–December 2017, several types of remediation efforts were installed on intermediate slopes: ClosureTurf™ (impermeable polyethylene plastic layer with an additional artificial grass layer on top), Posi-Shell™ (cement, bentonite, fiber spray mix), or enhanced vegetative cover (SCL 2017b). A system of landfill gas collection pipes was placed above the existing intermediate cover and below the impermeable plastic layer to capture gas in the area of the ClosureTurf™. Additionally, both horizontal and vertical wells were installed to capture LFG throughout the landfill. These remedial measures enabled the landfill operator to increase the vacuum to the landfill gas collection system in the impacted areas.

Figure 2 shows the AVIRIS-NG overpass during October 2017, after most of the infrastructure improvements had been installed. The methane concentrations across these slopes are dramatically reduced compared to the October 2016 overpass. Figure 2 also shows the time-series of odor complaints plotted alongside monthly-averaged AVIRIS-NG IMEs during various overpasses between 2016–2017. We show IMEs instead of emission rates as the plume length (L) is small, which is a known limitation

of the flux quantification method of equation (2) for small plumes (i.e. $L \rightarrow 0$, $Q \rightarrow \infty$; Varon *et al* 2018). Both datasets show the same trend in figure 2—odor complaints and methane drop off immediately as infrastructure is improved. Captured LFG flow was also reported by Sunshine Canyon Landfill to increase during this time period (SCL 2017b).

To optimize future LFG collection, Sunshine Canyon piloted a new design innovation for waste cell construction (SCL 2017a). During the construction of a new waste cell's bottom liner system, operators placed $5.5 \times 5.5 \times 3.7 \text{ m}^3$ rock filled baskets (called gabion cubes) along the bottom of the cell and tied these cubes directly to the leachate collection system. Vertical LFG wells are installed and tied into the gabion cubes after several layers of waste are deposited over the cubes. The gabion cubes are designed to improve upon standard landfill operations by enhancing collection of LFG and drainage of leachate directly into leachate collection system (SCL 2017a), and by allowing continuous drainage of liquids that may accumulate in the vertical LFG collection wells. Typically, to avoid potential damage to the liner system, LFG wells are generally not installed

near the landfill's bottom liner. However, this practice can lead to inefficient gas capture and leachate drainage. Because the gabion cubes are more porous than the surrounding waste cell, leachate and LFG flow towards the cubes, where they are more efficiently drained and collected, respectively.

AVIRIS-NG overflew Sunshine Canyon in October 2018, during the very brief time when a new cell was in the process of construction and the vacuum system was not yet fully operational. Figure 3 shows methane plumes detected at the new waste cell. Marker A in figure 3 shows a construction area where the edge of the bottom plastic liner is anchored during construction. Here we see LFG that is produced from deeper layers escaping through edges of the liner. Marker D is the location at the bottom of the side-slope of the active disposal cell at a period just before LFG well installation. Uncompacted loose soil allows for LFG to visibly escape at this location. Markers B and C are locations near where gabion cubes were placed near the edge of the bottom liner to enhance leachate flow and to enhance LFG collection. These plumes in figure 3 show the impact of the gabion cubes before the installation of the wells, which provided input on potential design improvements. The landfill operator now installs horizontal LFG collectors after a single lift of waste covers the gabion cube. This increases the effectiveness of the gabion cube and also accelerates the time frame for utilization of the gabion cube.

In contrast to the diffuse methane plumes observed at intermediate slopes in October 2016 (figure 2), the results of figure 3 show that gabion cubes were extremely effective at concentrating and enhancing the accumulation of LFG and leachate at the landfill. Unfortunately, the October 2018 overpass was at the end of the California Methane Survey, so we were unable to image the landfill once the vacuum system was fully operational. However, given the visible pooling of methane emissions at discrete locations in figure 3, we expect much of the $649 \pm 82 \text{ kg h}^{-1}$ estimated methane emission at the new cell to be mostly captured. The 2018 EPA reported emission rate for Sunshine Canyon is 1800 kg h^{-1} (EPA 2020). Collecting LFG from the new cell could represent a substantial fraction of the total landfill emission. Future AVIRIS-NG flights over Sunshine Canyon can provide additional validation (as in figure 2) that these improvements had the desired effect.

The validation of methane reduction as a result of infrastructure improvements was possible given the high frequency of overpasses during California Methane Survey. Satellite remote sensing represents an avenue to do this type of monitoring across a wide array of landfills with regularity. Many imaging spectrometers with AVIRIS-like instrument specifications and frequent revisit times will be launched in the 2020s. These instruments will not have the same

detection limit as AVIRIS-NG, but will theoretically have the capacity to detect large point source methane emissions (Cusworth *et al* 2019; Ayasse *et al* 2019).

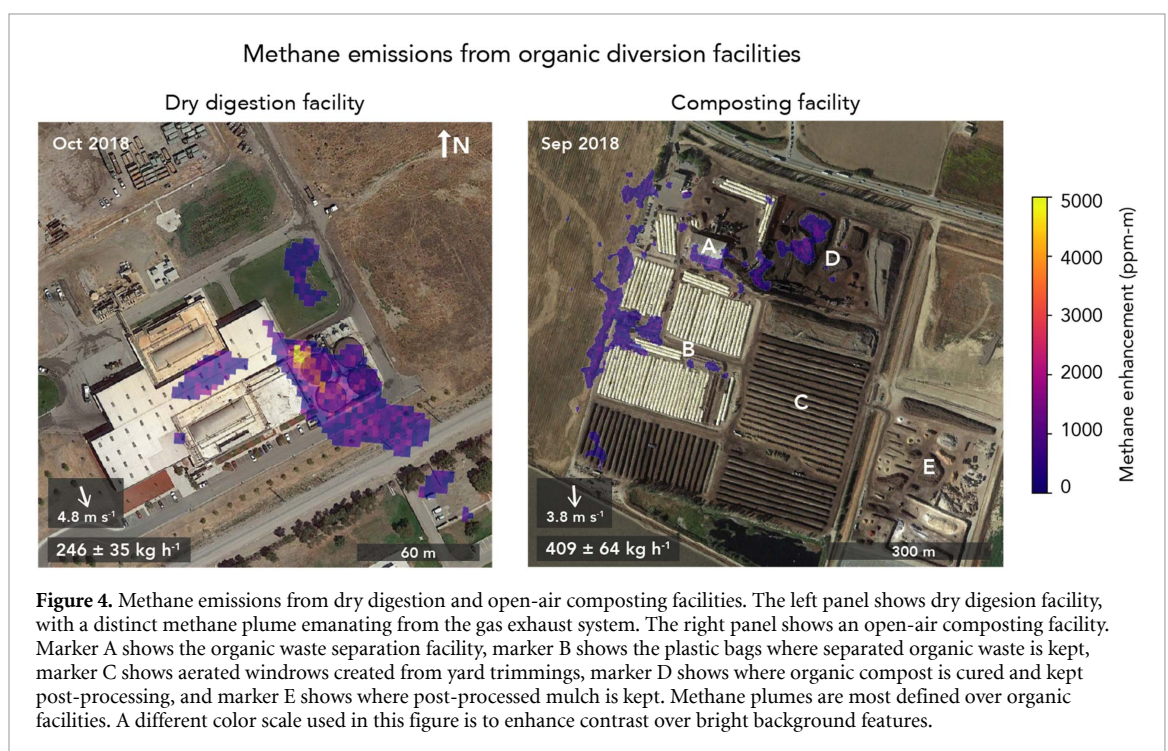
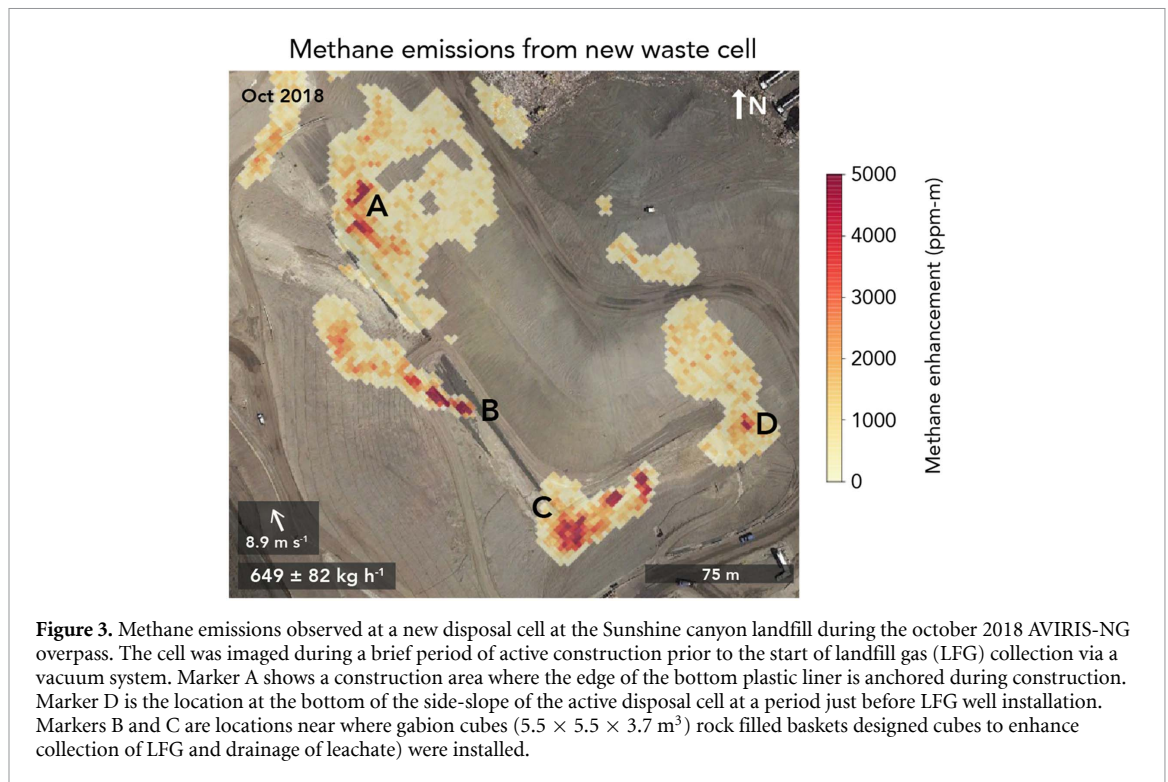
4.3. Unexpected emissions from organic waste processing facilities

The results from previous sections show that remote sensing can quantify known emissions from hard to measure locations and can provide validation for operational practices. However, remote sensing can also improve solid waste methane emission monitoring by localizing and quantifying unreported emission sources.

Composting and anaerobic digestion are seen as an avenue to reduce GHG emissions from landfills by diverting organic material from landfills. However, these facilities are not required to report to GHGRP or, in California, to the California Air Resources Board. Any fugitive emissions from these facilities would be unaccounted in statewide emission budget estimates. Figure 4 shows two types of organics processing facilities. The first is dry high solids digestion facility, where organic waste is loaded into sealed units (tunnel digestors), and sprayed with thermophilic methane producing bacteria. The gas is continually collected for 20 d and stored in two collection bladders, where it is then used to generate electricity. Any low quality gas (i.e. low methane content) is collected in an aeration system, sometimes combusted, and filtered through an organic bio-filter (CalRecycle 2020a).

Figure 4 shows a distinct methane plume emanating from the digestion facility ($247 \pm 35 \text{ kg h}^{-1}$) during the October 2018 AVIRIS-NG overpass. A distinct plume appears along the eastern edge of the facility. This is the location of the exhaust system, where the facility changes from operating under negative pressure (to prevent escaping gas) to positive pressure (to expel unused gas). The appearance of a plume along the exhaust system suggests a leak or loose seal that allows for the gas to escape before entering the bio-filter. The result also suggests that low quality gas may still have significant methane content. The magnitude of the methane emission from this facility ($247 \pm 35 \text{ kg h}^{-1}$) is larger than reporting threshold for State of California landfills (114 kg h^{-1}).

Figure 4 also shows an open air composting facility (CalRecycle 2020b). This facility accepts organic material from local municipal waste streams. Organic material is separated from inorganic waste in a separation facility (marked A in figure 4). The separated organic waste is then stored in 100 m long plastic bags that sit for approximately 14 weeks (marked B in figure 4), until the waste undergoes another round of separation and curing before being sold as compost (marked D in figure 4). The facility also accepts yard trimmings that are filed into 3.5 m high uncovered



windrows that are turned 1–2 times per week for 12–18 weeks (marked C in figure 4). Yard trimmings are processed as mulch and kept at location E on figure 4.

We estimate a $409 \pm 64 \text{ kg h}^{-1}$ total emission rate at the composting facility for the September 2018 AVIRIS-NG overpass. Many plume structures are visible in figure 4 at the locations of the organic separation facility and the organic waste bags. The conditions in these bags are likely anaerobic, and generated methane escapes through holes at their end

points. Plumes are also visible at marker D in figure 4, where consumer available compost is cured and subsequently sold. Visible methane plumes suggest that insufficient overturning of compost piles at this processing stage creates anaerobic conditions. No significant methane plumes are visible along the yard waste windrows, suggesting sufficient overturning and aeration.

The significant emissions detected at both facilities in figure 4 are unreported, and represent an

unexpected emission source for methane emission budget accounting. As composting has been encouraged and legislated in California for the goal of reducing GHG emissions, quantifying composting emissions in light of the total landfill sector is vital to assessing the effectiveness of this effort. We had limited temporal sampling of each of these facilities during the California Methane Survey, unlike Sunshine Canyon. We expect the emissions from composting to vary depending on the stage of organic decomposition, so ultimately more frequent revisit is needed to assess the full impact of composting on the methane emission budget.

5. Conclusions

Landfills are a major contributor to the anthropogenic methane budget. However, precise methane emission quantification is difficult due to constantly changing conditions and management practices. Federal legislation requires landfill emission reporting, but this estimate is based on a simple model estimate that calculates LFG generation and recovery as a function of waste-in-place (Alexander *et al* 2005). Remote sensing of landfills enables top-down monitoring of landfill emissions, and can fill in missing knowledge gaps about the dynamics of landfill methane emissions.

The AVIRIS-NG instrument was flown over several landfills during the California Methane Survey (Duren *et al* 2019). The plume imagery an emission estimates can be visualized on a web interface (MSF 2020). In this study, we showed three distinct monitoring use cases for monitoring landfill emissions using remote sensing:

Strong point source emissions from the landfill active face. We looked at AVIRIS-NG overpasses at the active face of the Portrero Hills landfill, and found that the emissions on the active face were consistent between years, and made up 11%–21% of the total landfill emission. Monitoring methane emissions on the active face of a landfill is difficult due to heavy traffic and because the active face changes location frequently. Remote sensing bypasses this *in situ* difficulty and is helpful for quantification of emissions in areas like these.

Emissions that result from changes in landfill infrastructure. We show an example at the Sunshine Canyon Landfill, where AVIRIS-NG detected large methane plumes emanating from intermediate cover slopes during its overpasses in 2016, which were caused by non-traditional industry practices. The landfill subsequently underwent costly infrastructure and operational changes to reduce LFG emissions. Subsequent AVIRIS-NG 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.

Unexpected emissions from organic waste processing facilities. We show two examples of unreported emissions by looking at a dry digestion and a composting facility. Methane emissions above the minimum GHGRP requirement for landfills were detected at both sites. Composting is often seen as a path to reduce landfill GHG emissions, but remote sensing provides an avenue to validate whether the associated emissions from composting facilities justify this assumption.

Remote sensing of landfill methane emissions is possible with targeted airborne campaigns. This capacity will be enhanced with the next generation of spaceborne imaging spectrometers (e.g. EnMAP, EMIT, SBG, CHIME), especially regions of the world where strict waste management regulation is not enforced, so large landfill methane point sources may be detectable from space. Imaging spectroscopy allows for process-level attribution of landfill methane emissions, which can guide advanced mitigation opportunities, which was evidenced by the Sunshine Canyon landfill. As solid waste management represents one of the single biggest anthropogenic methane emission sources, having frequent and reliable emission estimates is critical for achieving GHG emission targets.

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Data Availability

AVIRIS-NG radiance files are available at (Gao *et al* 1993; <https://avirisng.jpl.nasa.gov/dataportal/>). Retrieved methane concentrations from AVIRIS-NG radiances are available at the Methane Source Finder (MSF 2020; <https://methane.jpl.nasa.gov/>). Wind speed and directions are available through the Dark Sky application programming interface (Dark-Sky 2020; <https://darksky.net>). Wind speed and direction from the Sunshine Canyon Landfill are available on request. EPA methane reporting data is available

through the EPA GHGRP FLIGHT tool (EPA 2018; <https://ghgdata.epa.gov/>).

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