EXECUTIVE SUMMARY

Introduction

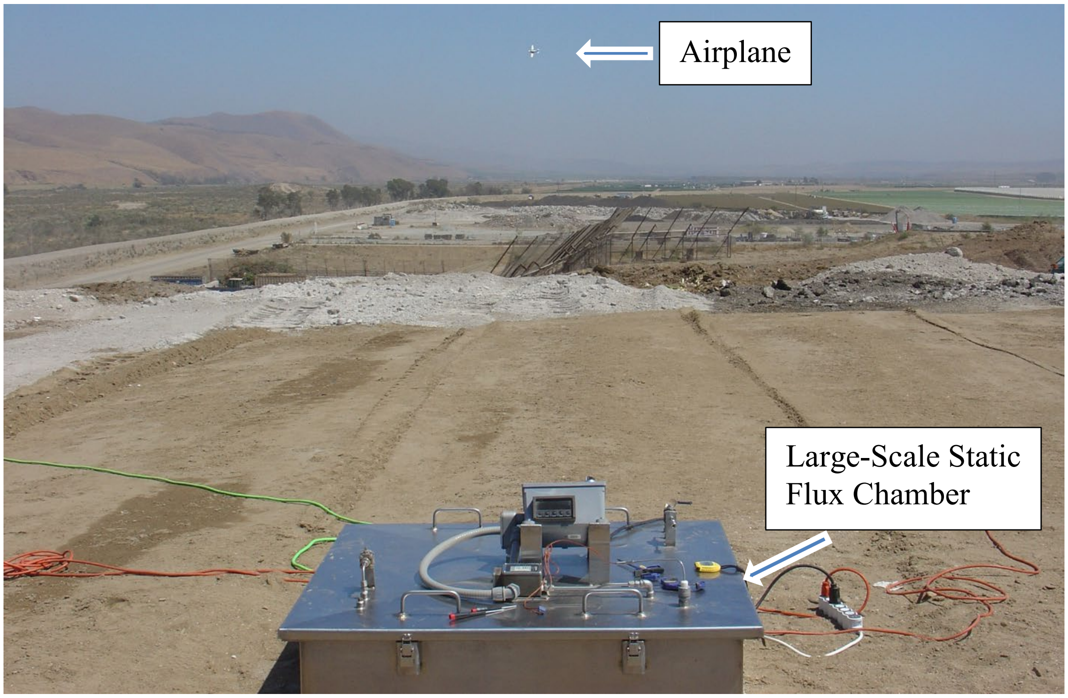
This investigation was conducted to provide detailed assessment of emissions of a total of 82 landfill gases (LFGs) that consisted of 4 greenhouse gases (methane, nitrous oxide, carbon dioxide, and carbon monoxide) and 78 non-methane volatile organic compounds (NMVOCs) from California landfills. The NMVOCs were categorized under 11 chemical families: reduced sulfur compounds, fluorinated gases, halogenated hydrocarbons, organic (alkyl) nitrates, alkanes, alkenes, aldehydes/alkynes, aromatic hydrocarbons, monoterpenes, alcohols, and ketones. In addition, efficiencies of gas collection systems in California landfills were assessed. The investigation included experimental analysis (field and laboratory testing) and modeling. More than 65,000 individual gas concentration measurements were used to determine the surface flux of the 82 target gases from 31 individual cover types using testing during both wet and dry seasons. Operational, environmental, and climatological factors that affect emissions and gas collection efficiency were analyzed. Fluxes for a great majority of the NMVOCs included in the study were determined for the first time from daily covers in landfills and flux data were provided for the first time for 8 chemical species. To the Principal Investigators' (PIs) knowledge, this study represents the most comprehensive landfill gas emissions and gas collection analyses conducted to date in California, U.S., and internationally.

Methods

The investigation consisted of four main phases: 1) comprehensive literature review related to landfill gas generation and emissions, 2) California-specific landfill classification scheme, 3) extensive field-testing program at California landfills and supplementary laboratory analysis, and 4) comprehensive analyses of landfill gas generation and collection efficiency. The literature review established the state-of-the-art for landfill gas generation, collection, and emissions as well as provided the basis for categorization of the gas species included in the investigation. A landfill classification scheme was developed first to categorize all active landfills in California and then to identify and select representative landfills for field testing. The classification scheme included criteria for landfill size (waste in place [WIP], disposal area, waste column height, and permitted throughput); proximity to population centers, oil/gas operations, and quaternary faults; climate; presence of a gas collection system; acceptance of waste tires; cover conditions (daily, intermediate, final); waste age; and landfill configuration and operational details.

The field investigation consisted of two types of measurement programs: aerial measurements of only methane and ethane at height above the landfill surfaces and ground-based measurements of all of the 82 landfill gas species included in the study directly on the landfill surfaces (Figure ES.1). The aerial testing was based on a temporally and spatially integrated mass balance measurement approach. The aerial tests were conducted using a single engine Mooney aircraft that was instrumented with a Picarro G2401-m Analyzer (cavity ring down spectrometer). The ground testing was based on time series gas concentration measurements conducted over a sealed known landfill surface area and gas volume. The ground tests were conducted using large-scale static flux chamber test instrumentation with dimensions of 1 m x 1 m areal extent (1 m^2 measurement area) and 0.4 m height. The aerial tests were conducted at 16 landfills and the static flux chamber tests were conducted at 5 landfills that were a subset of the 16 aerial measurement sites. The 16 aerial testing landfills included small (WIP < 4,000,000 m^3), medium (4,000,000 m^3 < WIP < 40,000,000 m^3), and large sites (WIP > 40,000,000 m^3) and were located at five different climatic zones representing the climate zones with active landfills in the State. The 5 ground testing landfills included medium (Santa Maria Regional, Teapot Dome) and large (Potrero Hills, Site A, Chiquita Canyon) sites and located in three different climatic zones that contain 98.8% of the waste in place in the State. The waste in place at the 16 aerial measurement landfills contained 30% of the total waste in place in landfills in California and the waste in place at the 5 ground measurement landfills contained 13% of the total waste in place in landfills in California. The field emissions tests were supplemented by determination of thicknesses of the cover materials at specific test locations, temperatures of covers, and in-place densities of covers. Extensive laboratory characterization of geotechnical properties of the cover materials was conducted on field samples from each tested cover system to provide mechanistic explanations of the observed flux behavior.

Figure ES.1 Synchronous Ground and Aerial Testing



The static flux chamber tests were conducted on all three cover categories (daily, intermediate, and final) used in active landfills. For a given cover category at a given site, all different material types used for that particular cover category were tested. Overall, based on cover categories and cover material types, static flux chamber tests were conducted at five to seven locations at a given landfill. Testing in the wet and dry seasons was conducted over the project period for both aerial and ground-based measurements. Gas collection efficiencies were determined using two main approaches: i) as a quotient of the reported gas collected at a given site and the summation of gas collected and emissions measured in the field tests and ii) as a quotient of the reported gas collected at a given site and modeled gas generation at the same site. Gas generation was modeled for methane using the LandGEM model specifically developed for this gas (not applicable to NMVOCs). To determine gas generation with LandGEM, two sets of parameters were used: default values provided in the LandGEM model and refined values obtained using an artificial neural network (ANN) modeling process. Gas production and collection efficiency analysis was conducted only for methane as commonly accepted and widely used analysis approaches are not available for trace gases such as nitrous oxide and the NMVOCs included in this investigation. Uncertainty estimates also were provided for both the field measurements as well as modeling analyses.

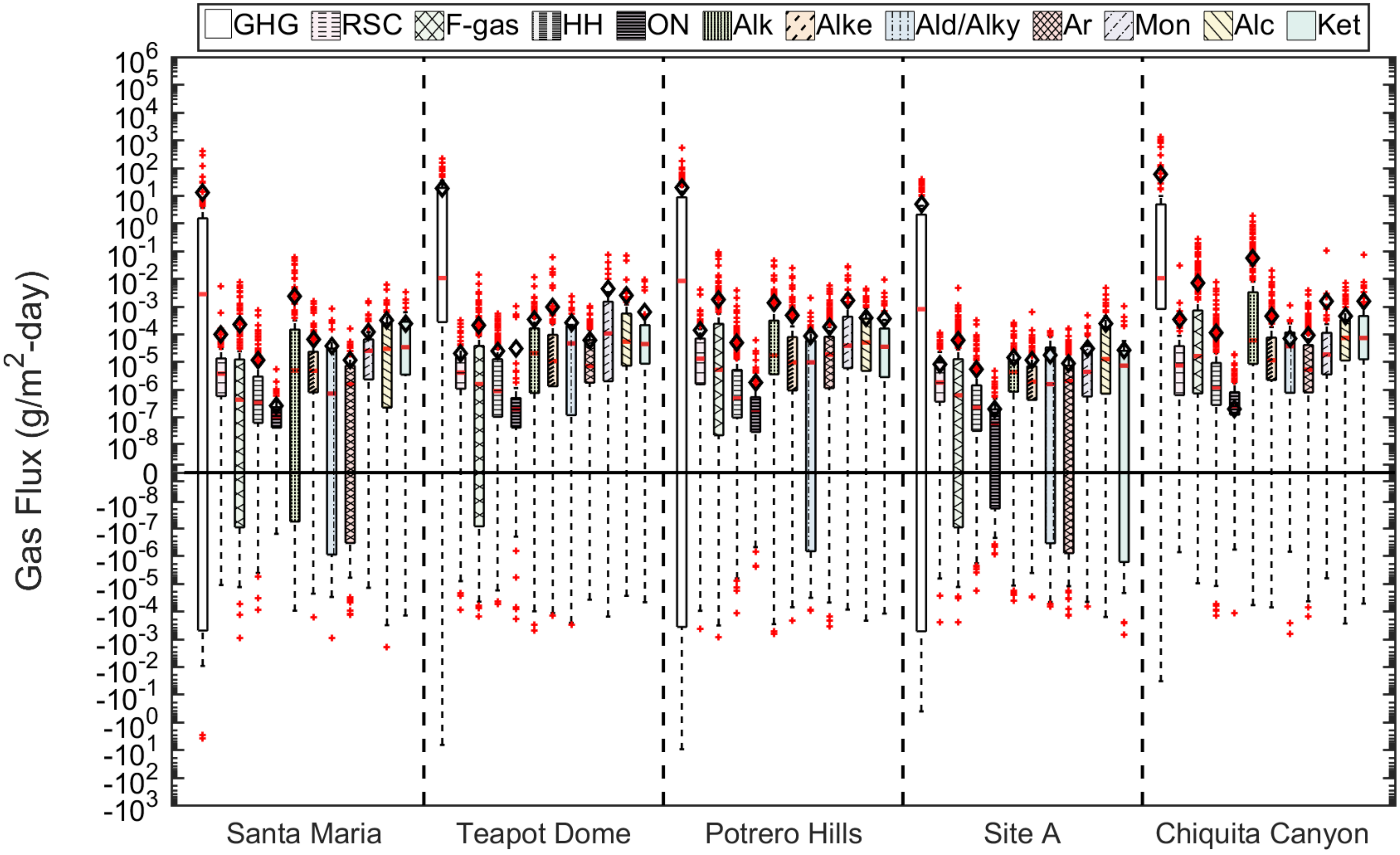
Results

Surface Gas Flux and Emission Results

The aerial testing program indicated that methane emissions increased from small to medium to large landfills, where the emissions from the small, medium, and large landfills varied from -25 to 11 kg/hr, 90 to 638 kg/hr, and 602 to 3275 kg/hr, respectively. The methane emissions from the large landfills were more than one to two orders of magnitude higher than the emissions from the small landfills, whereas the differences between the medium and large landfills were within the same order of magnitude. Even though the small landfills did not have active gas collection and removal systems, the measured emissions from these sites were very low. While the medium and large landfills had gas collection and removal systems, the emissions from these sites were high. High waste in place, high daily waste throughput, and large working face (i.e., active, uncovered waste placement area during operational hours at a landfill, which ranged between 65 and 12,100 m^2 in the investigation) likely resulted in high emissions.

A summary of the flux data obtained in the ground testing program is provided in Figure ES.2 by landfill site. The highest fluxes at each landfill site were obtained for GHGs, which included methane, nitrous oxide, carbon dioxide, and carbon monoxide. The mean and median GHG fluxes were positive at all sites. The GHG fluxes varied by up to two orders of magnitude between the landfills investigated. The results of this study indicated that NMVOCs are a significant and detectable fraction of the landfill gas emitted from the sites investigated with positive mean and median NMVOC fluxes obtained at all five landfills. The highest NMVOC fluxes were measured for the alcohols, ketones, and monoterpenes chemical families. Based on comparisons to flux data provided in the literature, the ranges of methane and nitrous oxide fluxes were lower (analysis of well-engineered California landfills), while the ranges for NMVOCs were higher (analysis of not previously tested chemicals and covers) in this test program.

Figure ES.2 Inter-landfill Flux Results (open black diamonds, red lines, solid red dots represent means, medians, and outliers, respectively)



Both positive (emissions to the atmosphere) and negative (uptake from the atmosphere) fluxes were measured. Positive fluxes resulted from higher concentrations in the waste mass than in the ambient air. Negative fluxes resulted from a combination of lower concentrations in the waste mass than in the ambient air and presence of vacuum pressure from gas collection and extraction systems drawing ambient air into the landfill system. A great majority of the measured fluxes were positive indicating net emissions of all of the 82 gases into the atmosphere. The measured flux ranges were -3.73×10^{0} to 9.62×10^{1} g/m^2-day, -4.10×10^{-3} to 1.45×10^{-1} g/m^2-day, and -1.93×10^{-3} to 1.81×10^{0} g/m^2-day for methane, nitrous oxide, and total NMVOCs, respectively. The variations of positive flux of a given chemical at a given landfill was up to 6 orders of magnitude and the variations of a given chemical between landfills was up to 7 orders of magnitude. Seasonal flux variations for a given site were low and generally were within one order of magnitude between the dry and wet seasons.

The overall variation in methane flux in the investigation was from -10^{0} to 10^{1} g/m^2-day (Figure ES.3). Variation by landfill and cover category was comparable and higher than variation by season. The methane fluxes from the medium sized landfills (Santa Maria Regional and Teapot Dome) were comparable to the fluxes from the larger sites (Potrero Hills, Site A, and Chiquita Canyon) indicating that factors other than size and scale of landfill operations contribute to and potentially control methane emissions. The methane fluxes decreased in order of daily to intermediate to final covers with a higher decrease from intermediate to final covers than from daily to intermediate covers. The highest methane fluxes were generally from alternative daily covers and in particular from autofluff. These thin, highly porous daily covers provided low resistance to methane flux. The thick engineered final cover systems with high fine soil content and use of geosynthetics at one site resulted in the lowest fluxes. The seasonal variations generally were within one order of magnitude indicating that landfill and cover conditions influence methane flux more than seasonal variations in California. This study for the first time provided flux data for an alternative cover system and also a comparison between an alternative and a conventional cover (Site A). The data indicated that methane flux from the alternative final cover was significantly higher than the methane flux from the conventional final cover, which may have resulted from a combination of the more interconnected pore structure of the coarser-grained alternative cover compared to the occluded pore structure of the finer-grained conventional cover and the lower thickness of the alternative final cover as compared to the conventional cover.

The overall range in nitrous oxide flux was from -10^{-3} to 10^{-1} (Figure ES.4). Variation by cover category was higher than variation by landfill and season, which were relatively comparable. Nitrous oxide fluxes at the medium-sized landfills were largely positive when compared to the larger landfills, with overall low probability for negative flux (all or most of interquartile ranges above zero in Figure ES.4). Waste composition may have caused these differences, where the amount of incoming wastes with high nitrogen content (i.e., crop wastes/residue, manure) are likely high due to the surrounding agricultural communities of Santa Maria Regional and Teapot Dome Landfills compared to the wastes from mainly urban sources at the large landfills in Northern and Southern California. Similar to methane flux, nitrous oxide fluxes decreased from the daily to intermediate to final covers with a higher decrease from intermediate to final covers than from daily to intermediate covers. The thin, highly porous daily covers provided low resistance to nitrous oxide flux. The thick engineered final cover systems with high fine soil content and use of geosynthetics at one site resulted in the lowest fluxes. The seasonal variations were generally within one order of magnitude indicating that cover conditions influence nitrous oxide flux more than seasonal variations in California.

Figure ES.3 Tornado Plot of Methane Flux as a Function of Landfill, Cover Type, and Season (open black diamonds, black lines, solid red dots represent means, medians, and outliers, respectively).

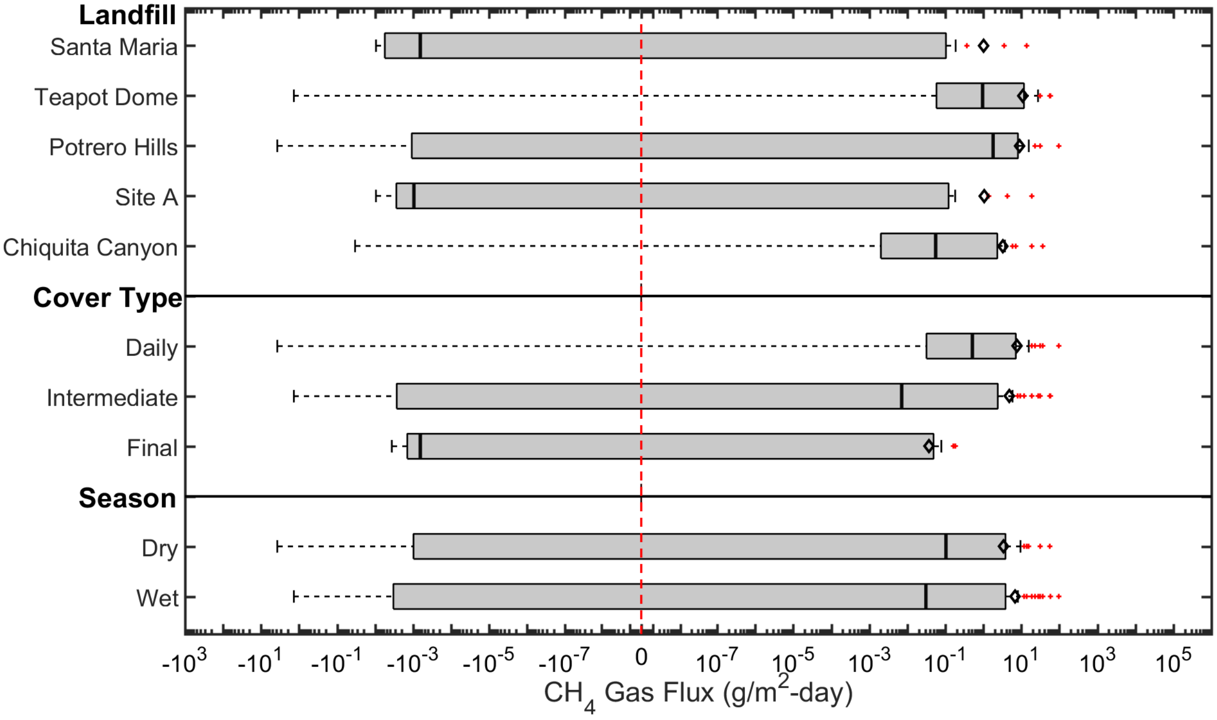
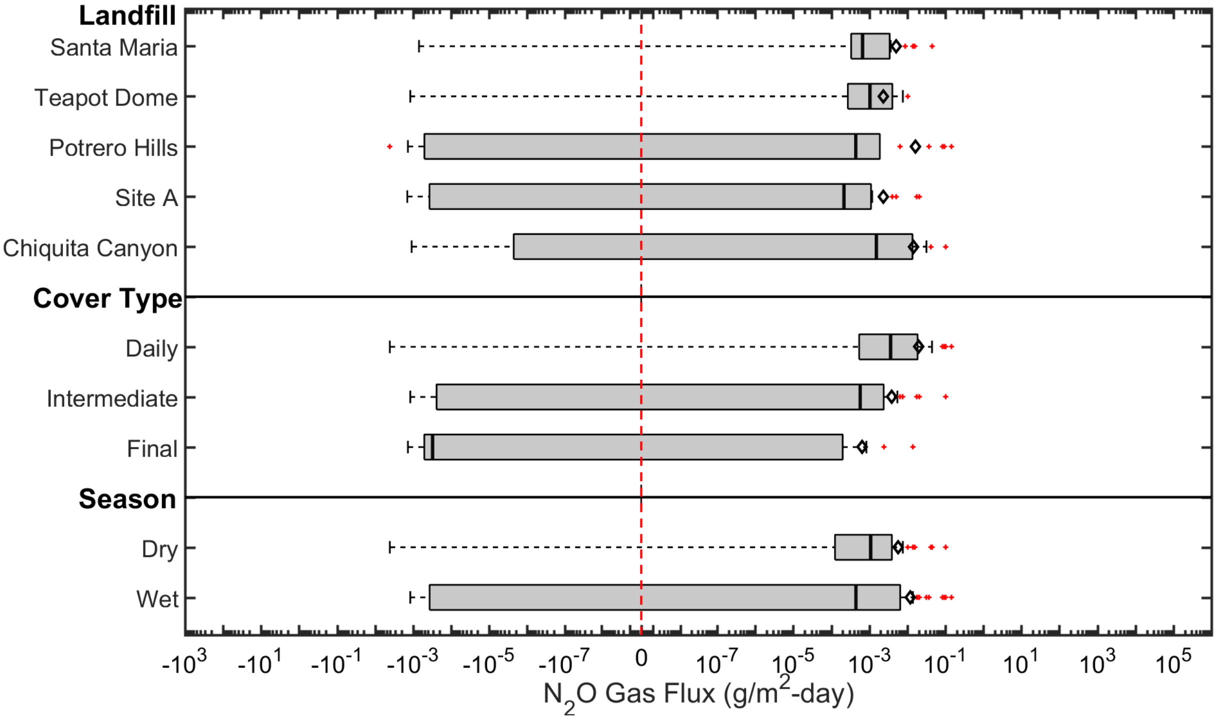
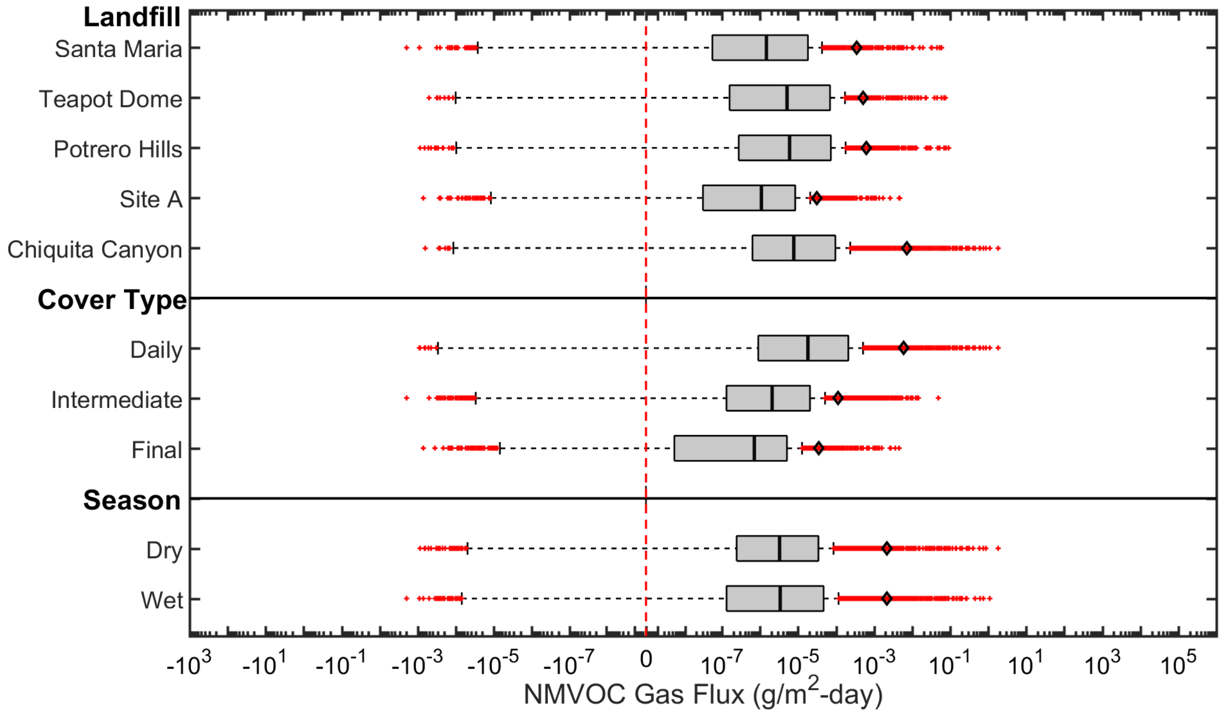


Figure ES.4 Tornado Plot of Nitrous Oxide Flux as a Function of Landfill, Cover Type, and Season (open black diamonds, black lines, solid red dots represent means, medians, and outliers, respectively).



The overall range in NMVOC flux was from -10^{-3} to 10^{0} g/m^2-day (Figure ES.5). Variation in total NMVOC flux was generally comparable across landfills, cover categories, and seasons with less variability compared to methane and nitrous oxide. Positive flux is dominant for the NMVOCs investigated with low probability of uptake (interquartile ranges above zero in Figure ES.5), even though all of the NMVOCs are trace components of landfill gas. Similar to methane and nitrous oxide fluxes, the NMVOC fluxes from the medium sized landfills (Santa Maria Regional and Teapot Dome) were comparable to the fluxes from the larger landfills, indicating that factors other than operational scale contribute to and potentially control NMVOC emissions. Cover category had the most significant effect on NMVOC fluxes, where the fluxes decreased from the daily to intermediate to final covers. In similarity to methane and nitrous oxide flux results, the thin, highly porous daily covers provided low resistance to NMVOC flux. In addition, the daily covers may have been sources of some NMVOCs. NMVOCs such as aromatic hydrocarbons, alkanes, and alkenes may have volatilized from the contaminated soil daily cover. The wood waste and green waste alternative daily covers (ADCs) are potential sources of monoterpenes and the autofluff ADC is a potential source of F-gases. The thick engineered final cover systems with high fine soil content and use of geosynthetics at one test site resulted in the lowest fluxes. The final cover NMVOC fluxes were in one case higher than those for methane and nitrous oxide. The seasonal variations were generally within one order of magnitude indicating the higher influence of the cover conditions on NMVOC flux than seasonal variations in California.

Figure ES.5 Tornado Plot of NMVOC Flux as a Function of Landfill, Cover Type, and Season (open black diamonds, black lines, solid red dots represent means, medians, and outliers, respectively).



Fluxes of the GHGs and NMVOCs as a function of cover type indicated that for daily covers, locations with autofluff or green wastes had the highest surface fluxes. For intermediate covers, fluxes were generally higher when green wastes were layered or mixed with soils than when soils were used alone for intermediate covers. For final covers, conventional covers were more effective for impeding methane flux compared to the alternative cover. The geosynthetics final cover had the highest nitrous oxide flux with lower flux for both the soil conventional and the soil alternative final covers. The NMVOC fluxes were highly similar through the three final cover types. Overall cover categories and types impacted methane and nitrous oxide fluxes more than NMVOC fluxes. Methane undergoes potential transformations (oxidation, dissolves in soil water, and also attaches to soil solid surfaces) in the cover materials, which affect the surface flux. Similarly, nitrous oxide undergoes transformations in the cover materials as well as is produced through natural biological processes in soil and vegetative covers. Less information is available on potential transformations of the NMVOCs in different landfill covers, which overall may not be significant as observed by the low variation of NMVOC fluxes with cover category and type. Coarser-grained covers with low density, porous structure, interconnected pores, and low thickness promote high fluxes, whereas finer-grained covers with cohesive soils, occluded pores/tortuous flow paths, and high thickness impede flux.

Whole-site emissions from small landfills were negligible even though these sites did not have gas collection and removal systems. Higher emissions were measured at medium and large landfills with gas management systems. Directly calculated and converted to CO_2-eq. emissions were $4.97\text{x}10^2$ to $1.26\ \text{x}10^5$ tonnes/year and $5.16\text{x}10^2$ to $1.62\text{x}10^5$ tonnes/year, respectively (1 tonne = 1 metric ton = 1 Mg) (Table ES.1). The difference in weighted emissions was more significant when CO_2 and CO were excluded. This result may be attributed to the high emissions of F-gases, with high global warming potential from Chiquita Canyon Landfill. The highest CO_2-eq. GHG contributions were from Potrero Hills, Teapot Dome, and Site Chiquita Canyon Landfills. NMVOCs contributed appreciably (0.36 to 36% CO_2-eq.) to whole site emissions even though these are trace components in landfill gas.

Table ES.1 – Direct and Weighted Total LFG Emissions with and without CO_2/CO (μ = mean, σ = standard deviation).

Landfill		Direct Emissions (tonnes/yr)		Weighted Emissions (tonnes/yr)	
		With CO_2/CO	Without CO_2/CO	With CO_2/CO	Without CO_2/CO
Santa Maria	μ	4.97E+02	6.85E-03	5.15E+02	1.89E+01
	σ	3.69E+01	1.97E-01	4.50E+01	2.58E+01
Teapot Dome	μ	7.26E+03	1.22E+03	4.06E+04	3.46E+04
	σ	4.28E+03	1.30E+03	3.67E+04	3.65E+04
Potrero Hills	μ	1.26E+05	1.35E+03	1.62E+05	3.80E+04
	σ	2.14E+04	1.11E+03	3.77E+04	3.11E+04
Site A	μ	9.21E+03	9.48E+02	3.55E+04	2.72E+04
	σ	3.19E+03	1.61E+03	4.52E+04	4.52E+04

Landfill		Direct Emissions (tonnes/yr)		Weighted Emissions (tonnes/yr)	
		With CO_2/CO	Without CO_2/CO	With CO_2/CO	Without CO_2/CO
Chiquita Canyon	μ	2.81E+04	4.38E+02	5.21E+04	2.44E+04
	σ	1.06E+04	3.76E+02	1.57E+04	1.16E+04

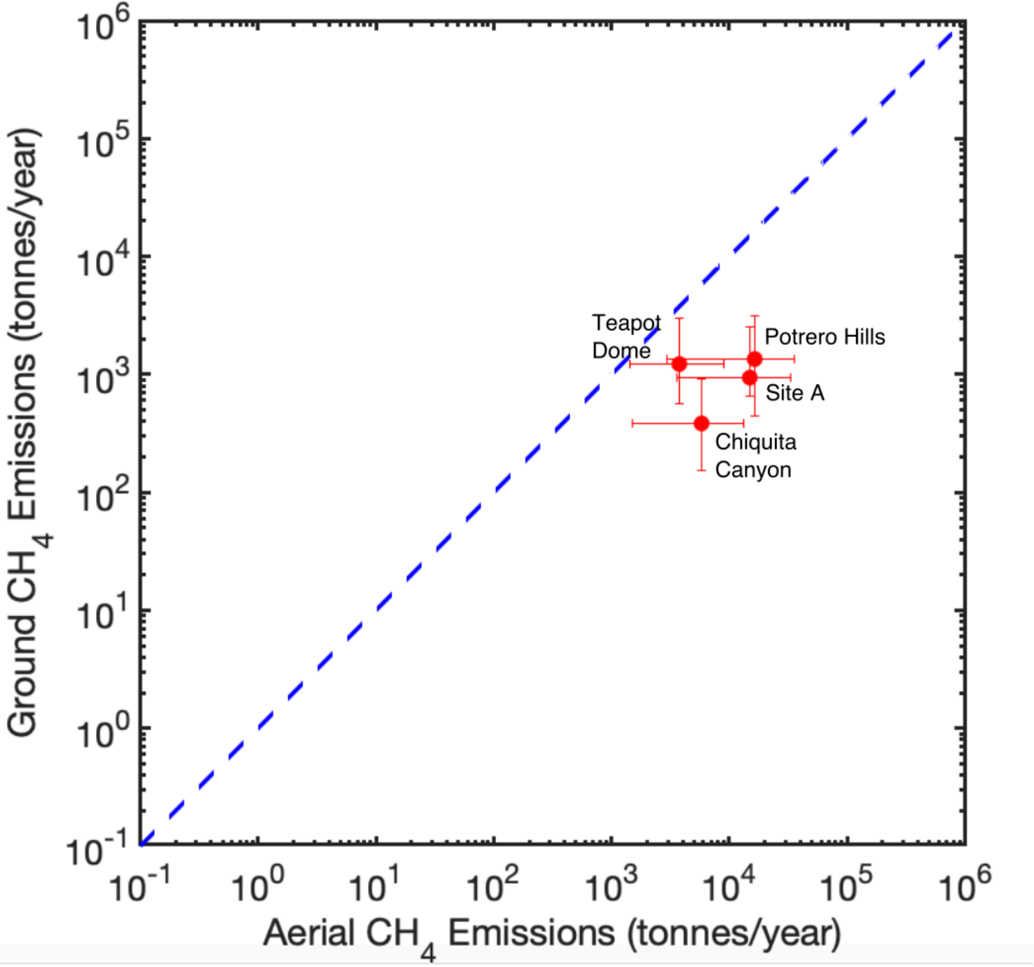
Acceptance of waste tires likely influenced flux of aromatic compounds with lower fluxes from sites that accepted tires with reduced sizes and large surface areas (e.g., tire chips) compared to the sites that accepted whole tires.

Based on data and analysis conducted at Santa Maria Regional Landfill for the soil intermediate cover: in general, GHG and NMVOC flux did not vary significantly with radial distance from a gas well (from 0.5 to 32 m); GHG flux decreased significantly at a cover thickness above 1.6 m, whereas the NMVOC fluxes were relatively constant (within one order of magnitude), when the cover thickness was varied from 0.4 to 1.9 m; the mean GHG and NMVOC fluxes were relatively constant (within one order of magnitude), whereas the median fluxes varied significantly due to diurnal variations (negative fluxes early morning and overnight, positive fluxes daytime).

Based on all of the data obtained in the test program, landfill gas flux and emissions were correlated to landfill areal coverage, percent area covered by daily and intermediate cover, and waste column height. The methane flux had negative correlation with site age and percent area covered by final cover. Specific correlations were developed to establish thresholds of geotechnical landfill operations for soil covers. Example thresholds include: use long-term cover thickness of at least 150 cm (methane) and 75 cm (NMVOCs); compact soil in cover for maintaining at least 2000 kg of mass in long-term cover systems; and use soil with at least 60% fines content and 12% clay content for long-term covers.

The ground-based methane emissions were generally close, yet consistently lower in magnitude compared to the aerial methane emissions estimates. A comparison of the results from the two measurement approaches is presented in Figure ES.6. The uncertainties in the aerial measurements were higher than the uncertainties in the ground-based measurements in the investigation as indicated by the larger 95% confidence intervals along the x-axis compared to the confidence intervals along the y-axis as presented in Figure ES.6. The average ground-based methane emissions estimates for Santa Maria Regional Landfill (not depicted in Figure ES.6) were -0.122 tonnes/year with 95% confidence intervals ranging from -0.201 to -0.043 tonnes/year and aerial estimates were 1684 tonnes/year with 95% confidence intervals ranging from -221 to 3589 tonnes/year. The aerial methane measurements were mainly sensitive to landfill size characteristics, whereas ground methane measurements were strongly correlated to areal extent of individual cover categories and also correlated to collection efficiencies.

Figure ES.6 Comparison of Ground- and Aerial-Based Methane Emissions Estimates (dashed line indicates 1:1 reference, error bars represent 95% confidence intervals of overall estimates).



Gas Collection Efficiency Results

Gas collection efficiencies were determined for a subset of the 16 landfills included in the investigation with active gas collection and removal systems. A total of 10 landfills were included in the determination of the collection efficiencies. Two approaches were used for determining collection efficiencies: measured and modeled analyses (Table ES.2). The measured collection efficiencies were determined using the methane recovery data reported by landfills and emissions calculated in the investigation. The methane recovery rates reported by the landfills varied between 7.77x10^2 and 4.15x10^4 tonnes/year. For the 10 sites, emissions data from the aerial measurements were used. The methane emissions determined in the aerial tests varied between 1,684 and 16,402 tonnes/year. Also, analysis was conducted for the 5 ground-testing sites using whole-site emissions determined from flux chamber tests. The methane emissions determined in the ground-based tests varied between -0.122 and 1,345 tonnes/year. The modeled efficiencies were determined using the methane recovery data reported by landfills (range of values provided above) and gas generation estimated using LandGEM model (using baseline default values). The LandGEM gas generation rates ranged between 3.91×10^4 to 1.41×10^8 m^3/year.

The measured and modeled gas collection efficiencies ranged from 23.2 to 91.4%, 38.9 to 100, and 24.5 to 75.9%, respectively (Table ES.2). The average efficiency was 54% for modeled collection efficiency analysis and lower than the average efficiency for the measured collection efficiency analysis (65% for aerial, 85% ground). Significant uncertainty was present for all of the collection efficiency determinations with higher uncertainties for the baseline and refined modeled collection efficiency analyses than the measured efficiency analysis. The measured efficiency analysis potentially overestimates the collection efficiency as only emissions are considered for mass balance and not other methane transport/transformation pathways (oxidation in covers, lateral migration). The high uncertainty in the modeled generation rates results from the uncertainty in the characteristics of the waste mass, environmental conditions, and gas generation mechanisms. A strong negative correlation was observed between measured collection efficiency and ground-based methane emissions. However, these trends were not fully confirmed when using modeled gas collection efficiencies. The high uncertainty in the predicted gas generation rates resulted in the weak correlations between modeled gas collection efficiencies and calculated emissions.

Table ES.2 – Summary of Measured and Modeled Methane Gas Collection Efficiencies (for year 2018)

Landfill	Measured Aerial Data		Measured Ground Data		Modeled LandGEM	
	$\overline{\alpha}$ (%)	95% C.I.	$\overline{\alpha}$ (%)	95% C.I.	$\overline{\alpha}$ (%)	95% C.I.
Santa Maria Regional	61.1	[42,100]	100	[100, 100]	51.5	[31.9, 82.8]
Teapot Dome	23.2	[18.4, 31.4]	38.9	[30.3, 54.4]	24.5	[14.7, 38.9]
Potrero Hills	47.3	[43.2, 52.3]	91.4	[88.9, 94]	60.2	[34, 93.5]
Site A	62.9	[57.7, 69.0]	96.4	[93.9, 98.9]	39.6	[24.6, 63.8]
Chiquita Canyon	84.1	[80.8, 87.7]	98.8	[98.3, 99.3]	62.5	[36.4, 98.2]
Frank R. Bowerman	58.7	[54.1, 64.1]	N/A	N/A	53	[30.8, 83.2]
Redwood	91.4	[89.2, 93.8]	N/A	N/A	75.9	[53.9, 100]
Simi Valley	78.3	[70.3, 88.5]	N/A	N/A	65.3	[38.9, 100]
Sunshine Canyon	86.8	[84.4, 89.4]	N/A	N/A	63.7	[36.1, 99.1]
Yolo County	57.6	[53.4, 62.4]	N/A	N/A	48	[29.8, 77.2]

Conclusions

Flux and emissions of methane, nitrous oxide, and NMVOCs are highly variable at a given landfill and also between landfills. The highest mean flux at each landfill was obtained for the main LFG, methane. NMVOCs were a significant and detectable fraction of the landfill gas emitted from the landfills investigated. The highest NMVOC fluxes were for alcohols, ketones, and monoterpenes. The NMVOCs had significant contributions to whole-site emissions in particular for CO_2-eq. emissions, even though these gases are all trace constituents in landfill gas. The high intra- and inter-landfill flux variation resulted from differences in cover characteristics, thickness, configuration, and placement/construction practices. Daily covers resulted in the highest flux measurements for the various gases analyzed in this investigation. Some of the measured emissions from daily and also intermediate covers were attributed to cover materials themselves based on their chemical/biological composition (e.g., auto fluff, green waste, contaminated soil). Soil covers were more effective than non-soil covers for a given cover category. Emissions decreased for all categories of gas species investigated from daily to intermediate to final covers, where the relative fractions of these covers at the study sites were 0.1 to 20% (daily), 25 to 99.8% (intermediate), and 0 to 40.7% (final). The relative proportions of the different cover categories control emissions and provide direct means for management of emissions. Differences were observed between aerial and ground measurements, which may have resulted from emissions from the active waste placement surface at the landfills (not measured in the ground tests) and the high uncertainties in the aerial measurements. Gas flux and emissions were primarily controlled by cover characteristics and landfill operational processes with relatively low secondary effects from seasonal differences. Due to large uncertainty in modeling gas generation, the use of collection efficiency as a measure of emissions may not be reliable.

INTRODUCTION

This investigation was conducted to provide detailed assessment of emissions of 82 gas species (main and trace constituents) from landfills in California. The main gases were methane and carbon dioxide. The trace gases included greenhouse gases and additional volatile organic compounds. The three main components of the study were conducting an extensive literature search; identifying main characteristics of California landfills and selecting specific sites for emissions analysis; and conducting an extensive field-testing program. The results of the project are presented in five distinct sections within this report.

The literature review is presented in Part 1. The review included information on landfill gas generation. Storage, transport, and collection of gas in landfill systems were described. Surface flux and emissions of both main and trace gases from landfills were provided. Characteristics and properties of chemical species included in the study were reviewed. Data on landfill gas composition and transformation pathways are summarized.

Landfill classification analysis is presented in Part 2 of this report. Initially a detailed analysis was conducted to identify the main characteristics of California landfills. This analysis was followed by selection of representative sites using the main factors and criteria established based on the landfill characteristics analysis.

The field test program is presented in Part 3. The field tests included two measurement programs: aerial measurements of methane and ethane above the landfill surfaces and measurements of all of the 82 gases directly on the landfill surfaces. Details of the two measurement programs including methods used and specific test protocols were described. Details of the supplementary field and laboratory tests were provided. Determination of methane generation and collection efficiency were presented.

Results of the investigation are presented in Part 4. Aerial measurement data for methane and ethane were included. Detailed results are presented for each landfill site with flux chamber testing for the two measurement seasons (wet and dry) establishing intra-landfill variations. Inter-landfill variations also were identified. Comparisons were made between seasonal measurements. Flux measurements were extended to whole-site emissions. Correlations between measured flux and emissions and landfill characteristics are presented. Assessment of gas collection efficiency was provided. Potential effects of tire disposal on gas emissions was identified.

Engineering significance of the investigation including main conclusions are provided in Part 5. Aerial and static flux measurements were compared. Perspectives were provided in relation to literature gas emissions data. The main factors that affect emissions were identified. Potential anthropogenic versus biogenic sources of the 82 gas species included in the investigation were assessed. Data and analysis were provided for potential indirect human health and climate change effects of the gases that typically are not considered greenhouse gases.