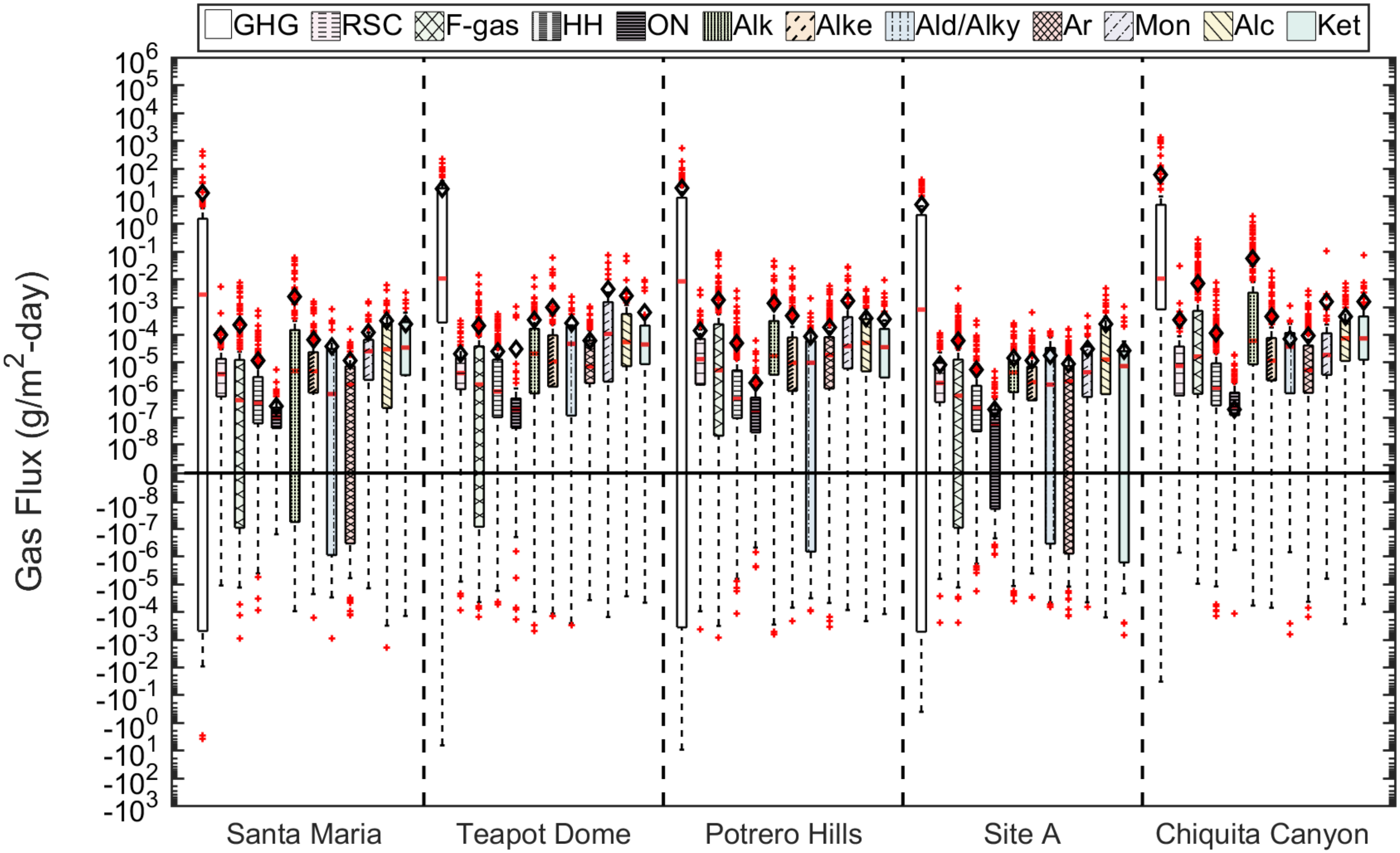
PART 5 – ENGINEERING SIGNIFICANCE

5.1 Gas Flux in California Landfills

This investigation was conducted to determine the flux of main and trace species in landfill gas in California landfills. Over 65,000 individual gas concentration measurements obtained during static flux chamber tests at five landfill sites over the two main seasons (dry and wet) were used to determine flux of a total of 82 individual gases categorized under 12 distinct chemical families. The main landfill gases analyzed were methane and carbon dioxide and the trace components included nitrous oxide, carbon monoxide, and 78 additional NMVOCs.

A summary of the flux data obtained in the investigation is provided in Figure 5.1. The highest fluxes at each landfill site were obtained for GHGs, which included methane, nitrous oxide, carbon dioxide, and carbon monoxide. The GHG fluxes varied by up to two orders of magnitude between the study sites. The results of this study also 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 landfill sites. Highest NMVOC fluxes were measured for the alcohols, ketones, and monoterpenes chemical families. Chiquita Canyon/Teapot Dome Landfills and Site A Landfill were associated with the highest and lowest flux measurements of these chemical families, respectively (Figure 5.1).

Figure 5.1 Inter-landfill Flux Results (open black diamonds, red lines, solid red dots represent means, medians, and outliers, respectively)

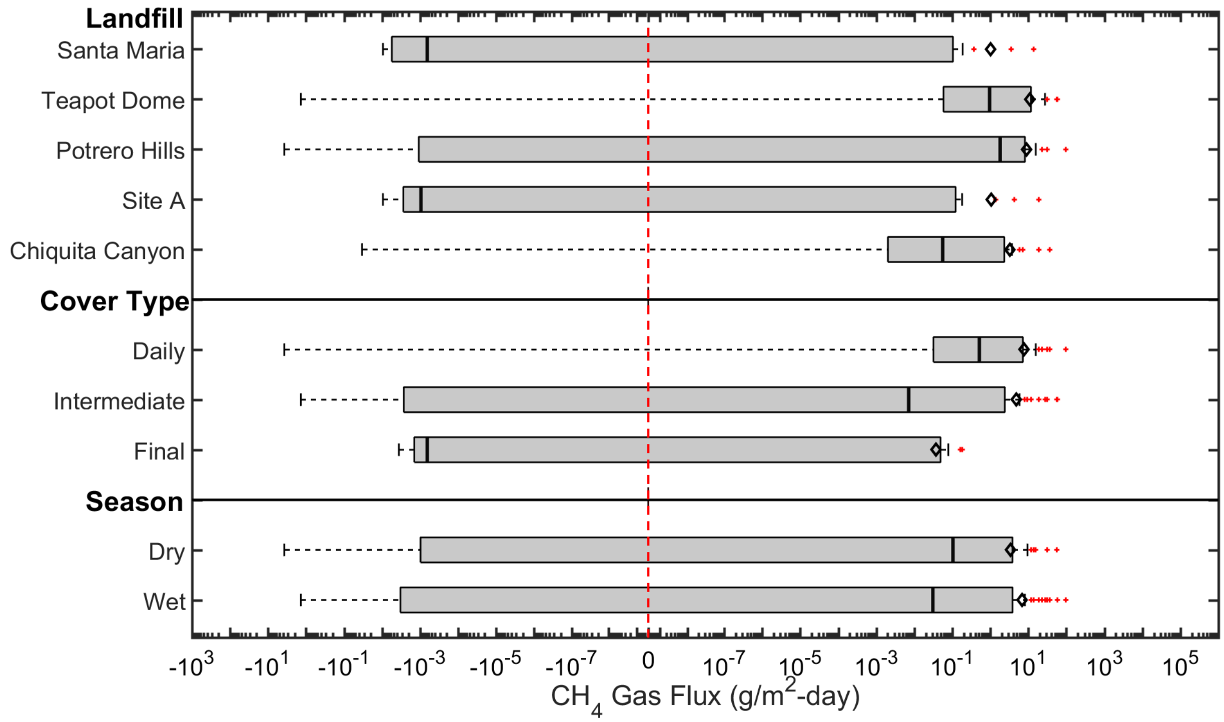


5.2 Variability of Gas Flux in California Landfills

Variation of methane flux as a function of landfill, cover category, and season is presented in a tornado plot in Figure 5.2. The overall range in measured methane flux was from -10^0 to 10^1 g/m^2-day. Variation by landfill and cover category was comparable and more significant than variation by season. The median flux at Site A was low compared to the other sites. The test locations at this site all had thick soil covers consisting of clayey/silty soils with no thin alternative covers such as green waste or autofluff. In addition, the variation in the moisture contents and temperatures of the soils was the lowest at Site A, which may have generated more stable environmental conditions for sustained methane oxidation. The methane fluxes from the medium sized landfills (Santa Maria and Teapot Dome) were comparable to the fluxes from the larger sites (Potrero Hills, Site A, and Chiquita Canyon), indicating the significance of factors other than operational scale on methane emissions. The methane 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 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 were within one order of magnitude indicating the more significant influence of the cover conditions on methane flux than seasonal variations in California.

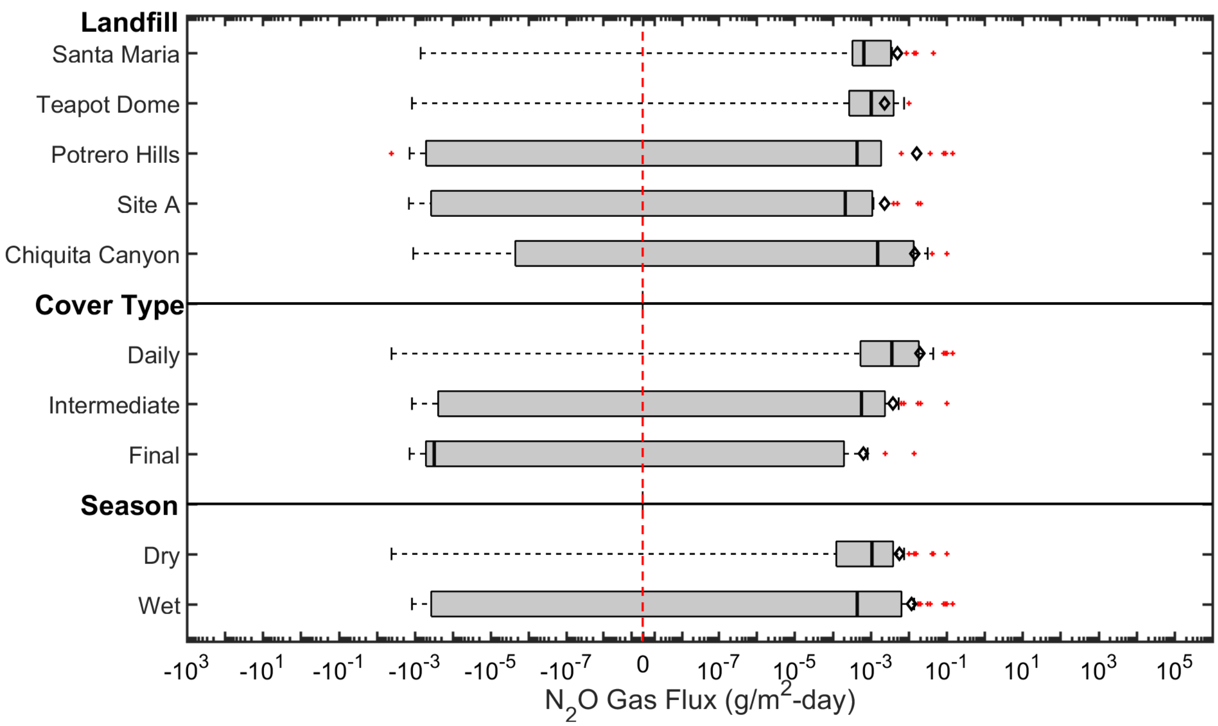
At Site A, methane flux from the alternative final cover was significantly higher than the flux from the conventional final cover. The large difference may have resulted from the more interconnected pore structure of the coarser-grained alternative cover compared to the occluded pore structure of the finer-grained conventional cover. 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. While good hydraulic performance of alternative covers against moisture ingress into landfills have been demonstrated, these covers may not be highly effective as barriers against gas flux.

Figure 5.2 Tornado Plot Summarizing the Variation in 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).



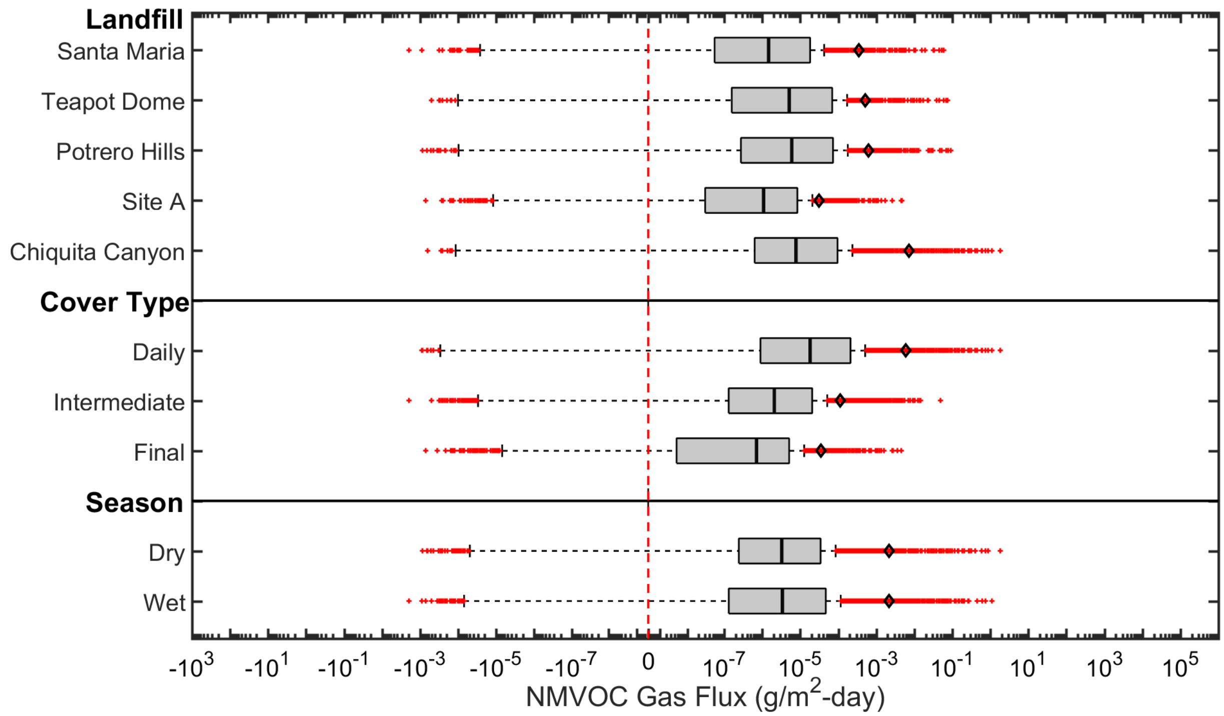
Variation of nitrous oxide flux as a function of landfill, cover category, and season is presented in a tornado plot in Figure 5.3. The overall range in measured nitrous oxide flux was from -10^{-3} to 10^{-1} g/m^2-day. Variation by cover category was more significant than variation by landfill and season, which were relatively comparable. Nitrous oxide fluxes at the medium sized landfills were largely positive (all or most of interquartile ranges above zero in Figure 5.3) with low probability for negative flux compared to the larger landfills. Waste composition may have resulted in 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 Porterville Landfills compared to the wastes from mainly urban sources at the large Northern and Southern California landfills. The 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. In similarity to methane flux results, 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 landfill resulted in the lowest fluxes. The seasonal variations were within one order of magnitude indicating the more significant influence of the cover conditions on nitrous oxide flux than seasonal variations in California.

Figure 5.3 Tornado Plot Summarizing the Variation in 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).



Variation of NMVOC flux as a function of landfill, cover category, and season is presented in a tornado plot in Figure 5.4. The overall variation in NMVOC flux was from -10^{-3} to 10^{0} g/m^2-day. Variation in total NMVOC flux was generally comparable across landfills, cover categories, and seasons and less than variations observed for methane and nitrous oxide. Positive flux is dominant for the NMVOCs investigated with low probability of uptake(interquartile ranges above zero in Figure 5.4), 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 and Teapot Dome) were comparable to the fluxes from the larger landfills, indicating the significance of factors other than operational scale on 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 NMVOCs. NMVOCs such as aromatic hydrocarbons, alkanes, and alkenes may have volatilized from the contaminated soil daily cover. The wood waste and green waste ADC materials 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 in some cases resulted in the lowest fluxes. The final cover NMVOC fluxes were in some cases higher than those for methane and nitrous oxide. The seasonal variations were within one order of magnitude indicating the more significant influence of the cover conditions on NMVOC flux than seasonal variations in California.

Figure 5.4 Tornado Plot Summarizing the Variation in 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).



Overall, methane, nitrous oxide, and total NMVOC emissions are affected most by cover category/type, followed by site specific operational practices and scale, and then by season. The violin plots presented in Figures 5.5 and 5.6 provide probability density estimates for the different cover categories included in this investigation. For methane and GHGs, a higher probability of fluxes between 10^{-5} to 10^0 g/m^2-day was observed for the daily covers compared to the intermediate and final covers. The intermediate and final cover systems demonstrated a wider range in probable flux between 10^2 and 10^{-6} and 10^1 and 10^{-6} g/m^2-day, respectively. The relative amount of negative fluxes increased from daily to intermediate to final covers. Chiquita Canyon and Site A Landfills were generally associated with the highest (most positive) and lowest (most negative) GHG fluxes, respectively (Figure 5.5). For NMVOCs, the highest probability density of positive fluxes was observed between 10^{-8} and 10^{-2}, 10^{-8} and 10^{-3}, and 10^{-8} and 10^{-4} g/m^2-day for the daily, intermediate, and final covers, respectively. The highest probability density of negative fluxes was observed between -10^{-8} and -10^{-3}, -10^{-8} and -10^{-4}, and -10^{-8} and -10^{-5} g/m^2-day for the daily, intermediate, and final covers, respectively. Chiquita Canyon, Potrero Hills, and Site A Landfills were associated with the majority of positive fluxes for daily, intermediate, and final covers, respectively. Negative fluxes were most likely associated with Site A Landfill for all cover categories.

Figure 5.5 Distribution of Methane Fluxes by Cover Category (open black diamonds, red lines, and solid red dots represent means, medians, and outliers, respectively).

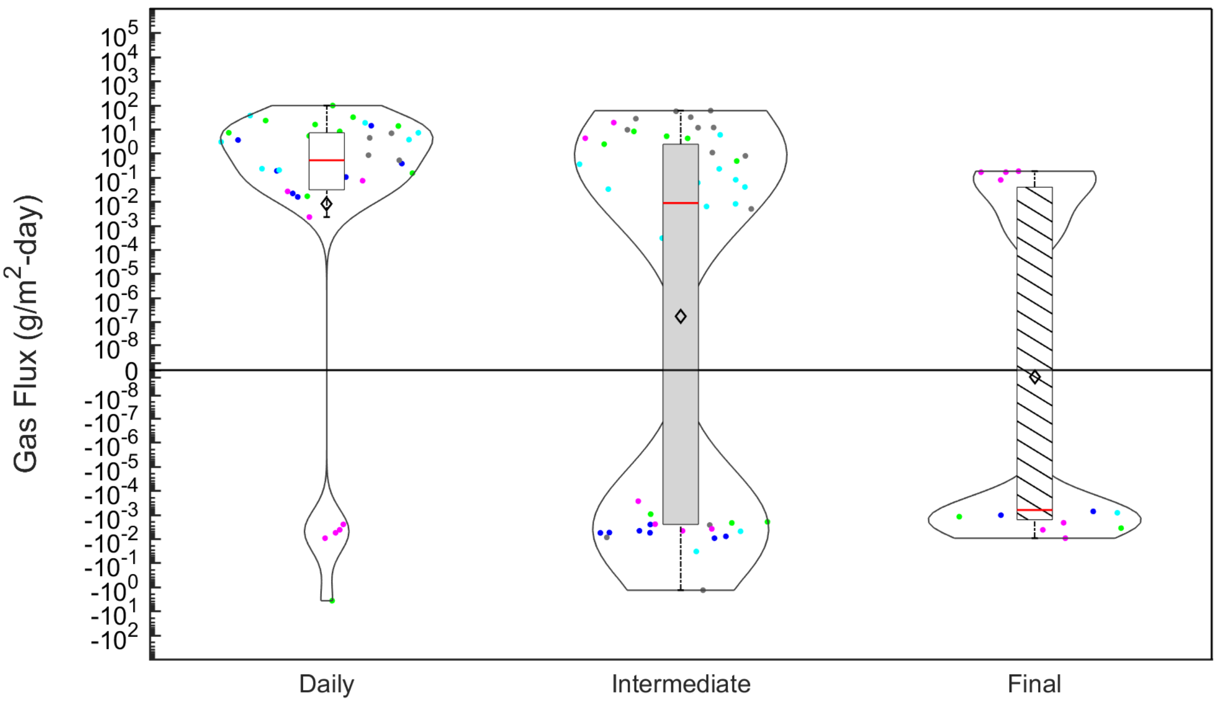
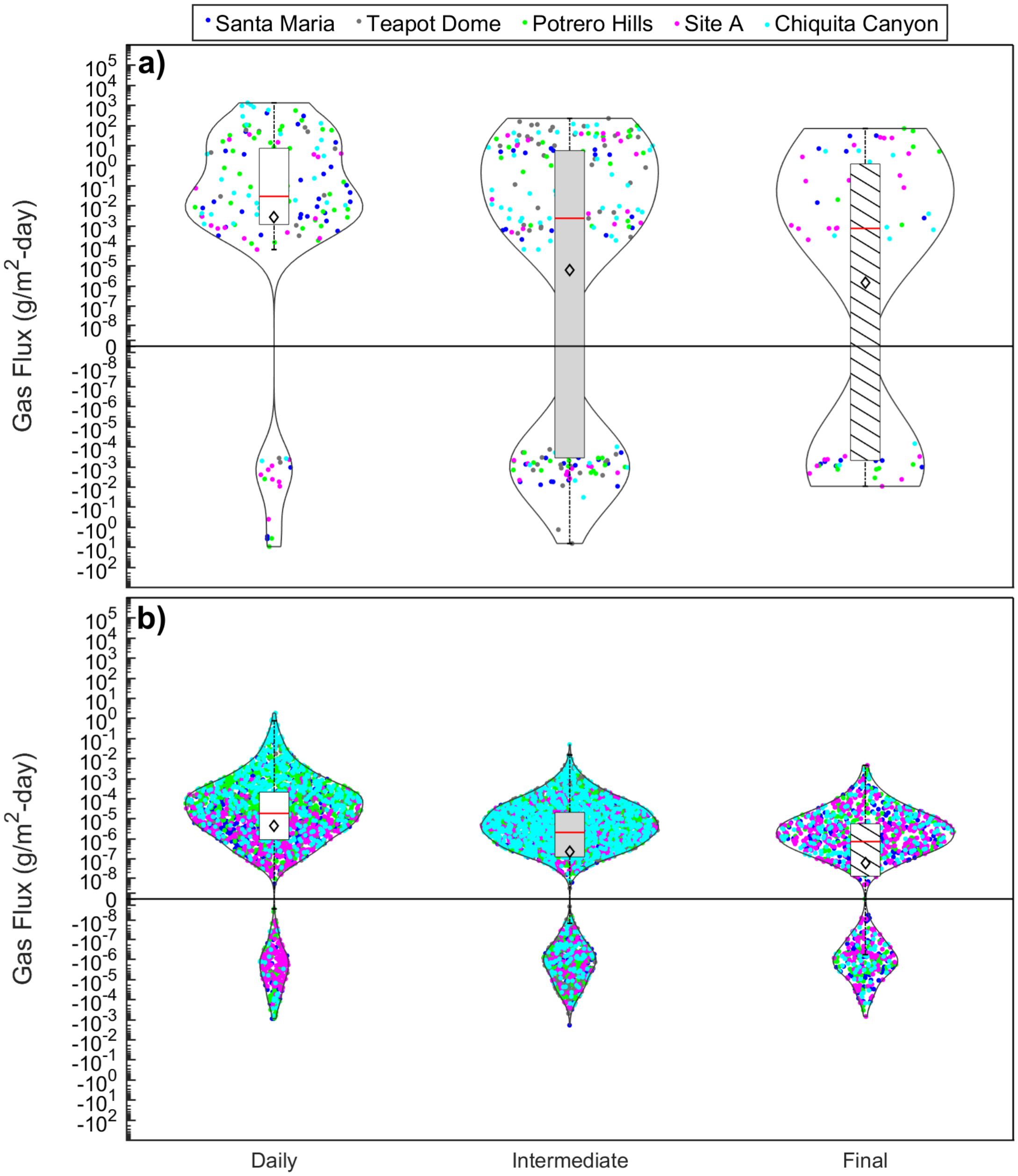


Figure 5.6 Distribution of a) GHG and b) NMVOC Fluxes by Cover Category (open black diamonds, red lines, and solid red dots represent means, medians, and outliers, respectively).

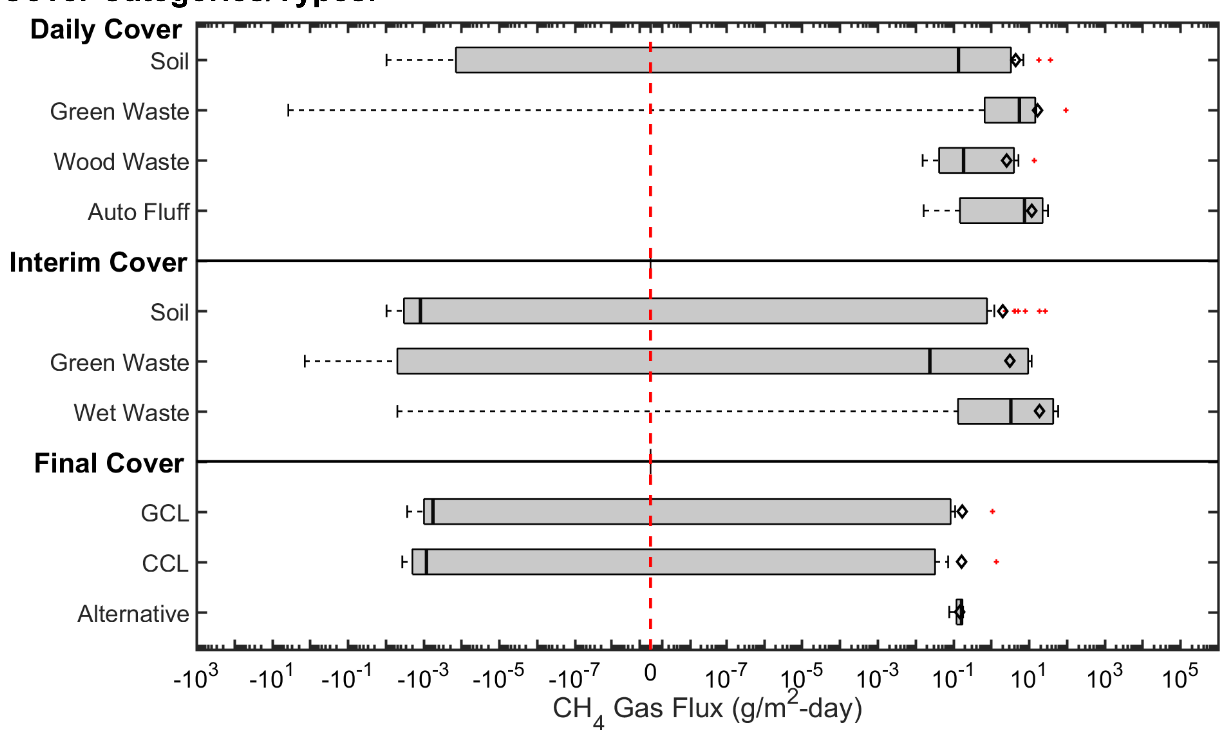


5.3 Influence of Cover Type on LFG Surface Fluxes

Analysis presented in Section 5.2 indicated that cover categories was the most significant factor affecting LFG surface fluxes as compared to site specific operational practices/scale and seasons. Thus, the influence of different cover types within each category (i.e., daily, intermediate, final) was further investigated herein. For daily cover categories, fluxes were grouped into cover types that included soils, green wastes, wood wastes, and autofluff. For intermediate cover categories, fluxes were grouped into cover types that included soils, soil/green wastes (green waste overlying soil), and landfill areas receiving placement of waste during the wet season (referred to as wet waste). Final cover categories were grouped into cover types that included conventional compacted clay liners (CCLs), conventional geosynthetic clay liners (GCLs), and alternative final cover systems. Fluxes were combined across sites and seasons to investigate trends in LFG fluxes (i.e., methane, nitrous oxide, and total NMVOCs) with cover category and type.

Surface flux of methane decreased from daily to intermediate to final covers (Figure 5.7). The highest methane fluxes were generally from alternative daily covers and in particular typically from autofluff. The variations of methane flux within the individual alternative daily covers were low and the overall methane fluxes were high. The variations of flux through soil daily covers were higher than the variations through the alternative daily covers with overall lower methane fluxes for soil daily covers. For intermediate covers, methane fluxes through soil covers were lower (with potential for uptake) than covers with green waste and covers over wet waste. For final covers, the fluxes were lower through the conventional covers (CCL and GCL) than the alternative cover. The median methane fluxes from the alternative final cover had low variability and was significantly higher than the methane fluxes from the conventional covers (Figure 5.7).

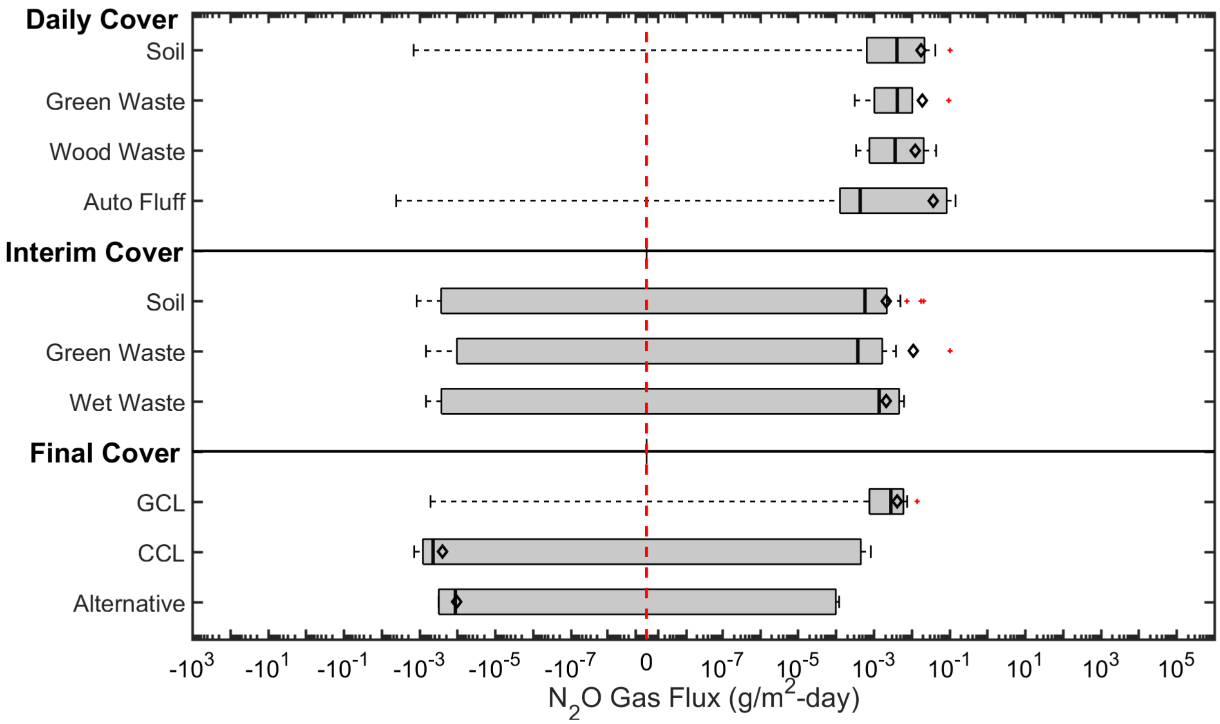
Figure 5.7 Summary of CH_4 Fluxes as a Function of Daily, Intermediate, and Final Cover Categories/Types.



Surface fluxes of nitrous oxide were generally highest from daily cover locations and similar between the three daily cover types with somewhat lower values for autofluff (Figure 5.8). The intermediate cover N_2O fluxes were relatively similar between the three cover types and overall slightly lower than the daily cover nitrous oxide fluxes.

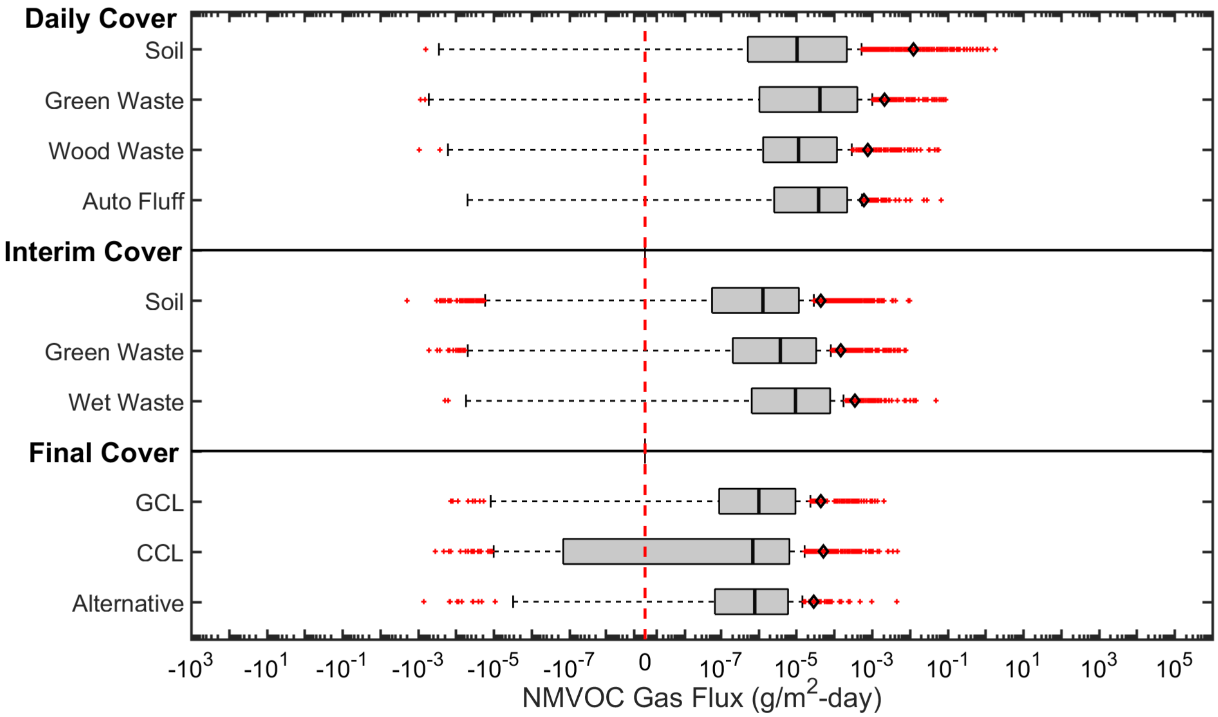
For final covers, the highest nitrous oxide fluxes were for the GCL cover and lower for the soil and alternative covers. The variation in flux was highest within the conventional CCL final covers.

Figure 5.8 Summary of N_2O Fluxes as a Function of Daily, Intermediate, and Final Cover Categories/Types.



While the surface flux of NMVOCs decreased from daily to intermediate to final covers, the variations between the cover categories were low (Figure 5.9). The variation for a given cover type also was low for all three cover categories (daily, intermediate, and final). The lowest NMVOC fluxes were associated with soil materials for the three cover categories. All of the measured NMVOC median and mean fluxes were positive indicating high probability of emissions over uptake.

Figure 5.9 Summary of NMVOC Fluxes as a Function of Daily, Intermediate, and Final Cover Categories/Types.



Overall 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. Both of these materials had low densities, high porosities, high void ratios, low solids content, low water content, and high volumetric air content both in the wet and dry seasons. Higher gaseous fluxes were associated with the lack of material (solids or water) to physically or chemically impede or retard gas transport in daily cover locations overlain with autofluff or green waste. The relatively low methane fluxes and large variations in soil daily covers resulted from mainly the data associated with thicker extended soil daily covers used in some cases at some of the study sites. For intermediate covers, the highest fluxes for the GHGs and NMVOCs were associated with the wet waste locations mainly due to the potential large amount of methane generation in the wet wastes as well as the coarser cover soils (high amount of interconnected pores for gaseous transport). For final covers, conventional covers were significantly more effective for impeding methane flux compared to the alternative cover due to the high fines content, clay content, and occluded pores resulting in tortuous gas transport paths. For nitrous oxide, the GCL cover had the highest flux with low nitrous oxide fluxes for both the CCL and the alternative final covers. The NMVOC fluxes were highly similar through the three final cover types. Overall cover categories and types had impacted GHG 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. Potential transformations of NMVOCs in different landfill covers have not been investigated extensively. NMVOCs may not be affected by cover characteristics to the same extent as methane and nitrous oxide (observed low variation of NMVOC fluxes with cover category and type).

5.4 Aerial versus Ground-Based Methane Fluxes

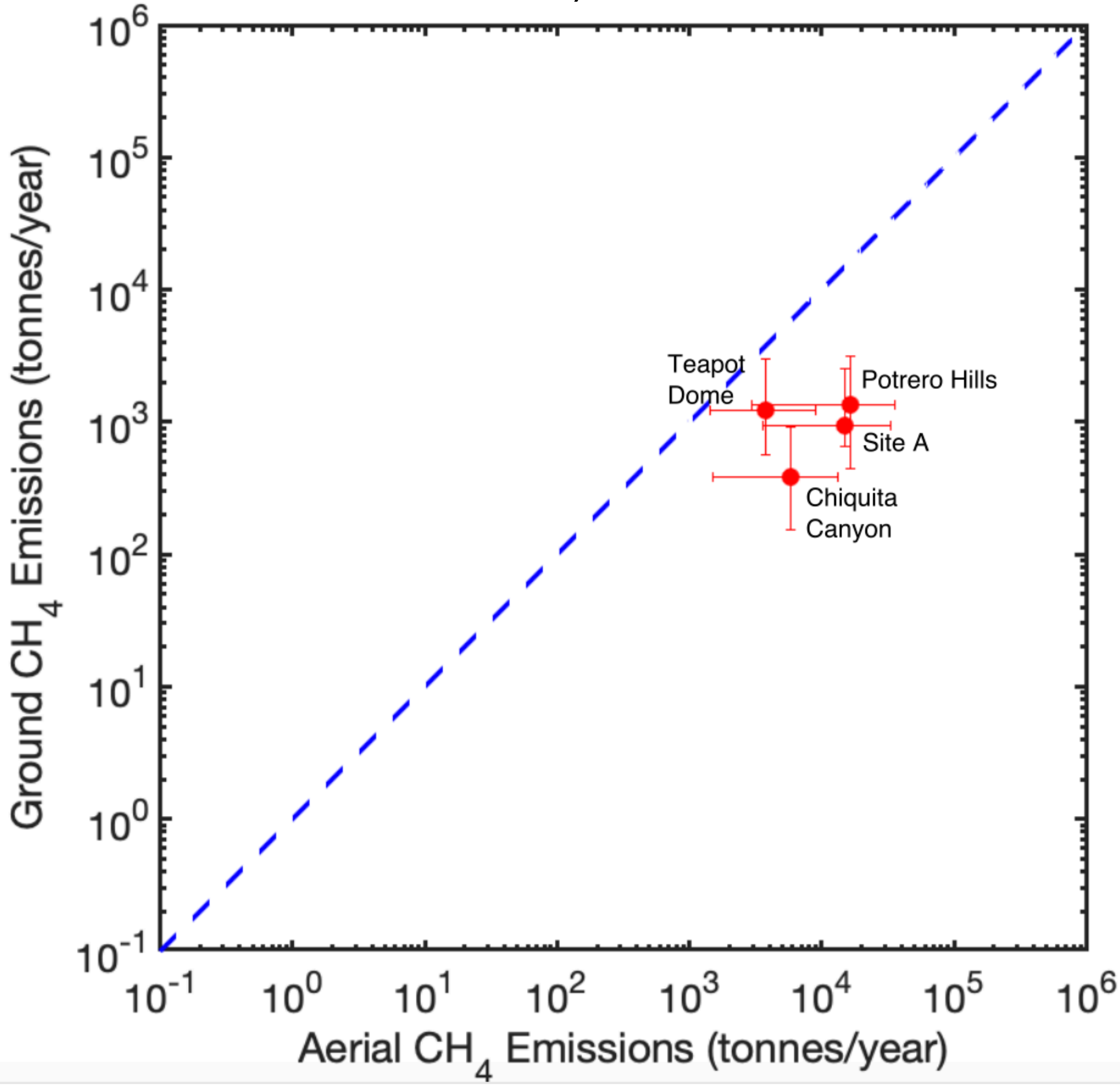
The field investigation of flux included two types of measurement programs: aerial and ground. The aerial testing provided results only for methane (other gases of interest could not be measured with this method) and overall estimates for whole-site emissions. The ground-based testing provided direct flux results for all 82 target gas species and allowed for detailed assessment of the effects of variable surface conditions on the emissions of the target gases from the tested landfills. Methane emissions based on the two testing programs are compared in Table 5.1 and Figure 5.10. The ground-based methane emissions were consistently lower in magnitude compared to the aerial methane emissions estimates. Yearly methane emissions estimated from the ground-based field-testing campaigns for Santa Maria Regional Landfill resulted in a negative whole site emissions. The average ground-based methane emissions estimates for Santa Maria Regional Landfill (not depicted on the log scale presented in Figure 5.10) 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 inventory values generally were between the ground-based and aerial-based measured emissions, with the exception of Teapot Dome Landfill (lower inventory values) and Chiquita Canyon Landfill (higher inventory values). The variability in emissions estimates (95% confidence intervals) also is included in Figure 5.10. For a majority of the landfills, the variability in emissions estimates was lower for the ground-based measurement method compared to the aerial method. Emissions from the active waste placement surface (not measured in the ground tests) and the uncertainties in the aerial measurements likely collectively contributed to the differences between the aerial and ground measurements. Nevertheless, magnitude and variation of methane emissions were captured using both methodologies in the test program.

Table 5.1 Comparison of Ground, Aerial, and CARB Inventory of CH_4 Emissions

Site	Ground-Measured CH_4 Mean Direct Emissions (tonnes/year)	Aerial-Measured CH_4 Mean Emissions (tonnes/year)	CARB Inventory of CH_4 Emissions (tonnes/year)[a]
Santa Maria Regional Landfill	-0.122	1684	148
Teapot Dome Landfill	1220	3799	142
Potrero Hills Landfill	1344	16402	2941
Site A Landfill	945	14792	12627
Chiquita Canyon Landfill	381	5804	5916

[a]Spokas et al. (2015)

Figure 5.10 Comparison of Ground and Aerial Based Methane Emissions Estimates (dashed line indicates 1:1 reference, error bars represent 95% confidence intervals of overall estimates).



Estimates for flux of CH_4 from the active face region of the ground testing sites is summarized in Table 5.2. The estimates were calculated using an assumption that the difference in emissions between aerial- and ground-based measurements was entirely from the active face. This calculation assumes that both methods of measurement are valid and that no additional emissions sources are present. The active face flux values were relatively high compared to measured values of covered regions using ground-based techniques (ranging from one to several orders of magnitude higher than the daily cover direct measurements).

Table 5.2 Estimation of Flux from Active Face Regions

Site	Difference between Ground-Based and Aerial-Based Emissions (tonnes/year)	Active Face Size (m^2)	Estimated Flux from Active Face Region (g/m^2-day)
Santa Maria Regional Landfill	1684	700	6.59×10^{3}
Teapot Dome Landfill	2579	1200	5.89×10^{3}
Potrero Hills Landfill	15058	3000	1.37×10^{4}
Site A Landfill	13847	6100	6.22×10^{3}
Chiquita Canyon Landfill	5423	5600	2.65×10^{3}

5.5 Comparison to Literature Results

This study represents to the PIs knowledge, the most comprehensive field investigation of gas emissions from municipal solid waste landfills in California, the U.S. and internationally. Previous investigations have focused primarily on measuring fluxes of the major greenhouse gases (methane, nitrous oxide, carbon dioxide), with little emphasis placed on NMVOC flux determination. In addition, as reviewed in Section 1, few previous studies have measured fluxes of NMVOCs from daily cover systems (mainly data from a previous study conducted by the PIs for CARB). Out of the 82 chemicals analyzed in this study, 8 gases previously have not been measured in landfill settings. These chemicals consisted of dimethyl sulfide, dimethyl disulfide, carbon disulfide, HFC-365mfc, n-undecane, n-propyl benzene, 2-butanol, and butanone.

Analysis of data collected from the literature review indicated varying ranges of methane, nitrous oxide, carbon dioxide, and NMVOC flux measurements across MSW landfills around the world. The reported methane fluxes ranged from -4.5×10^{1} to 4.15×10^{4} g/m^2-day as compared to -3.73×10^{0} to 9.62×10^{1} g/m^2-day observed in this study. Nitrous oxide fluxes reported in the literature ranged from -2.54×10^{-3} to 3.76×10^{0} g/m^2-day compared to 4.10×10^{-3} to 1.45×10^{-1} g/m^2-day observed in this study. Carbon dioxide fluxes reported in the literature ranged from -4.5×10^{1} to 1.24×10^{5} g/m^2-day compared to -9.60×10^{0} to 1.31×10^{3} g/m^2-day observed in this study. Total NMVOC fluxes reported in the literature ranged from -1.66×10^{-3} to 3.00×10^{-1} g/m^2-day compared to -1.93×10^{-3} to 1.81×10^{0} observed in this study. In general, the range of the major greenhouse gases observed from the literature was greater than the ranges reported from California landfills in this study. This result may be due to the wide range in landfills, climatic zones, and cover conditions associated with the sites reported in the literature, including several refuse disposal sites in Africa, India, and Asia where cover systems were not in place. The range in total NMVOC emissions observed from California landfills was slightly larger than that reported in the literature. This result may be due to the higher number of NMVOC chemicals included under the scope of this study.

5.6 Anthropogenic vs. Biogenic Sources of LFG

The sources of the main chemical families investigated in this study are classified as anthropogenic, biogenic or both anthropogenic and biogenic in origin and presented in Table 5.3. The major greenhouse gases (methane, nitrous oxide, and carbon dioxide) are generally biogenic in origin due to anaerobic and aerobic waste degradation as well as oxidation processes occurring in the soil covers. On-site vehicle emissions, flaring and combustion of LFG, and operation of heavy equipment also may contribute to carbon monoxide, carbon dioxide, NOx and SOx emissions and therefore the GHGs were classified as both biogenic and anthropogenic in origin. The origin of RSC emissions is primarily biogenic from anaerobic or aerobic conversion processes of sulfur present in the organic fraction of MSW. However, sulfur can also be released during decomposition of waste tires and other C&D wastes, such as gypsum board. F-gases are strictly anthropogenic in origin and are present in foam insulation materials, refrigerants, fire suppressants (i.e., Halons), cleaning agents, and medical aerosols. The halogenated hydrocarbons are strictly anthropogenic and generally originate from pesticides, adhesives, plastic materials, and rubber. Even though the origin of the alkyl nitrates is not well documented in the landfill environment, the alkyl nitrates are potentially formed from chemical reactions involving byproducts of microbial metabolic processes and other inorganic nitrogen sources present in the landfill environment; thus, they are classified as both anthropogenic and biogenic in origin. The alkanes and alkenes mainly originate from manufactured products such as paper, plastic packaging, personal care products, cleaning solvents, and cooking fuels. As microbial production of low molecular weight alkanes and alkenes has been documented in soil ecosystems, these chemical families are classified as anthropogenic and biogenic in origin. The aldehydes and alkynes originate from biological conversion processes as well as off gassing from chemical products such as paints, adhesives, and plastic materials. The aromatics, in similarity to the halogenated hydrocarbons, are strictly anthropogenic in origin and enter the waste stream through household cleaning solvents, personal care products, household spray applications, paints, textiles, cooking fuels, and furniture. The monoterpenes, alcohols, and ketones are biogenic and anthropogenic in origin, where the production of alcohols and ketones is mostly due to anaerobic fermentation occurring within the landfill environment. Production of monoterpenes is approximately equally divided between off gassing from personal care products, household sprays and detergents and generation during decomposition of green and wood wastes (Table 5.3).

Table 5.3 – Classification of Chemical Family Sources in the Landfill Environment

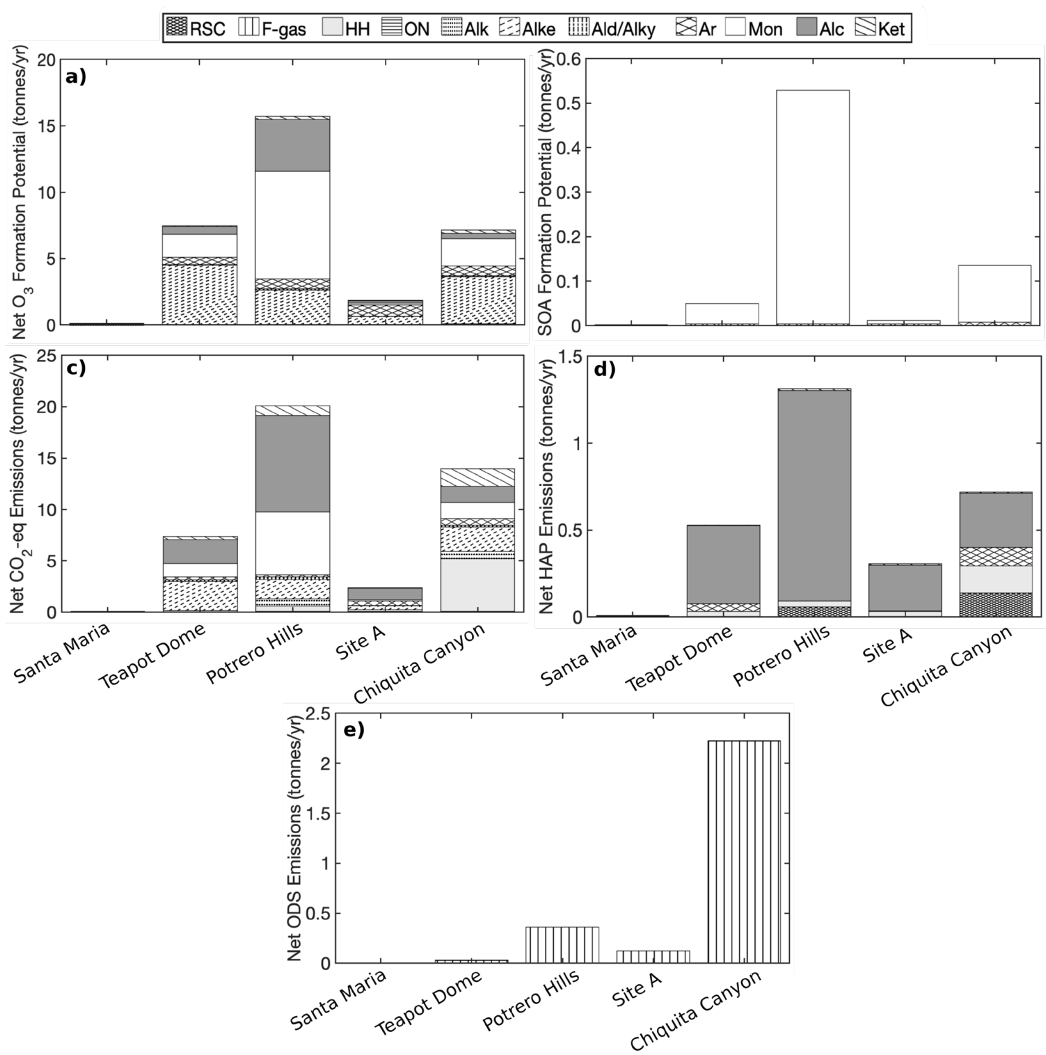
Chemical Family	Anthropogenic	Biogenic	Both
GHGs			X
RSC			X
F-gas	X		
HH	X		
ON			X
Alk			X
Alke			X
Ald/Alky			X
Ar	X		
Mon			X
Alc			X
Ket			X

5.7 Indirect Effects of Landfill NMVOC Emissions on Human Health, Air Quality, and Climate Change

The indirect effects of fugitive NMVOC emissions on human health, air quality, and climate change are assessed in Figures 5.11 and 5.12. Overall, from the 5 ground-based test sites, large differences in indirect emissions were observed between sites and chemical families. The calculated O_3 and SOA formation potentials, along with the combined GWP (exclusive of the F-gases), HAP emissions, and ODS-weighted emissions (inclusive of F-gases) are provided for each site, categorized by chemical family in Figure 5.11. Overall, Potrero Hills Landfill contributed the most to overall ozone, SOA, CO_2-eq. emissions, and HAPs as compared to all other sites (Figure 5.11). Chiquita Canyon was associated with the highest ODS-weighted emissions (Figure 5.11) and Santa Maria Regional Landfill had low indirect effects overall. The alkenes contributed highly to ozone formation potentials at each landfill, as the measured fluxes and MIR values were relatively high compared to other chemical families (Figure 5.11a). SOA formation potentials across all sites were generally low in magnitude (< 1.4 tonnes/year) and were largely dominated by the monoterpene chemical family, as the FAC values were the highest (~30%) for the alpha and beta pinene NMVOC species (Figure 5.11b and Table 1.1). Even though greenhouse gas associated emissions had the highest y-axis scale over all other metrics (0-120 tonnes/year), the impacts on climate change were relatively low compared to the F-gases (up to 100,000 tonnes/year). The monoterpene chemical family contributed the most to net greenhouse gas emissions, which can be attributed to the high number of carbon atoms comprising each molecule in this particular chemical family (C# up to 10). In addition, the alkene chemical family indirectly contributed to climate change impacts due to the presence of indirect GWPs for ethene, propene, and isoprene (Figure 5.11c). In theory, indirect GWPs can be obtained for every reactive NMVOC involved in tropospheric O_3 production. However, to date, no studies have modeled the full range in indirect GWPs for each of the NMVOC species included in Table 1.1 (Collins et al. 2002).

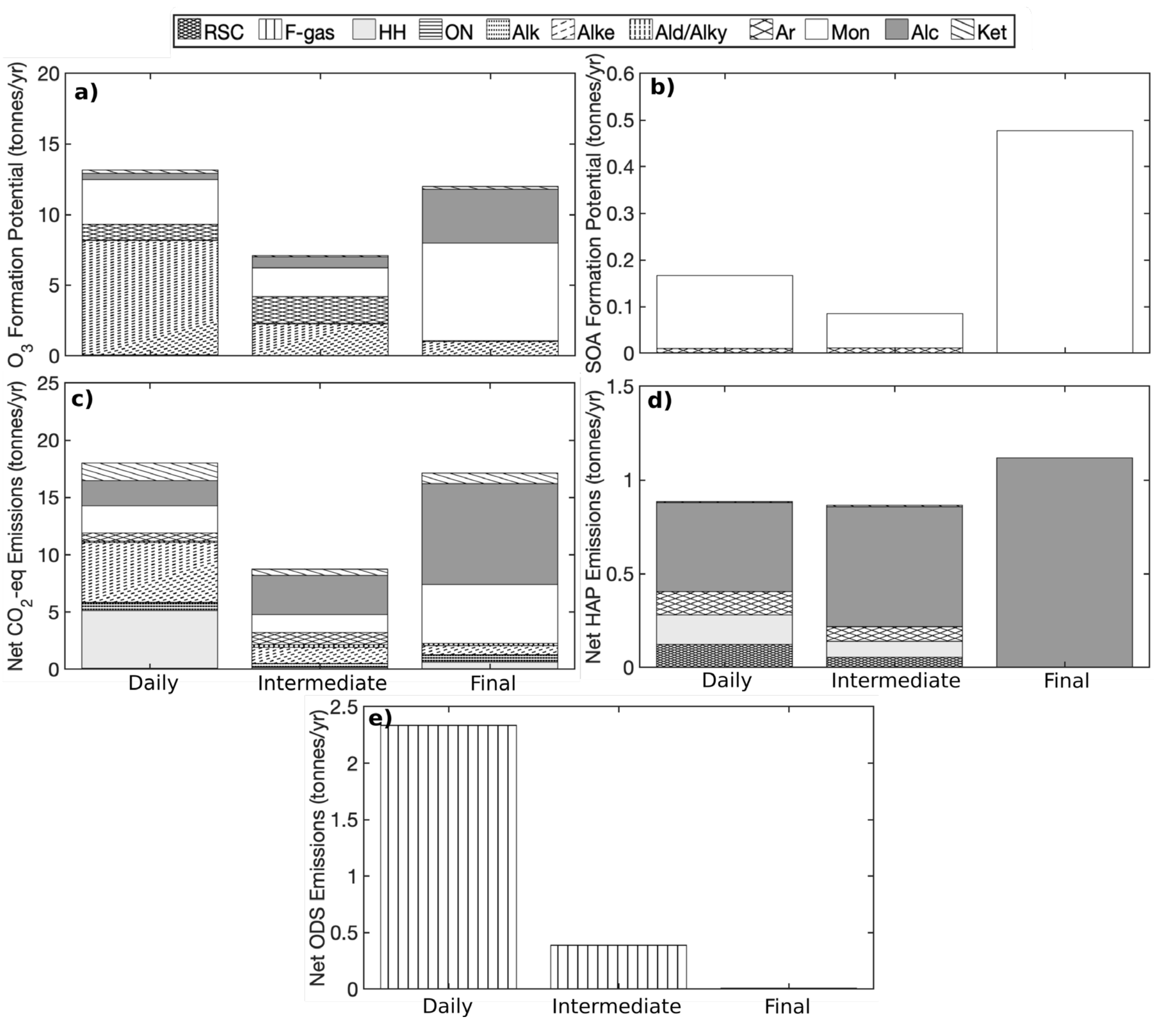
Out of all metrics investigated, HAP emissions were the most comparable across all landfill sites (Figure 5.11d). Alcohols made up a significant fraction of the total HAP emissions, particularly for the Teapot Dome Landfill. Methanol was the only species within the alcohol family that was considered a HAP. Reduced sulfur compounds, halogenated and aromatic hydrocarbons, and alkanes were predominant HAPs at Teapot Dome, Potrero Hills, Site A, and Chiquita Canyon Landfills. Within these chemical families, BTEX (benzene, toluene, ethylene, xylene isomers) and methylene chloride and trichloroethylene (TCE) are acute and chronically toxic environmental pollutants. ODS-weighted emissions were dominated by the F-gas chemical family, which included chlorofluorocarbons (CFCs, Class I ODS), halons (H1211, Class I ODS), and hydrochlorofluorocarbons (HCFCs, Class II ODS) (Figure 5.11e). Of these species included in the analysis, H1211 had the highest ODS value and, based on the median value of flux estimates, contributed most to ODS-weighted emissions.

Figure 5.11 Summary of the net a) O_3 formation potential, b) SOA formation potential, c) indirect and direct global warming potential, d) HAP emissions, and e) ODS weighted emissions by NMVOC chemical family and landfill site.



The calculated O_3 and SOA formation potentials, along with the combined GWP (exclusive of the F-gases), HAP emissions, and ODS-weighted emissions (inclusive of F-gases) are provided for each cover category, categorized by chemical family in Figure 5.12. Net ozone formation potential and ODS weighted emissions were highest from the daily cover categories, whereas SOA formation, net indirect/direct GWP weighted emissions, and HAP emissions were greater from the final cover categories. All indirect emissions were generally lowest from the intermediate cover categories (Figure 5.12). Similar to results presented in Figure 5.11 above, monoterpenes, alcohols, and alkenes were the chemical families that contributed most to indirect climate effects across the cover categories surveyed.

Figure 5.12 Summary of the net a) O_3 formation potential, b) SOA formation potential, c) indirect and direct global warming potential, d) HAP emissions, and e) ODS weighted emissions by NMVOC chemical family and cover category.



5.8 Additional Emission Control Measures

The recommendations for reducing emissions are provided under two main headings. First, potential measures are provided related to cover systems in landfill facilities. Second, discussion is provided related to other aspects of landfill operations, monitoring, and modeling.

5.8.1 Cover Category and Type

Soil covers were observed to be more effective than non-soil covers for a given cover category. For both daily and intermediate covers, emissions were generally lower from soil covers than for non-soil covers for cases investigated in this study. Higher material content in the covers (increased density, increased thickness) was directly aligned with lower fluxes [Sections 4.7 and 4.8]. While the use of non-soil materials as daily and/or interim cover allows for repurposing various waste and byproduct materials, these materials are not as effective as natural soils in reducing gas flux from landfill systems both for main (methane, carbon dioxide, nitrous oxide, and carbon monoxide) and trace NMVOC landfill gas constituents [Section 5.3]. In addition, for interim cover applications, natural soil covers were more effective at limiting gas emissions than composite soil/non-soil material covers (homogeneous mixtures or layered systems) [Section 5.3].

Flux decreased from daily to intermediate to final covers for all sites analyzed in this investigation [Section 5.1]. The decreases between daily and intermediate covers were greater than the decreases between intermediate and final covers. While the emissions were lower from thicker covers than thinner covers, increasing the thickness of the covers is not critical beyond certain limits [Section 4.13]. Proper use and management of the individual cover systems can be effective as control measures to reduce emissions from landfill facilities.

Daily and intermediate covers are temporary systems that affect emissions of a landfill in the relatively short-term. Final covers are used essentially in perpetuity as barriers against emissions and thus the performance and durability of these systems is critical.

Specific recommendations for the individual cover categories are provided below:

Daily Covers

- Minimize the areal extent of daily cover.
- Reduce duration of time period that daily cover is serving as barrier between the waste mass and the atmosphere.
- Avoid highly porous and open structure bulk materials (e.g., green waste, wood waste, and auto fluff [Section 5.3] as well as construction/demolition waste [Section 4.3.3.2]) for use in covers for extended periods (months, years).

Intermediate Covers

- Thickness – increasing thickness of intermediate covers is effective up to approximately 1 meter. Additional cover thickness beyond this value does not provide significant reduction in emissions [Section 4.13, Appendix A4].

- Place interim cover as quickly as possible (days to weeks, not months).
- Fines content for soil (% passing 0.075 mm) over 30% is more effective in controlling emissions compared to soils with lower fines content [Section 4.8].

Final Covers

- Based on comparison of a conventional cover and an alternative final (i.e., evapotranspirative) cover at one of the sites investigated, the gas flux from the alternative cover was higher than the flux through the conventional cover [Section 5.3]. The differences in flux were particularly significant for methane. To the PIs knowledge this was the first-time gas flux was measured through a water balance cover system.
- Higher plasticity soils (PI over 20%) are more effective in controlling emissions compared to soils with lower plasticity [Section 4.8].
- Based on thresholds developed for geotechnical landfill operations for soil covers, 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 [Appendix A4].

5.8.2 Other Aspects of Landfill Operations, Monitoring, and Modeling

- Minimize the size of active working face to reduce direct atmospheric exposure of freshly placed waste as well as all underlying wastes [Section 5.4].
- If specific regions of a landfill are designated for waste placement during wet weather conditions, apply more robust cover configurations for these regions than for other regions at the site to attain similar barrier function against gas flux [Section 5.3].
- Due to large uncertainty in modeling gas generation, the use of collection efficiency as a measure of emissions is not recommended [Section 4.9].
- Top-down aerial measurements can provide whole site emissions and may be used to estimate overall site data for methane emissions.
- Bottom-up ground measurements using flux chambers provide discrete measurements for individual cover types and categories for methane as well as a large number of additional gases, which cannot be obtained with aerial measurements. The ground-based measurements are effective for assessing individual cover systems and for comparing materials/designs for the individual covers. In addition, ground measurements provide data on the flux/emissions of trace gases.
- Both top-down and bottom-up measurements provide context for methane emissions from landfills and combining the methods has benefit of obtaining methane emissions information at different scales [Section 5.4].
- Specific to N_2O emissions, avoid concentrated placement of organic sludges (e.g., waste-water treatment plant sludge) within the landfill system [Section 4.3.3.2].
- NMVOCs are trace components in LFG yet are a significant and detectable fraction of landfill gas with net positive fluxes from all cover categories and appreciable portions of total emissions. NMVOC emissions can be included in

GHG inventories as well as used in air quality studies and impacts on public health and the environment.

- Emissions of different chemicals vary in magnitudes as well as in the underlying trends with physical, operational, and climatic conditions. Different physical, chemical, biological, thermal, and biochemical processes affect the different types of gas species that may be present in a landfill environment affecting the potential transformation of the chemical species. Therefore, from an analysis and modeling standpoint, investigations conducted for a given chemical/chemical family cannot be applied or scaled for other chemicals/chemical families. As methane does not serve as a surrogate for other chemicals, applying conventional methane modeling methods to other chemical species is not recommended [Part 5].
- The acceptance of waste tires was not determined to have significant effect on emissions overall [Section 4.10]. The two potential chemical families with direct tire relevance are RSCs and aromatic hydrocarbons. For RSC (reduced sulfur compounds) emissions, limited influence of presence of tires was measured. The presence of tires may potentially have sorptive capacity for aromatic hydrocarbons and resulted in the reduced emissions of these compounds [Section 4.10.3].
- Based on measured variability of emissions from different sized facilities, a holistic analysis approach is recommended for gas emissions from landfills, independent of facility size [Parts 4 and 5].

5.9 Future Research

Based on findings of the current investigation, the following future research priorities are identified:

- Quantify emissions of emerging chemicals and rank these chemicals for public health and climate change effects.
- Evaluate alternative final (evapotranspirative) covers from a gas emissions perspective. Significant analysis has been conducted for barrier performance against moisture infiltration of these systems, however commensurate analyses have not been conducted for gas transport. Preliminary results herein suggest that further investigation is warranted.
- Establish efficacy of specialty geomembranes that include devoted gas barrier layer.
- Investigate emissions of compost facilities.
- Improve modeling of gas transport through cover systems including multi-phase and multi-component analyses.
- Improve biological degradation and transformation of gases emitting from landfills using bio-cover principles.
- Similar to design methods for hydraulic performance of barriers, establish quantitative design parameters for performance of cover materials as gas barriers, ensuring quality control in construction and operations.
- Establish site-specific gas emissions performance for native soils typically used for cover applications and other cover materials, similar to requirements for hydraulic barrier performance. For example, in evaluating the use of green

waste erosion control cover over an interim soil cover on a slope, the potential additional biogenic VOC emissions (attributed to the presence of green waste cover) needs to be balanced against the erosion control function. Loss of integrity and effectiveness of the intermediate soil cover occurs due to erosion.

- Establish methodology for measurement of landfill gas flux at active working face locations. Direct adoption of static flux chamber method is difficult at these locations due to safety concerns in a heavy equipment work zone, large particle sizes of waste, difficulty with driving chamber into waste surface, and developing hydraulic seal around chamber perimeter in the highly porous waste material.