CALIFORNIA
AIR RESOURCES BOARD

Research Webinar: California Landfill Gas Emissions

March 4, 2021
2:00 p.m. – 3:30 p.m. (PST)

CalRecycle Contract: DRR16109 and CARB Contract: 16ISD006

Final Report and Presentation available at:
https://ww2.arb.ca.gov/resources/documents/landfill-gas-research

Estimation and Comparison of Methane and Nitrous Oxide Emissions and Gas Collection System Efficiencies in California Landfills

Presentation of Final Report
Jim Hanson, Ph.D., PE
Nazli Yesiller, Ph.D.
Derek Manheim, Ph.D.

CARB Webinar: March 4, 2021

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Research Overview

- Detailed assessment of California landfill gas emissions
  - California landfill characterization – selection of test sites
  - 82 landfill gas (LFG) species investigated
  - Field analysis and supplementary laboratory testing
  - Emissions determined using static flux chamber and aerial methods
- Gas collection efficiency estimates
  - Aerial measurements, ground measurements, LandGEM (USEPA model)
- Results
  - Effects of gas collection system provided
  - Intra- and inter-landfill variations provided
  - Effects of cover characteristics provided
  - Effects of operational, environmental, and climatic conditions assessed

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Landfill Classification

Main Factor			Variation
Facility Size	Waste in place		Amount of waste disposed at the site
	Disposal area		Permitted waste footprint area
	Waste column height		Average depth of waste at the site
	Permitted throughput		Annual waste intake
Climate			Classification designation by Köppen Geiger System
Oil and Gas Operations			Oil and gas operation sites, proximity of the landfill to these
Fault Lines			California quaternary faults, proximity of the landfill to faults
Population Density			Urban and rural areas
Gas System			Yes, no
Tire Disposal			Yes, no
Cover Conditions		Daily	Conventional-soil type and thickness Alternative daily covers (ADCs) including green waste, construction & demolition, biosolids, tarp, spray-on products
		Intermediate	Soil type and thickness
		Final	Presence of final cover: Yes, no Type and thickness of final cover - Traditional: single covers [compacted clay (CCL), geosynthetic clay liner (GCL), geomembrane (GM)]; composite covers [GM-CCL, GM-GCL] - Alternative: monolithic or capillary break
Relative Fraction of Cover Categories			Relative areas of daily, intermediate, and final covers (% of waste footprint)
Working Face			Size of active waste disposal area
Range for Age of Waste			Age of wastes
Landfill Configuration			Canyon, area
Operational Conditions			In relation to N_2O emissions, leachate recirculation, biosolids

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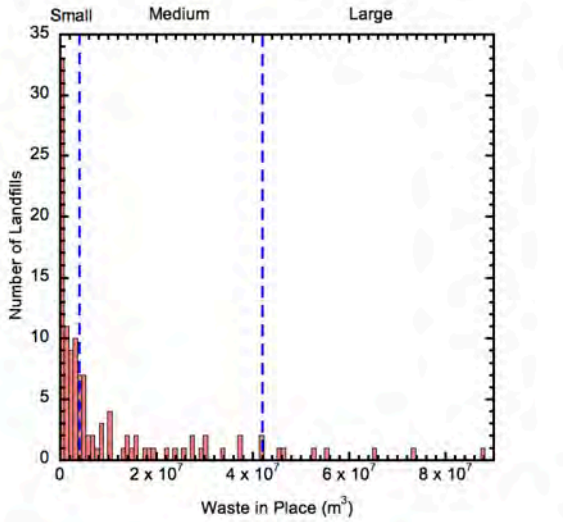
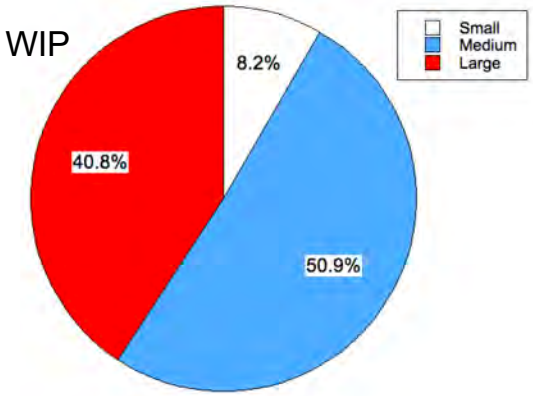
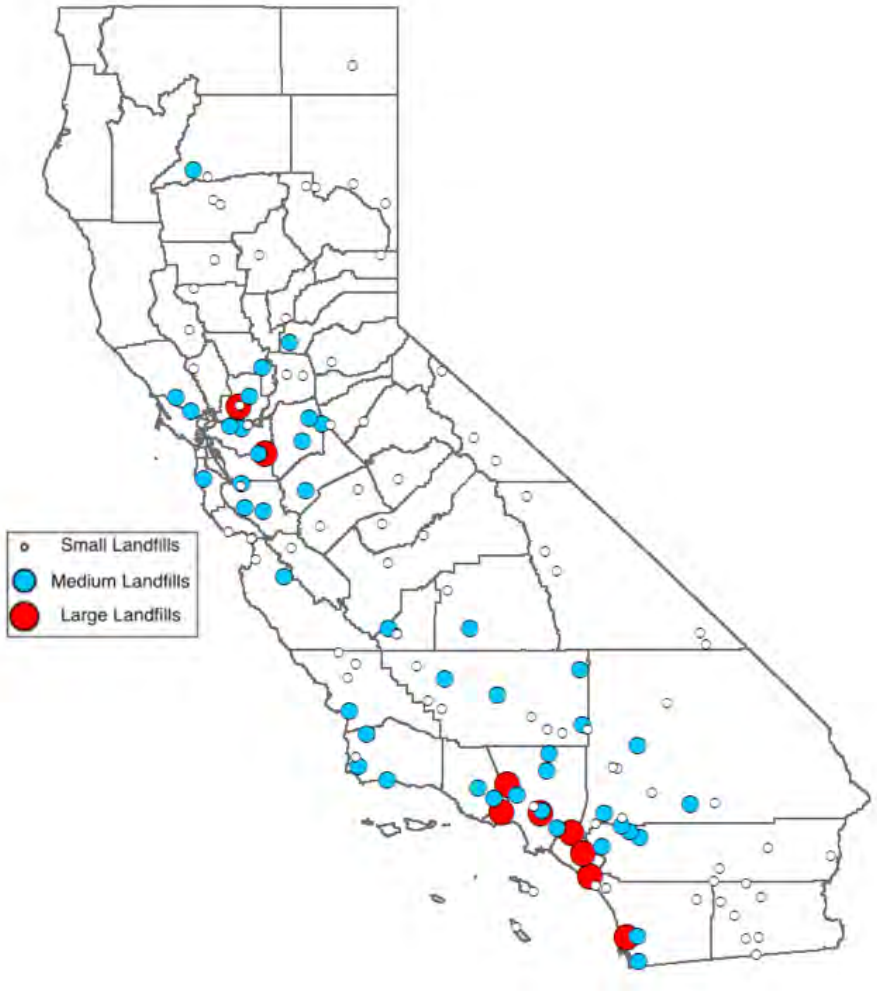
Landfill Size







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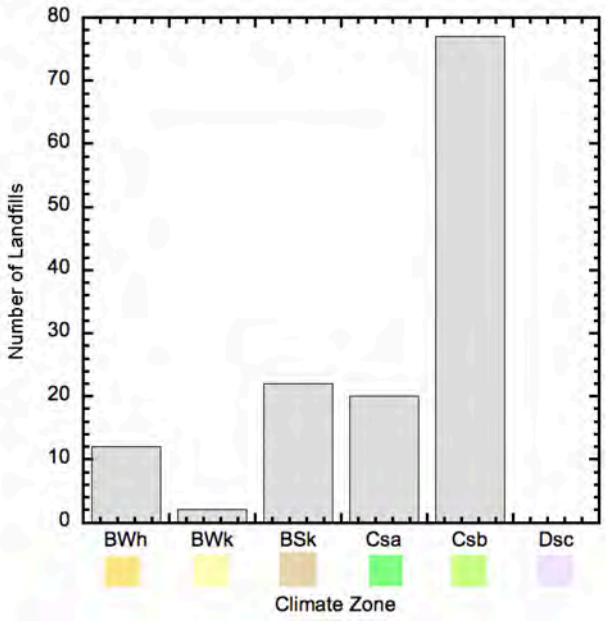
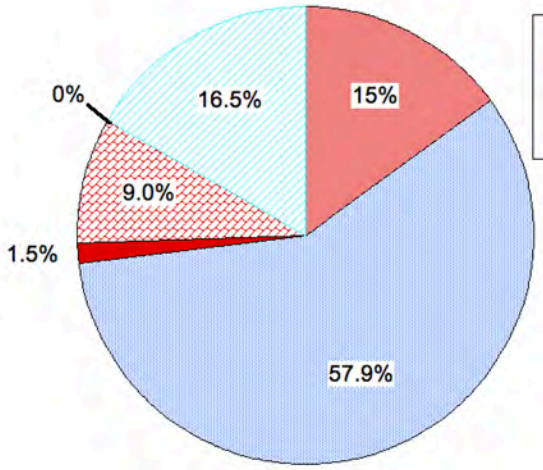
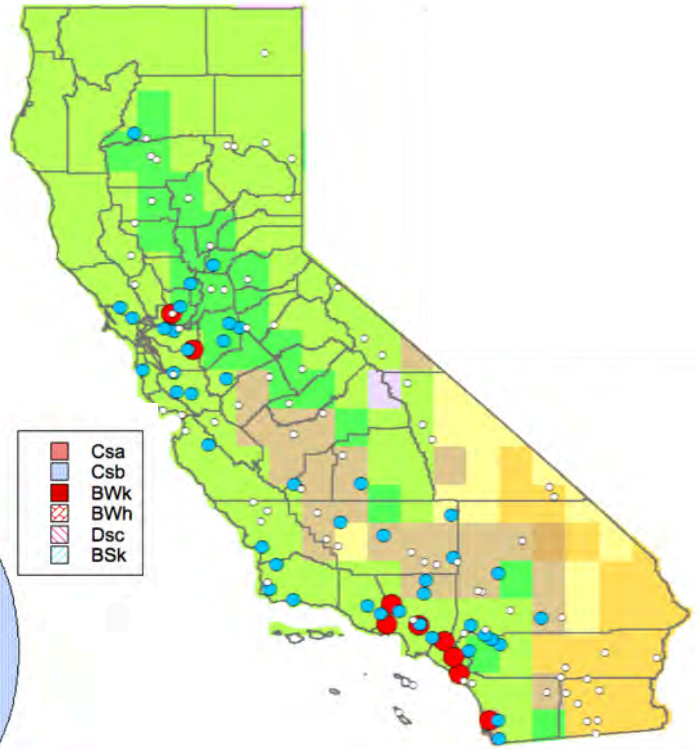
Landfill Climate



BWh: arid, desert, hot
BWk: arid, desert, cold
BSk: arid, steppe, cold
Csa: temperate, dry summer, hot summer
Csb: temperate, dry summer, warm summer
Dsc: cold, dry summer, cold summer





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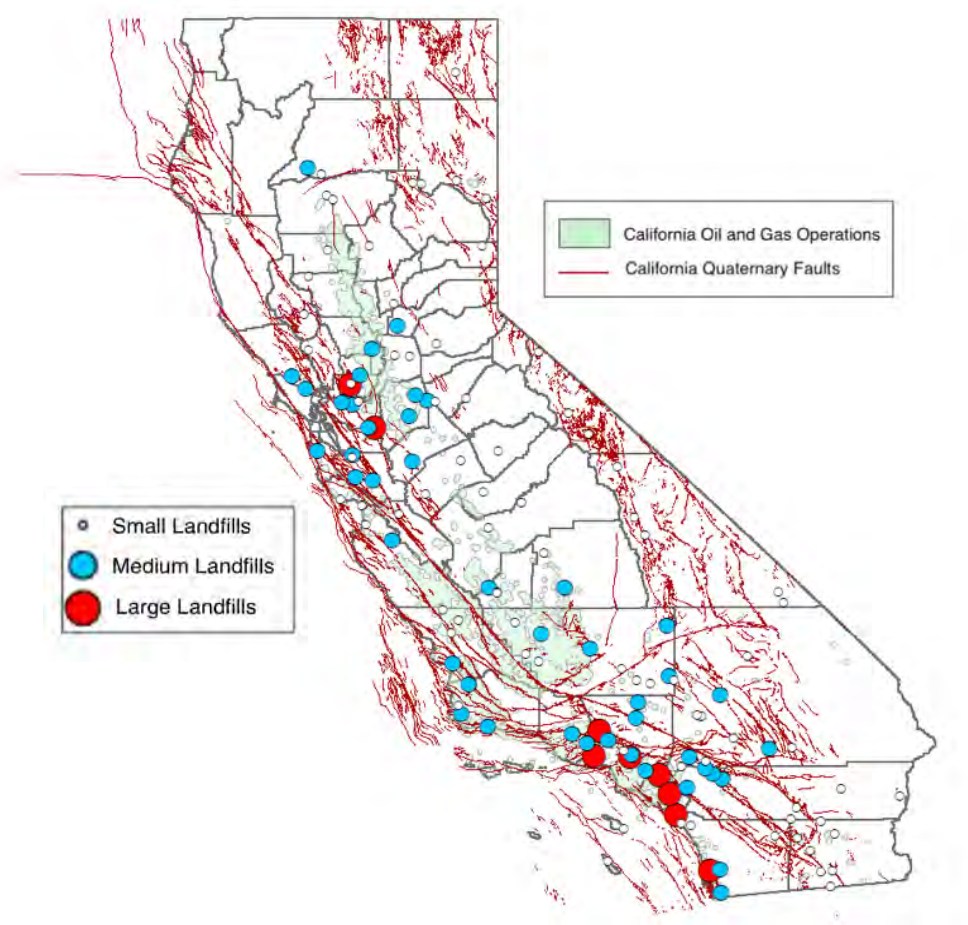
Landfill Location – Oil and Gas, Fault Lines



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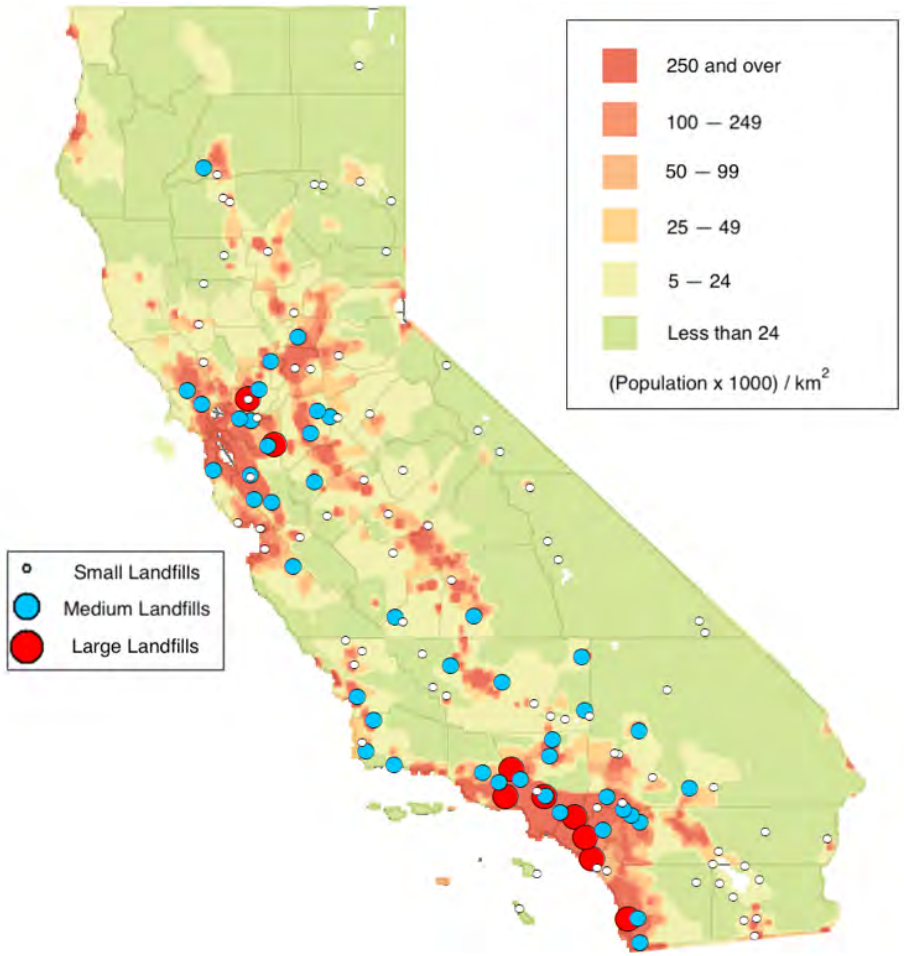
Landfill Location – Population Density



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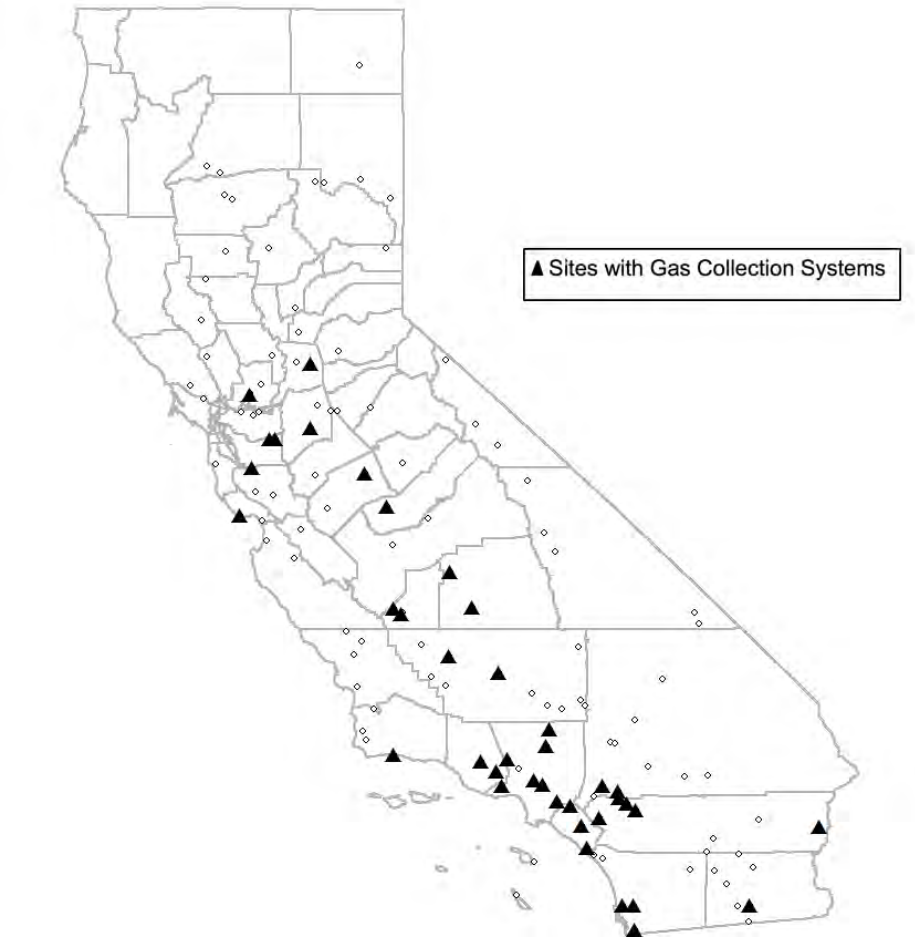
Landfill Operations –Gas Collection System



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Landfill Operations –Tire Disposal

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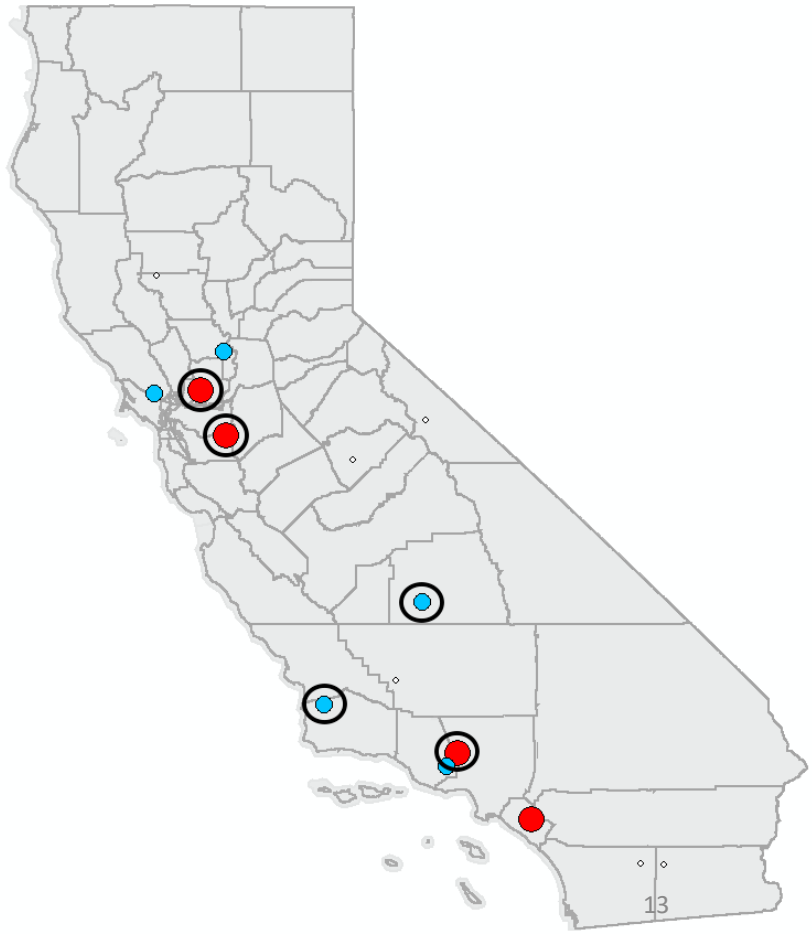
Landfills Selected for Research

No.	Landfill Name	Size	WIP* (m^3)	Permitted Throughput (tons/day)	Climate Zone	Gas Collection System	Tires	Active Face (m^2)	Cover Fraction[a] (%)		
									D	I	F
1	Stonyford Disposal Site	S	71,513	10	Csb	No	Yes	65	1.7	96.5	1.8
2	Salton City Solid Waste Site	S	152,082	6,000	BWh	No	No	NR	NR	NR	NR
3	Borrego Landfill	S	278,752	50	Bsk	No	Yes	NR	NR	NR	NR
4	Pumice Valley Landfill	S	292,496	110	Csb	No	No	1200	NA	25	0
5	Mariposa County Sanitary Landfill	S	594,757	100	Csa	No	Yes	200	20	80	0
6	Taft Recycling and Sanitary Landfill	S	2,767,148	800	BWk	No	Yes	NR	NR	NR	NR
7	**Teapot Dome Disposal Site**	M	5,369,126	800	BSk	Yes	No	1200	15.5	84.5	0
8	**Santa Maria Regional Landfill**	M	8,385,395	858	Csb	Yes	Yes	700	0.1	69.3	30.6
9	Redwood Landfill	M	17,643,577	2,300	Csb	Yes	Yes	2000	0.2	99.8	0
10	Simi Valley Landfill and Recycling Center	M	27,697,889	9,250	Csb	Yes	No	12100	0.7	99.3	0
11	Yolo County Central Landfill	M	37,490,107	1,800	Csa	Yes	Yes	11800	1.4	57.9	40.7
12	**Chiquita Canyon Sanitary Landfill**	L	42,266,798	6,000	Csb	Yes	No	5600	8.3	63.8	27.8
13	**Site A**	L	45,108,745	11,150	Csb	Yes	Yes	6100	0.6	89.5	9.9
14	Frank R. Bowerman Sanitary Landfill	L	46,637,855	11,500	Csb	Yes	No	NR	NR	NR	NR
15	**Potrero Hills Landfill**	L	52,928,614	4,330	Csa	Yes	Yes	3000	3	91	6

*Sites listed in order of WIP; Data from SWIS database (2017)
NR – Not Reported
[a]D = daily, I = Intermediate, F = Final



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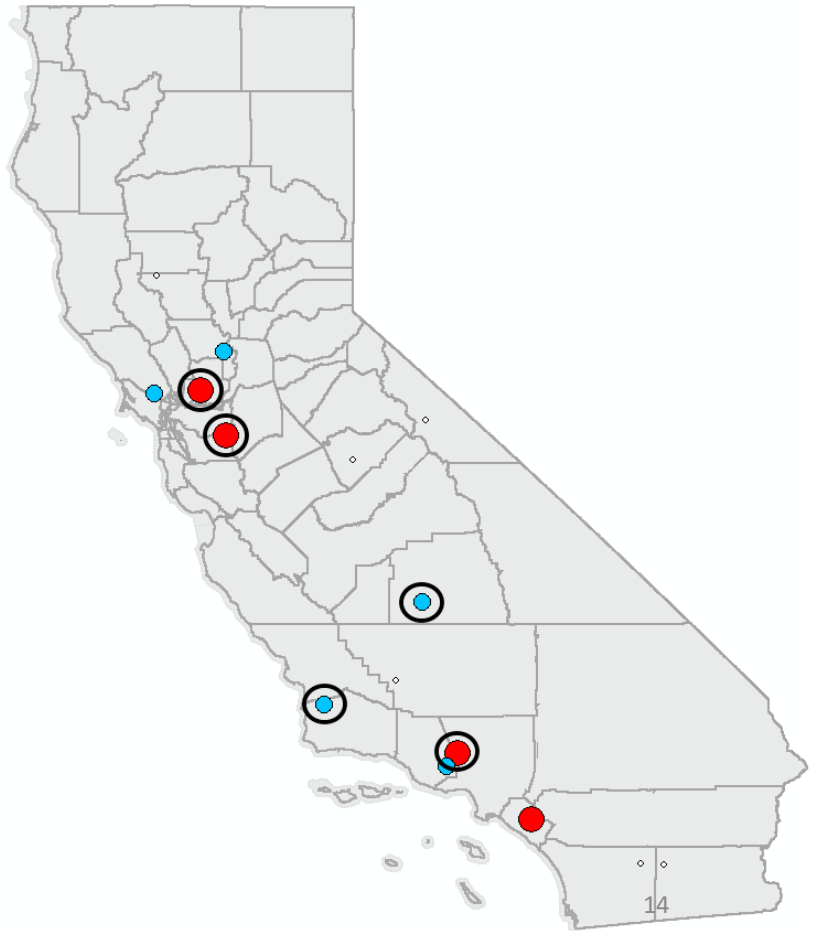

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Field Investigation

- Aerial Tests
  - Emissions estimates were obtained
  - Whole site emissions
  - Data for methane emissions
  - 16 landfills tested (30% of waste-in-place in California)
  - Cavity ring down spectroscopy used
- Ground Tests
  - Flux was measured
  - Flux data by cover type
  - Flux converted to emissions using relative areal extent of different cover types
  - Data for all 82 gases obtained
  - 5 landfills tested (13% of waste-in-place in California)
  - Large scale flux chambers: (1 m x 1 m x 0.4 m)
  - Measurements and sample collection for geotechnical properties
- Tests conducted in wet and dry seasons

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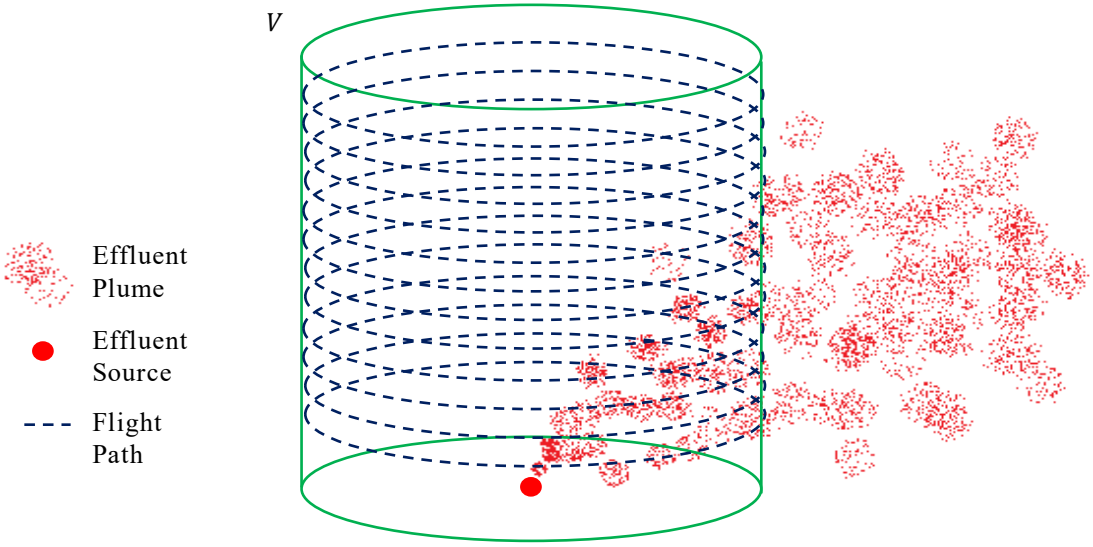
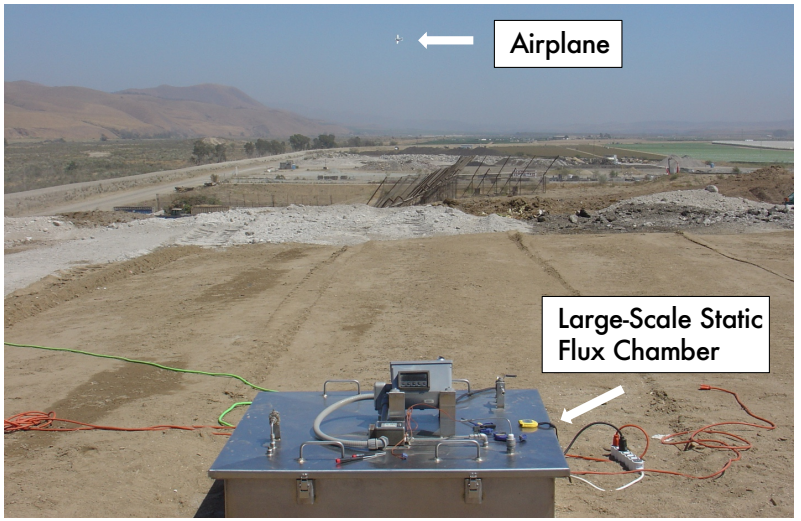
Field Investigation – Aerial Measurements

- Mass balance method
- Single engine plane equipped with Picarro G2401-m Analyzer





$$Q_c = \langle \frac{\partial m}{\partial t} \rangle + \iiint \nabla \cdot \boldsymbol{F}_c dV = \left\langle \frac{\partial m}{\partial t} \right\rangle + \oint \boldsymbol{F}_c \cdot \hat{\boldsymbol{n}}\, dS$$

Q_c: emission rate
F_c: flux
M: mass
V: volume

Field Investigation – Ground Measurements

Installation of flux chamber

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Field Investigation – Ground Measurements

Dual chambers installed at each measurement location

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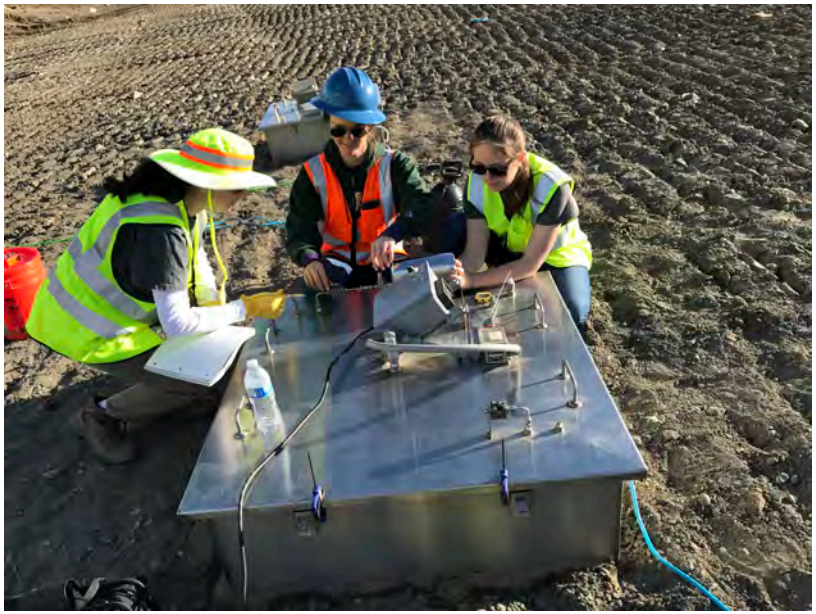
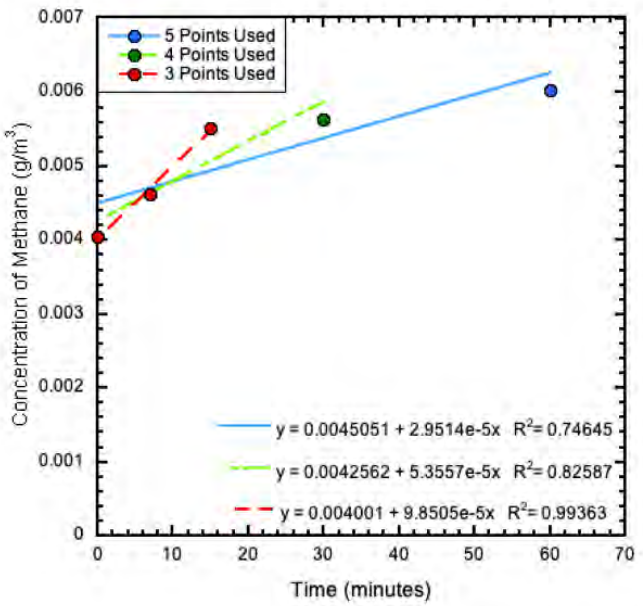
Field Investigation – Ground Measurements

Flux determined using concentration measurements over time





$$F = \frac{dC}{dt} * \frac{V}{A}$$

F: surface flux
dC/dt: concentration gradient (the rate of change of concentration over time within the flux chamber)
V: volume within the static flux chamber
A: area of the landfill surface enclosed by the chamber

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Field Investigation – Additional Tests

Drilling for temperature sensor installation, temperature measurement, cover thickness measurement, raw gas concentration measurement

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Field Investigation – Additional Tests

Cover temperature measurement, sand cone test

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Field Investigation – Additional Tests

Cover thickness determination

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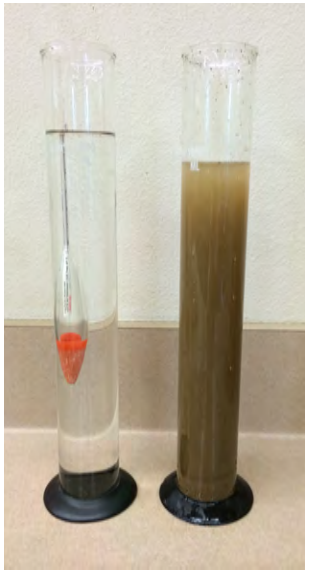
Laboratory Geotechnical Characterization

Sieve, hydrometer, Atterberg limits, cover materials



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Field Investigation – Ground Measurements

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Landfill Cover Characteristics

- 3 common cover categories in active landfills
  - **Daily** – soil, alternative daily covers (green waste, contaminated soil, auto fluff, construction and demolition waste); regulatory requirement: 6 in. compacted earthen material, 11 other materials, approved other
  - **Intermediate** – soil, soil+green waste; regulatory requirement: 12 in. compacted earthen material (no waste > 180 days), approved alternative material
  - **Final** – conventional (compacted earthen material), alternative (monolithic); regulatory requirement: 2-feet foundation layer, 1-foot impermeable layer at 1 x 10^{-6} cm/sec (cannot be more permeable than bottom liner), 1-foot vegetation layer, approved alternative material
- A total of 31 distinct cover types tested

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Ground Measurements – Example

Chiquita Canyon Landfill

Cover Type	Cover Type Description	Thickness (cm)
DC-Cl	Daily Cover - Clean Soil	34
DC-Co	Daily Cover - Contaminated Soil	50
IC-S	Interim Cover - Soil	30
IC-W	Interim Cover - Winter (Placement of Waste)	40
IC-OGW	Interim Cover - Old Green Waste	65
IC-NGW	Interim Cover - New Green Waste	98
FC	Final Cover	150

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Ground Measurements – Overview

Landfill Name	Landfill Location	Waste in Place[a] (m^3)	Waste in Place[b] (m^3)	Landfill Climate Zone	Annual Ppt. (mm)[c]	Avg. Daily Temp (°C)[c]	Test Locations per Season
Santa Maria Regional Landfill	Santa Maria	1,360,577	8,385,395	Csb	462	14.9	5
Teapot Dome Disposal Site	Porterville	3,038,622	5,369,126	Bsk	278	17.4	5
Potrero Hills Landfill	Suisun City	26,454,935	52,928,614	Csa	462	18.2	7
Site A	Livermore	44,173,397	45,108,745	Csb	387	15.8	6
Chiquita Canyon Landfill	Castaic	55,227,178	42,266,798	Csb	630	16.1	7

[a]WIP values reported by sites
[b]WIP values obtained from SWIS (2017)
[c]NOAA 30-year average for 1981-2010

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Landfill Gas Constituents Analyzed

- Baseline GHGs
  - 4 gases: Methane, carbon dioxide, nitrous oxide, and carbon monoxide
  - Methane and carbon dioxide: main LFG constituents
- Non Methane Volatile Organic Compounds
  - 78 NMVOCs: Under 11 chemical families
    - Reduced Sulfur Compounds
    - F-Gases
    - Halogenated Hydrocarbons
    - Organic Alkyl Nitrates
    - Alkanes
    - Alkenes
    - Aldehydes/Alkenes
    - Aromatic Hydrocarbons
    - Monoterpenes
    - Alcohols
    - Ketones

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Landfill Gas Constituents – Characteristics

Chemical Family	Acronym	Potential Source(s)	Example Species	Environmental Impact
Reduced Sulfur Compounds	RSC	Food/Green Waste, C&D Waste, Waste Tires	Carbonyl sulfide, Carbon disulfide	Olfactory nuisances
F-Gases	F-gas	Insulation foams (appliance and C&D wastes), refrigerants, aerosol sprays, fire suppression materials	CFC-11, HCFC-141b, HFC-245fa, H-1211	Direct/Indirect Climate Forcings
Halogenated Hydrocarbons	HH	Textiles, Household Cleaners, Plastics	Chloroform, Trichloroethylene, 1,2-DCE	Hazardous Air Pollutants, Ozone Depleting Substances, Direct/Indirect Climate Forcings
Organic (Alkyl) Nitrates	ON	Oxidation Byproduct	Methyl nitrate, Isopropyl nitrate	Tropospheric Ozone Formation Potentials, Secondary Organic Aerosol Formation Potentials
Alkanes	Alk	Household Cleaners, Plastics, Cooking Waste, Paper Waste	Propane, n-Undecane	Tropospheric Ozone Formation Potentials, Direct/Indirect Climate Forcings
Alkenes	Alke		1-Butene, Isoprene	
Aldehydes/ Alkynes	Ald	Food Waste, Household Cleaners, Cooking Waste, Personal Care Products, Household Sprays, Plastics, Papers, Textiles, Furniture	Acetaldehyde, Butanal	
Aromatic Hydrocarbons	Ar		Benzene, Toluene, Ethylbenzene, Xylenes, Ethyltoluenes	Hazardous Air Pollutants, Tropospheric Ozone Formation Potentials, Secondary Organic Aerosol Formation Potentials
Monoterpenes	Mon	Green Waste, C&D Waste, Household Cleaners and Sprays, Personal Care Products	α-Pinene, β-pinene, Limonene	Tropospheric Ozone Formation Potentials, Secondary Organic Aerosol Formation Potentials
Alcohols	Alc	Food Waste, Household Cleaners, Personal Care Products, Household Sprays	Methanol, 2-Butanol	Tropospheric Ozone Formation Potentials, Direct/Indirect Climate Forcings
Ketones	Ket		Acetone, Butanone	

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Landfill Gas Constituents – Sources

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

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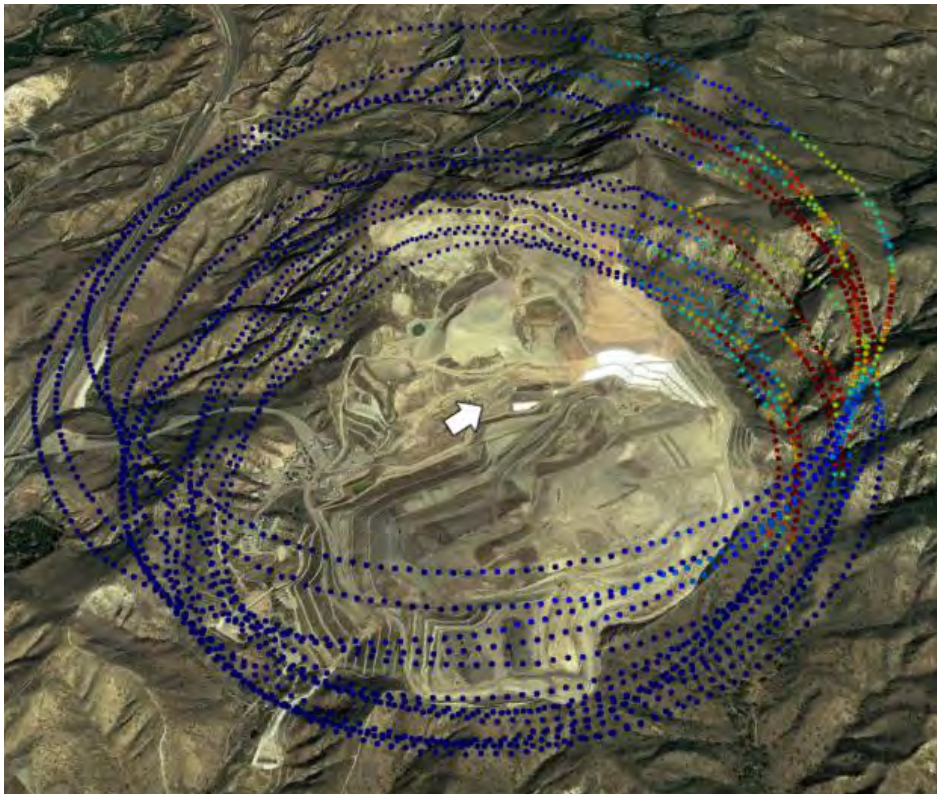
Results: Aerial Tests

Flight data, colors proportional to emissions



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Results: Aerial Tests

Site	Date	CH_4 Emission (kg/hr)	UC[1] (kg/hr)	Laps	Wind Direction	Wind Speed (m/s)	Lowest Altitude (m)	Highest Altitude (m)
Stonyford Disposal Site	11/17/17	0.6	0.7	11	354	4.4	62	334
Stonyford Disposal Site	12/6/17	6.1	1.4	20	359	9.6	61	620
Salton City LF	12/4/17	10.8	3	12	5	9.6	46	305
Borrego LF	12/4/17	4.1	1.2	17	109	2.1	48	458
Pumice Valley Landfill	12/6/17	-0.2	1.7	16	18	2	37	620
Mariposa County LF	10/18/17	9	14.7	10	239	2.3	171	495
Taft Recycling Center	10/18/17	-24.6	32.8	4	9	1.6	144	543
Teapot Dome LF	10/18/17	293.7	99.9	10	250	1.1	112	435
Teapot Dome LF	1/11/20	283.8	131.5	14	278	2.3	117	424
Santa Maria Regional LF	11/10/17	90.1	39.1	14	289	10.4	105	491
Santa Maria Reginal LF	7/24/18	312	77.1	17	288	4	61	374
Redwood Landfill	11/17/17	139.8	41.5	8	12	4.8	64	208
Simi Valley LF	12/4/17	637.7	337.2	8	39	16.2	264	518
Yolo County Central Landfill	11/17/17	375.6	68.4	11	344	7.4	61	306
Chiquita Canyon LF	11/10/17	1306.4	207.2	15	236	4.9	167	475
Chiquita Canyon LF	4/19/18	601.9	79.4	27	236	5	81	589
Chiquita Canyon LF	7/24/18	733.8	128.4	17	234	6.8	166	617
Sunshine Canyon LF	4/19/18	718.5	155.4	28	194	3.5	81	871
Sunshine Canyon LF	7/24/18	712	113.6	16	177	4.9	108	512
Site A	12/7/17	1357.6	547	11	77	3.4	122	409
Site A	8/27/18	2076.7	239.7	26	233	3.9	111	843
Frank R Bowerman LF	11/10/17	3275.4	668.5	15	234	1.7	80	876
Potrero Hills LF	12/7/17	2004.2	416.6	12	40	8.6	59	364
Potrero Hills LF	8/23/18	1717.9	251.6	14	245	8.7	81	459

CalRecycle Contract: DRR16109 and CARB Contract: 16ISD006
Final Report and Presentation available at: *https://ww2.arb.ca.gov/resources/documents/landfill-gas-research*

Results: Aerial Tests

Site	Date	CH_4 Emission (kg/hr)	UC[1] (kg/hr)	Laps	Wind Direction	Wind Speed (m/s)	Lowest Altitude (m)	Highest Altitude (m)
Stonyford Disposal Site	11/17/17	0.6*	0.7	11	354	4.4	62	334
Stonyford Disposal Site	12/6/17	6.1*	1.4	20	359	9.6	61	620
Salton City LF	12/4/17	10.8*	3	12	5	9.6	46	305
Borrego LF	12/4/17	4.1*	1.2	17	109	2.1	48	458
Pumice Valley Landfill	12/6/17	-0.2*	1.7	16	18	2	37	620
Mariposa County LF	10/18/17	9*	14.7	10	239	2.3	171	495
Taft Recycling Center	10/18/17	-24.6*	32.8	4	9	1.6	144	543
Teapot Dome LF	10/18/17	293.7	99.9	10	250	1.1	112	435
Teapot Dome LF	1/11/20	283.8	131.5	14	278	2.3	117	424
Santa Maria Regional LF	11/10/17	90.1	39.1	14	289	10.4	105	491
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*BDL - below detection limit

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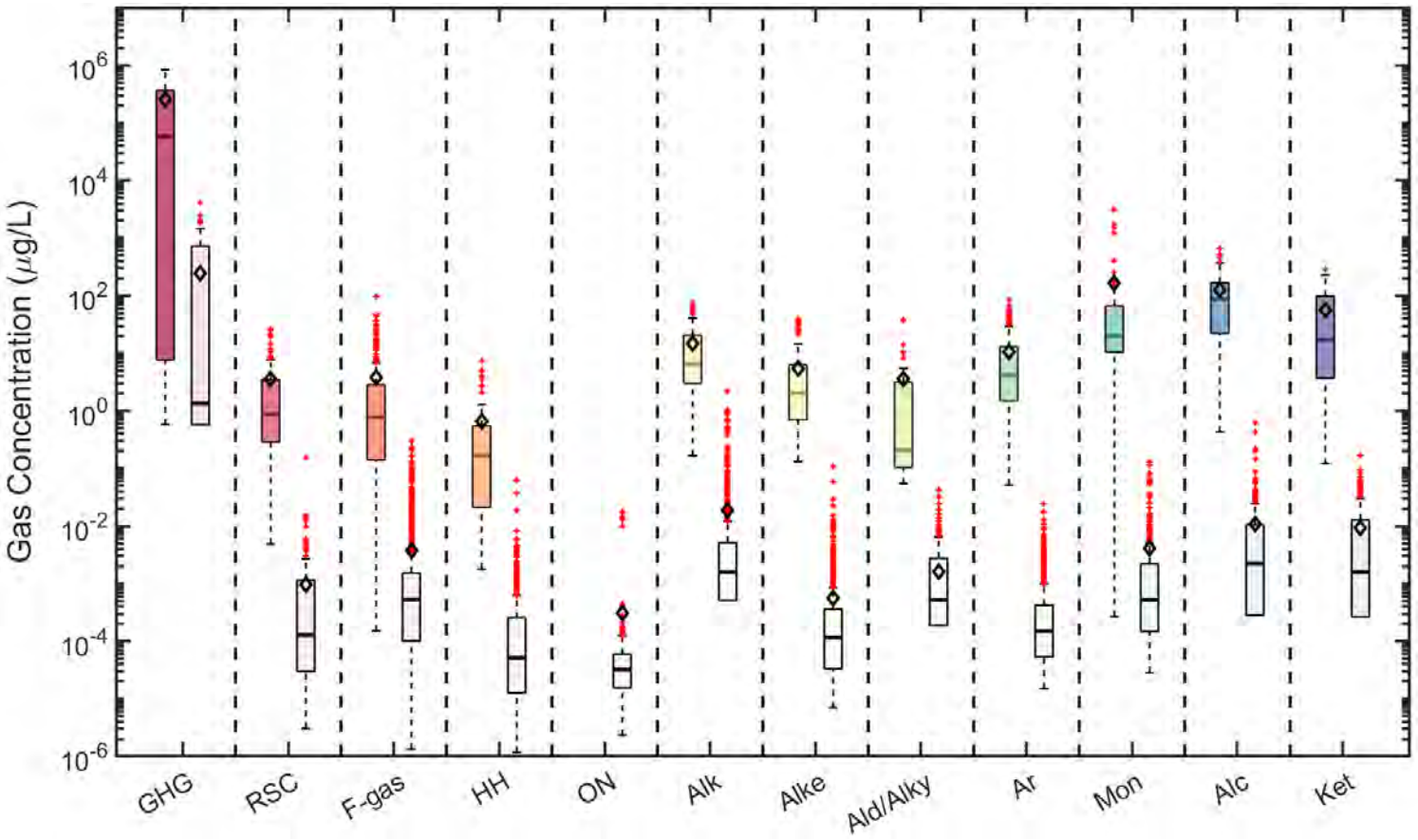
Ground – LFG and Ambient Gas Concentrations



Dark: LFG

Light: Ambient

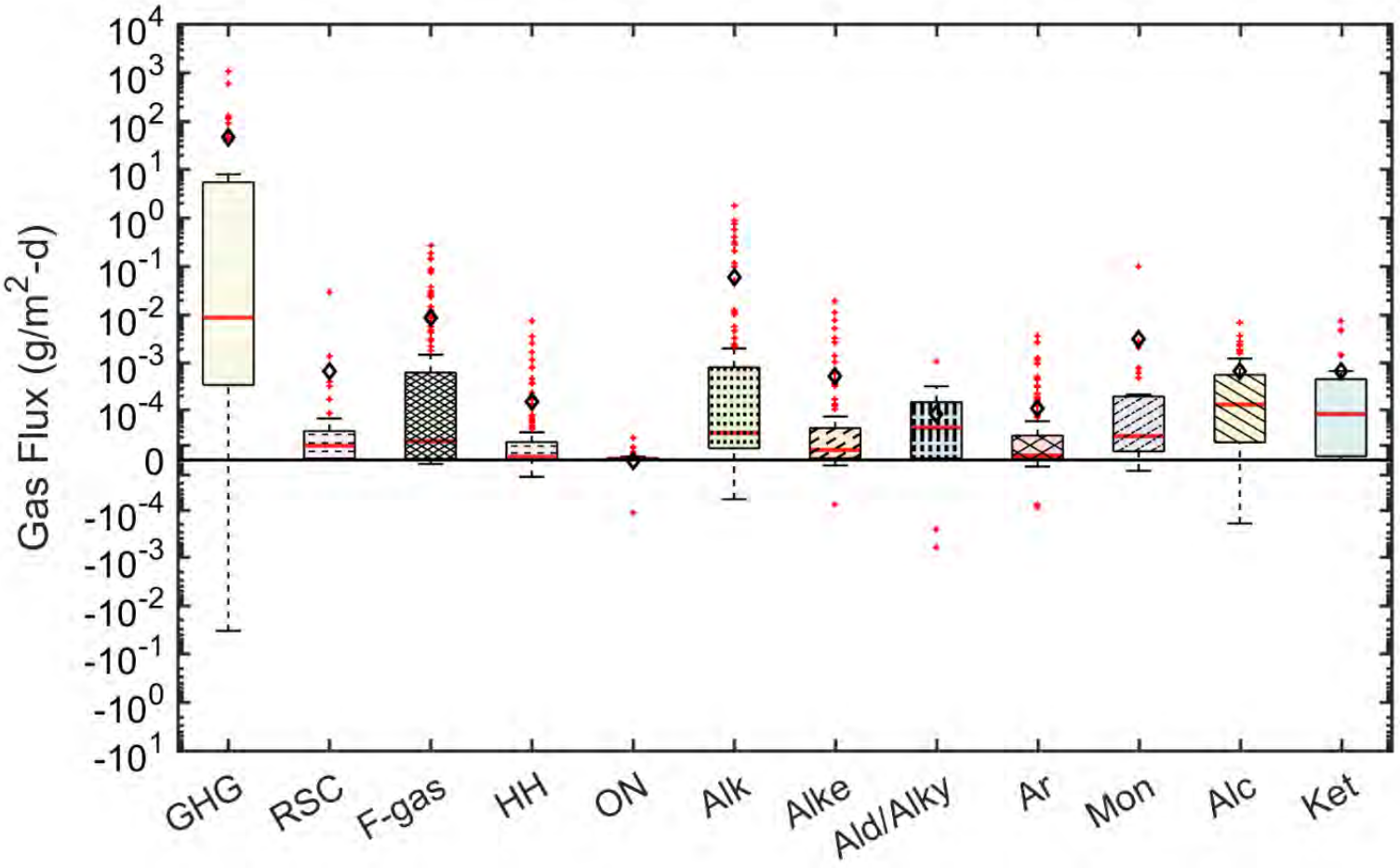
CalRecycle Contract: DRR16109 and CARB Contract: 16ISD006
Final Report and Presentation available at: *https://ww2.arb.ca.gov/resources/documents/landfill-gas-research*

Results – Ground Tests

- 4 types of flux data: positive, negative, low regression, BDL
- Positive flux measured for all 82 gases
- Methane Flux
  - Overall: -3.7×10^{0} to 9.6×10^{1} g/m^2-day
  - Positive: 3.0×10^{-4} to 9.6×10^{1} g/m^2-day
  - By landfill: Min 10^{-4} to 10^{-2}; Max 10^{1} g/m^2-day
- Nitrous Oxide Flux
  - -4.1×10^{-3} to 1.5×10^{-1} g/m^2-day
- NMVOC Flux
  - -1.9×10^{-3} to 1.8×10^{0} g/m^2-day

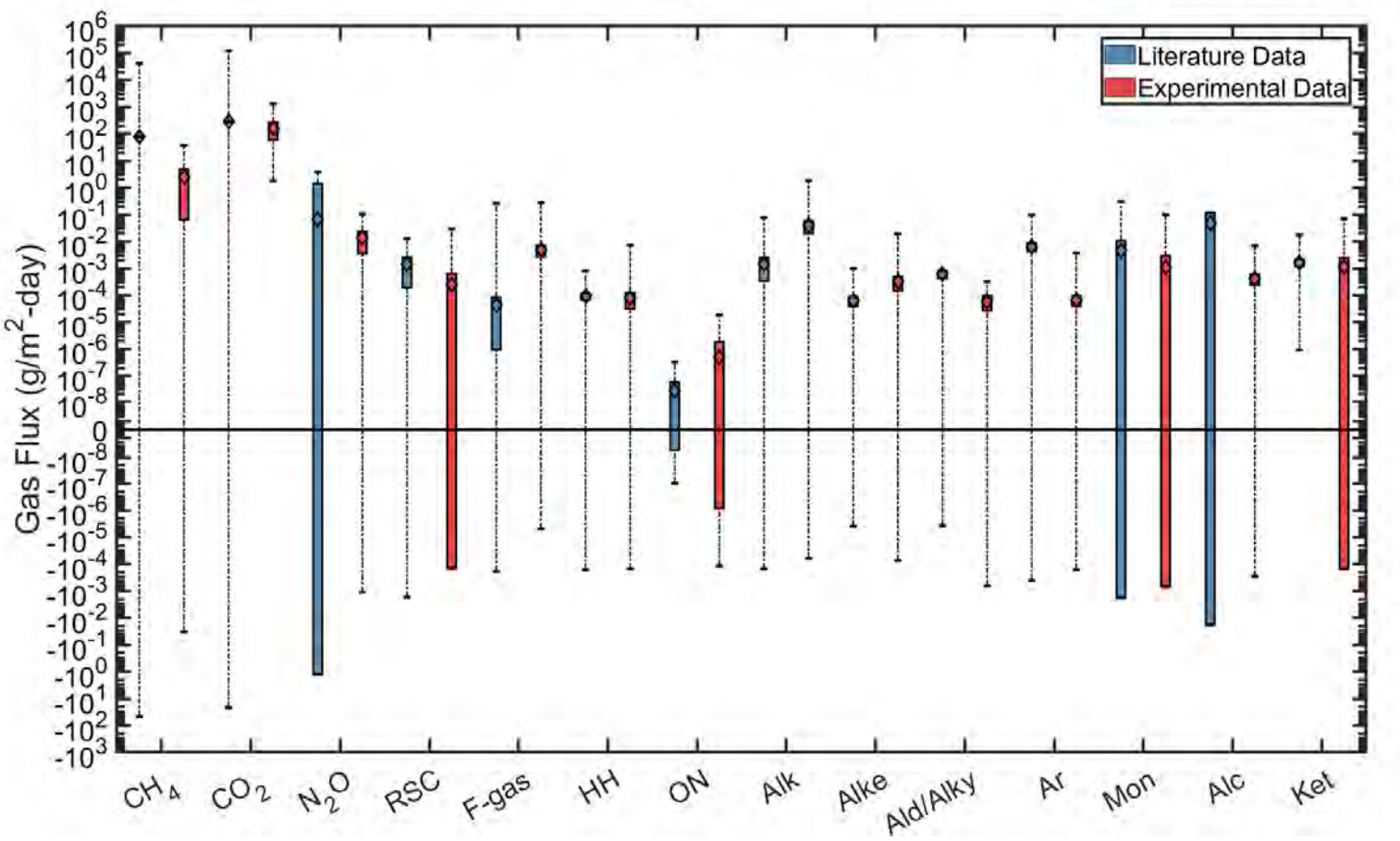
CalRecycle Contract: DRR16109 and CARB Contract: 16ISD006
Final Report and Presentation available at: *https://ww2.arb.ca.gov/resources/documents/landfill-gas-research*

Overall Flux Data



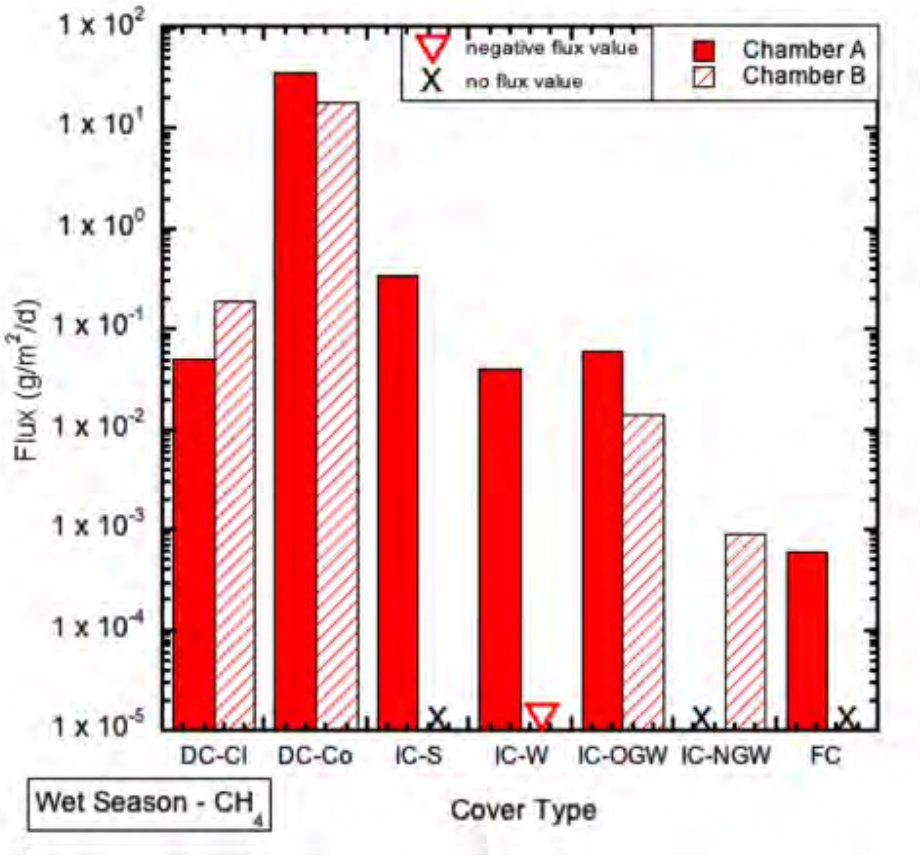
CalRecycle Contract: DRR16109 and CARB Contract: 16ISD006
Final Report and Presentation available at: *https://ww2.arb.ca.gov/resources/documents/landfill-gas-research*

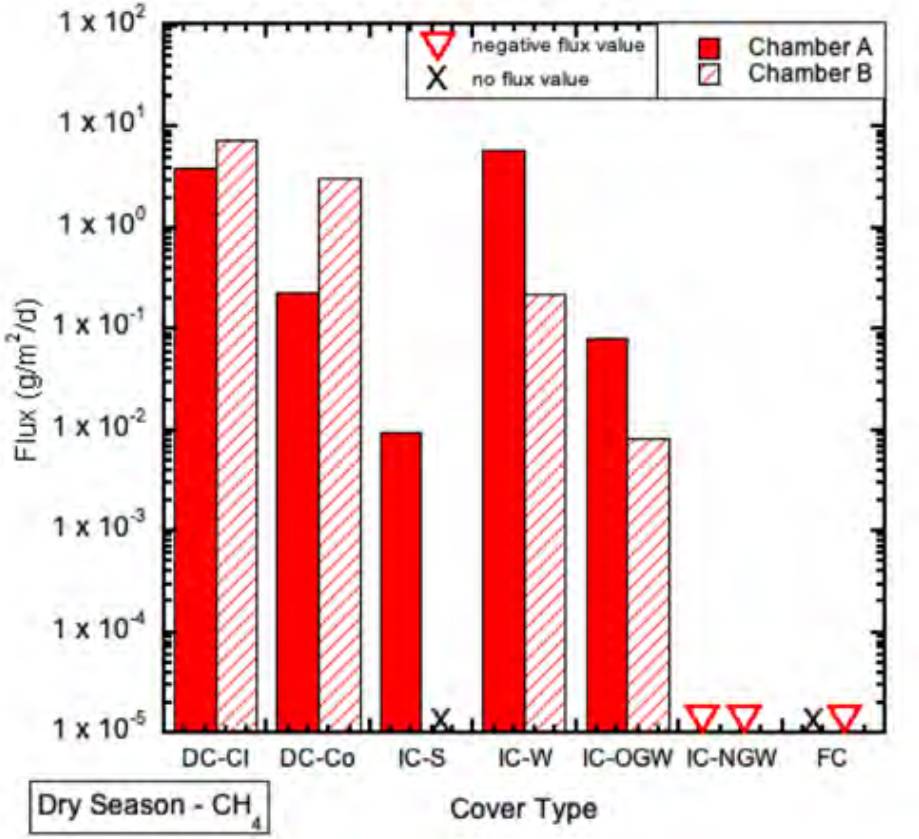
Flux Data – Literature and Current Investigation



CalRecycle Contract: DRR16109 and CARB Contract: 16ISD006
Final Report and Presentation available at: *https://ww2.arb.ca.gov/resources/documents/landfill-gas-research*

Flux Data – Intra Landfill





CalRecycle Contract: DRR16109 and CARB Contract: 16ISD006
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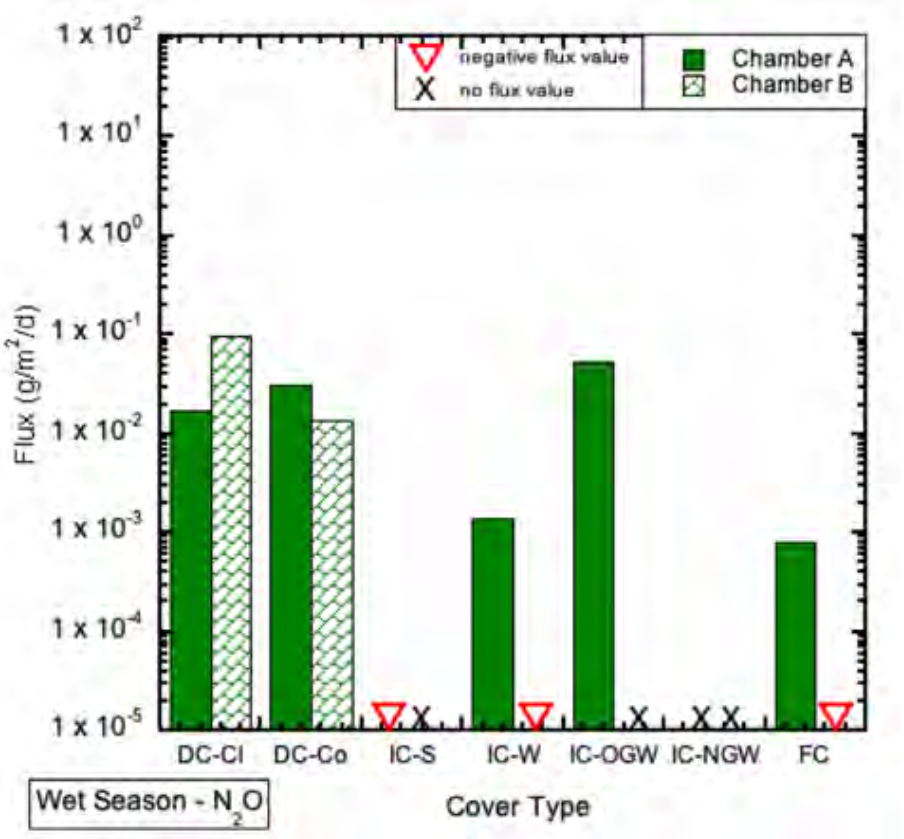
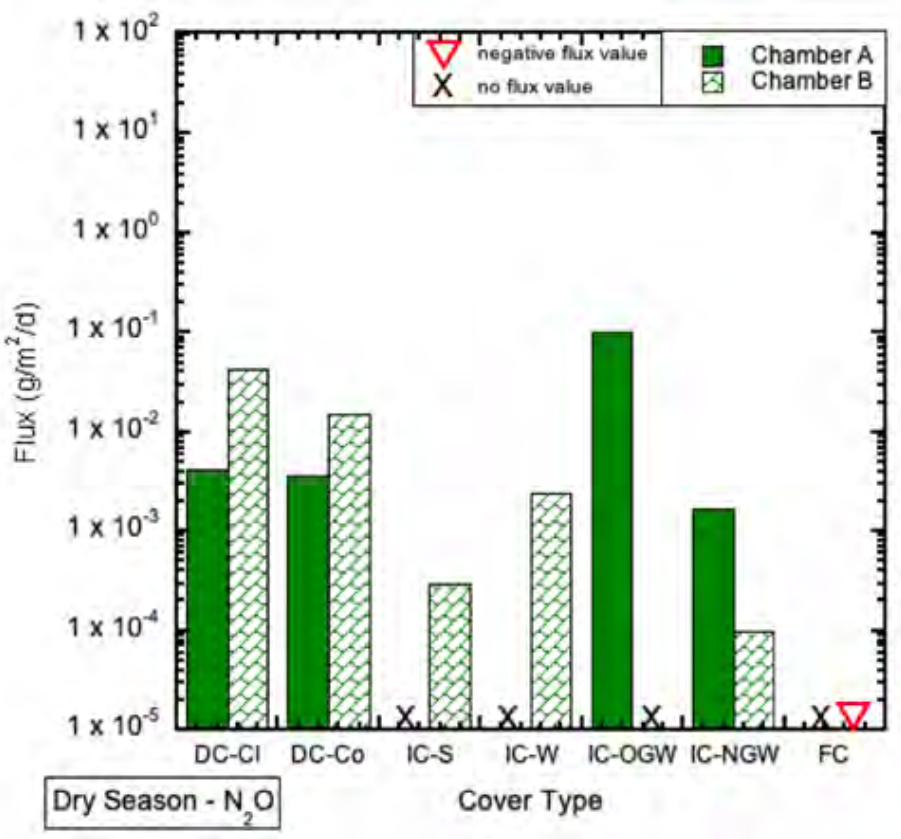
Flux Data – Intra Landfill





CalRecycle Contract: DRR16109 and CARB Contract: 16ISD006
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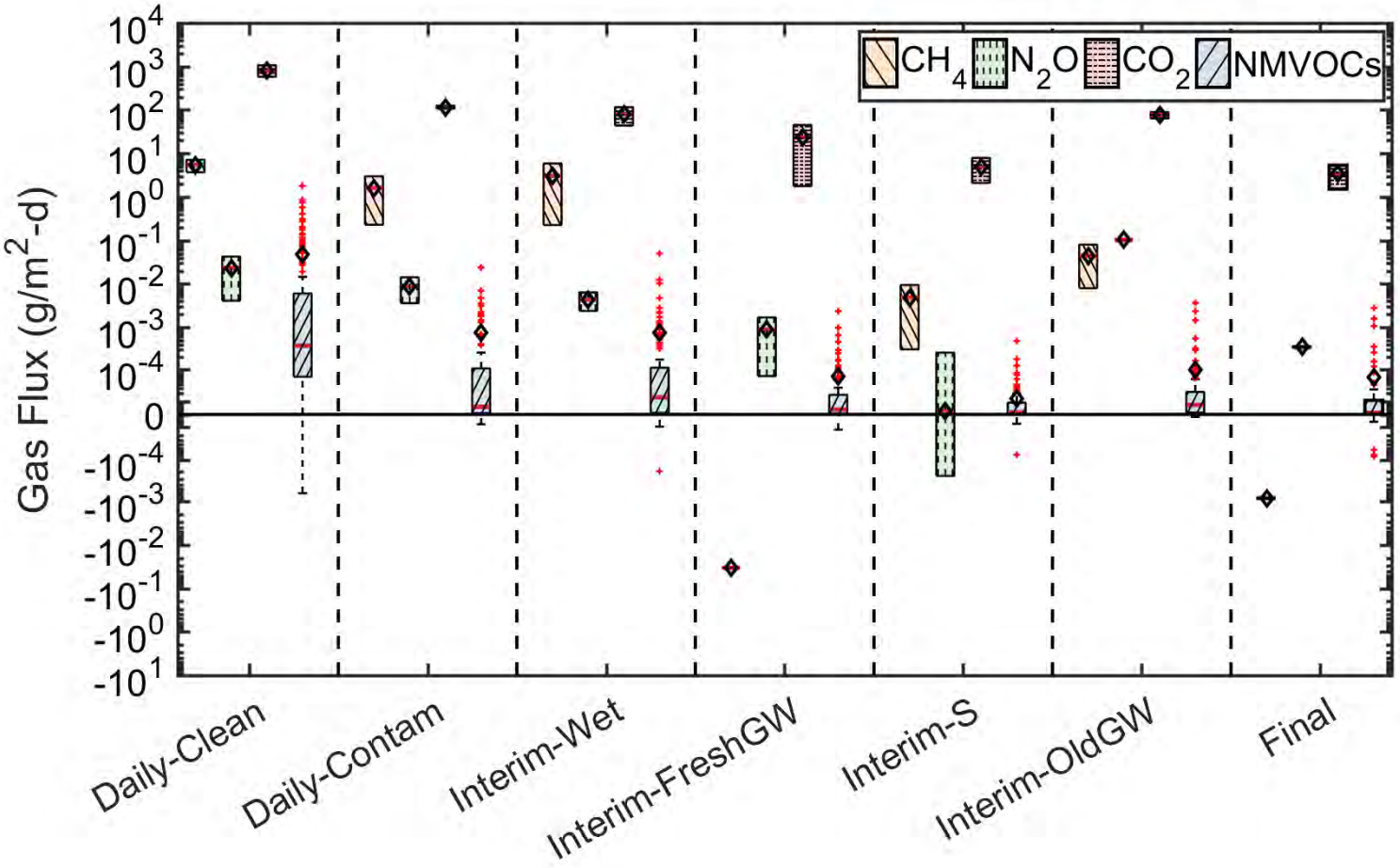
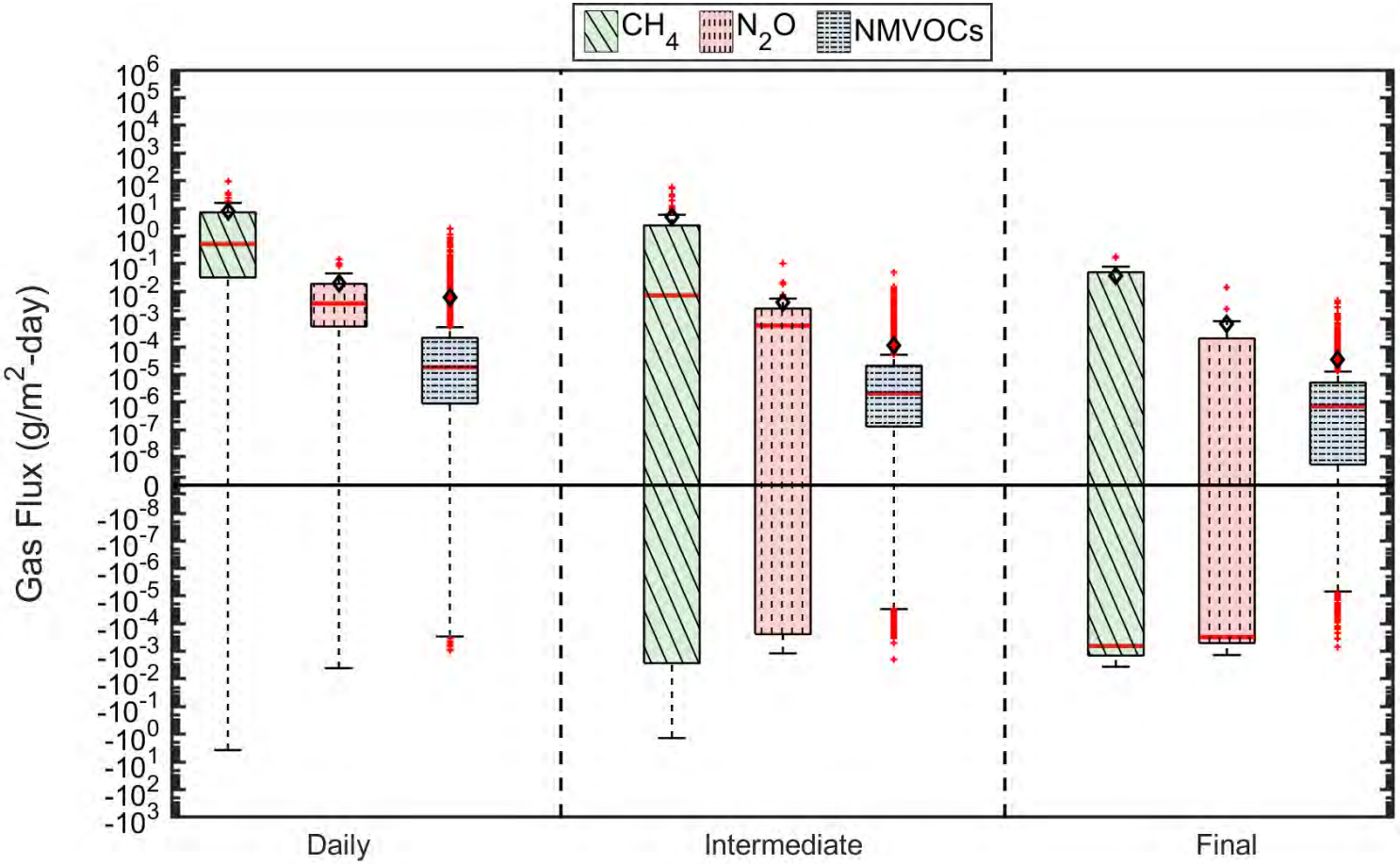
Flux Data – Intra Landfill



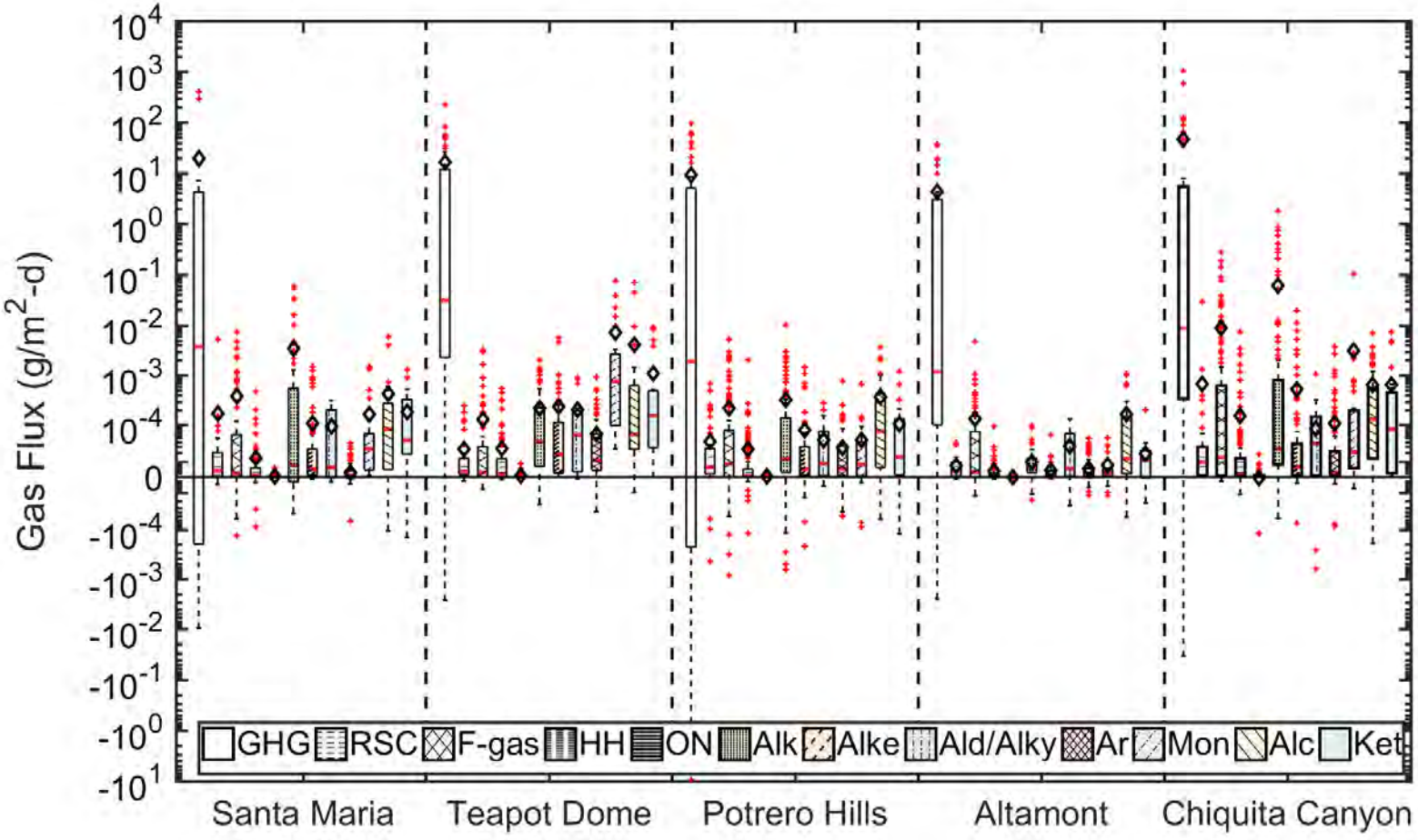
CalRecycle Contract: DRR16109 and CARB Contract: 16ISD006
Final Report and Presentation available at: *https://ww2.arb.ca.gov/resources/documents/landfill-gas-research*

Flux Data – Cover Type



CalRecycle Contract: DRR16109 and CARB Contract: 16ISD006
Final Report and Presentation available at: *https://ww2.arb.ca.gov/resources/documents/landfill-gas-research*

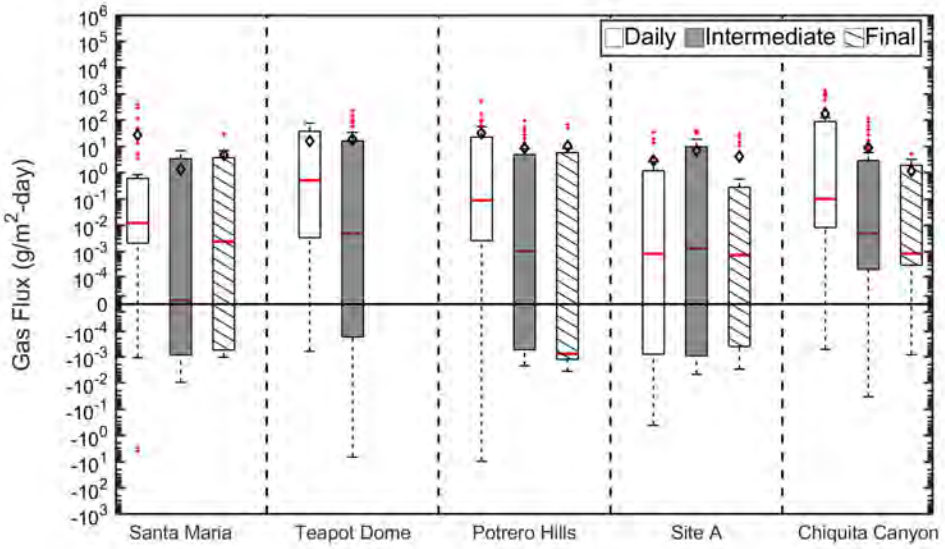
Flux Data – Inter Landfill



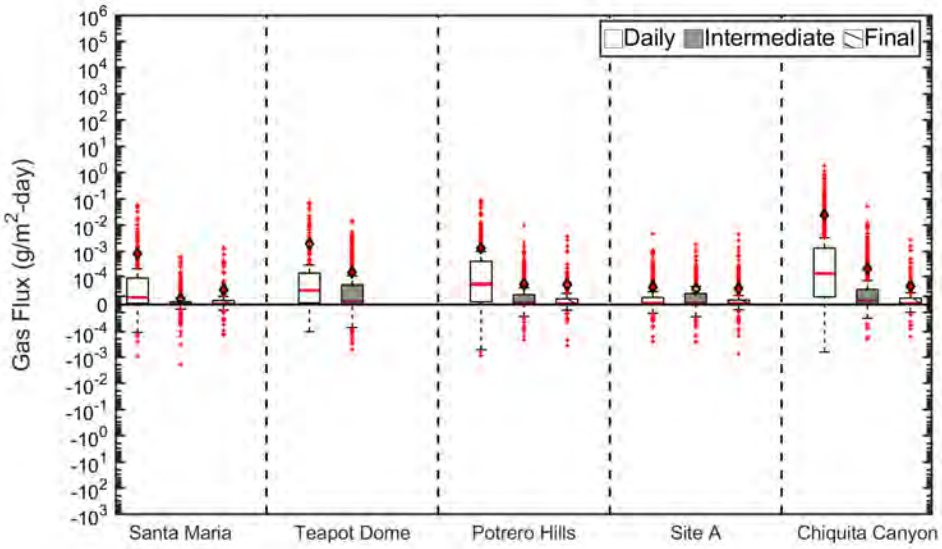
CalRecycle Contract: DRR16109 and CARB Contract: 16ISD006
Final Report and Presentation available at: *https://ww2.arb.ca.gov/resources/documents/landfill-gas-research*

Flux Data – Inter Landfill by Cover Type

GHGs



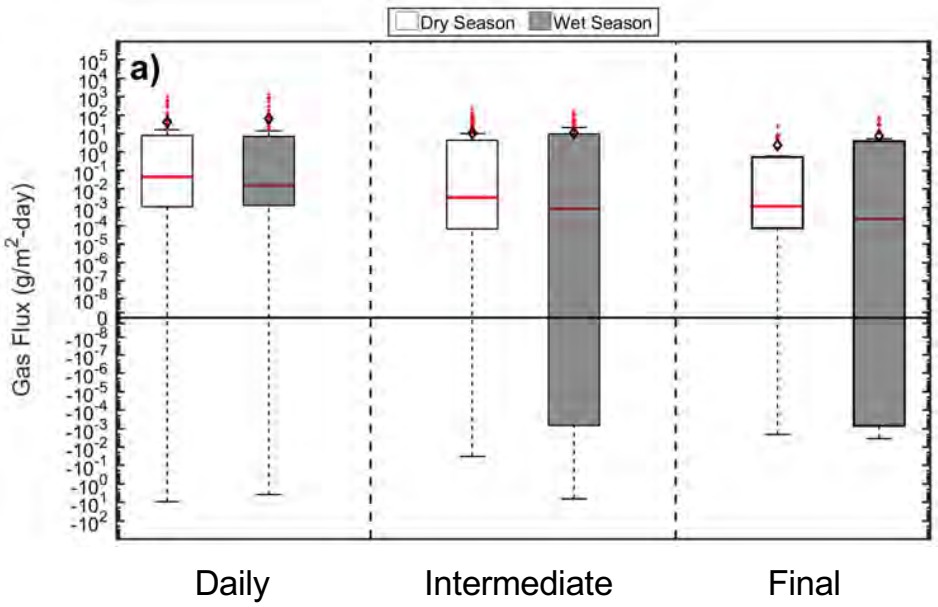
NMVOCs



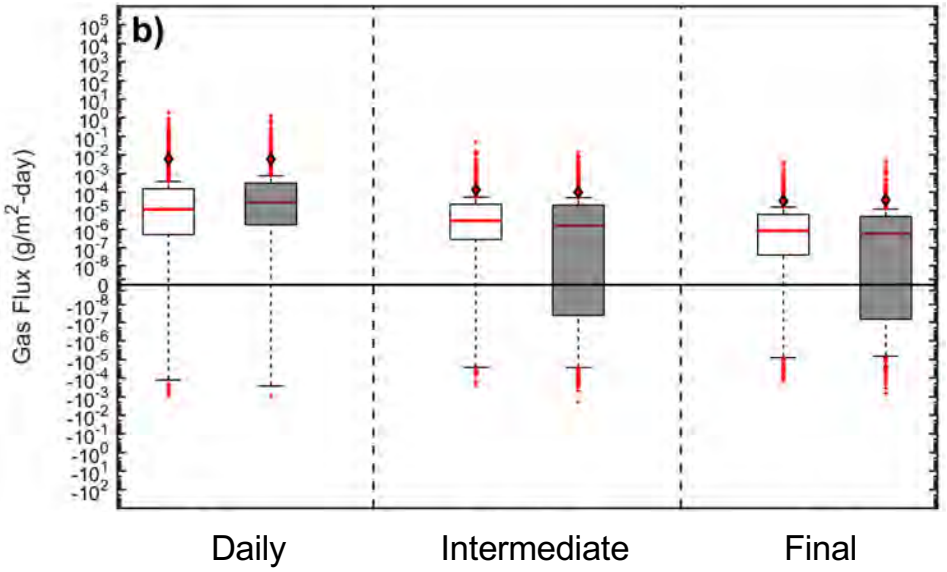
CalRecycle Contract: DRR16109 and CARB Contract: 16ISD006
Final Report and Presentation available at: *https://ww2.arb.ca.gov/resources/documents/landfill-gas-research*

Flux Data – Seasonal Comparison

GHGs

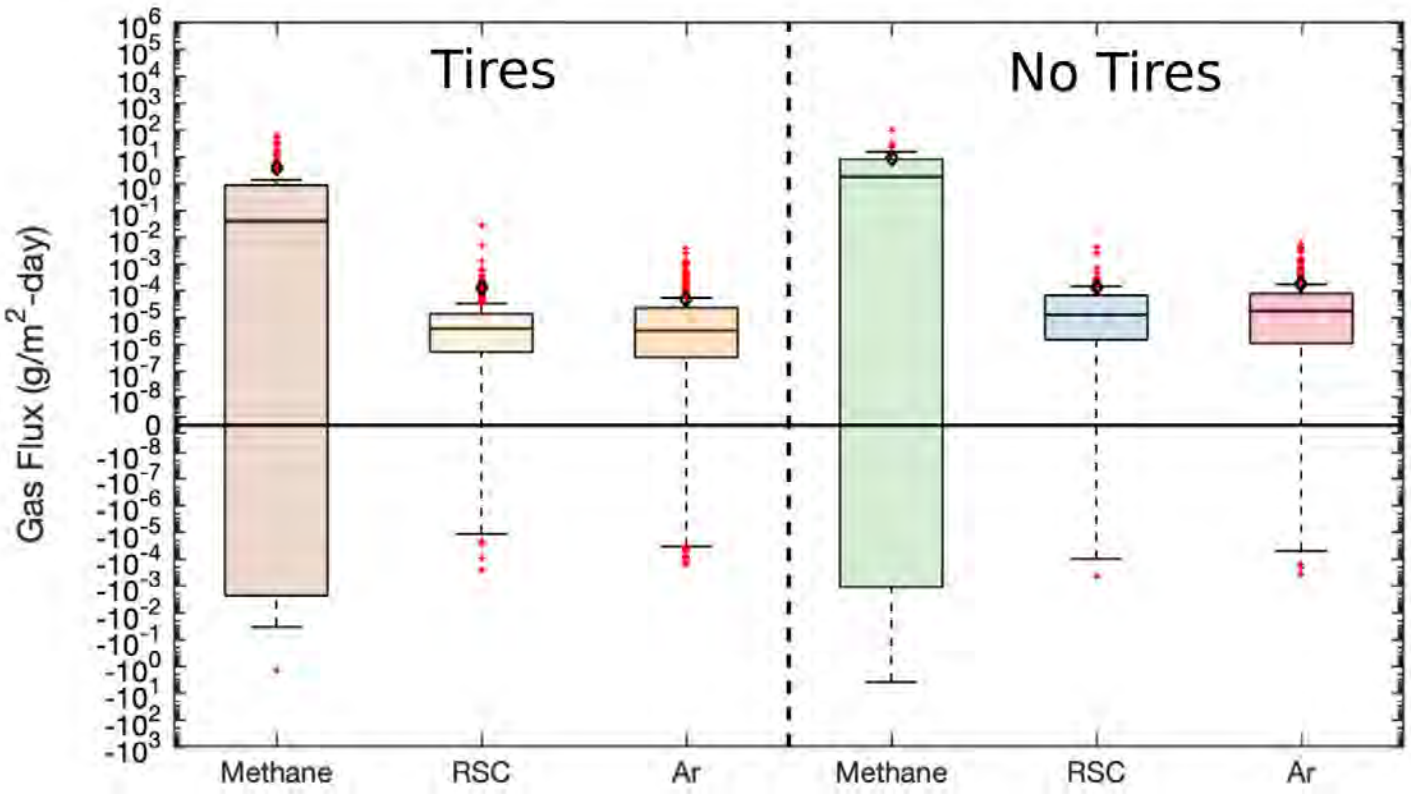


NMVOCs



CalRecycle Contract: DRR16109 and CARB Contract: 16ISD006
Final Report and Presentation available at: *https://ww2.arb.ca.gov/resources/documents/landfill-gas-research*

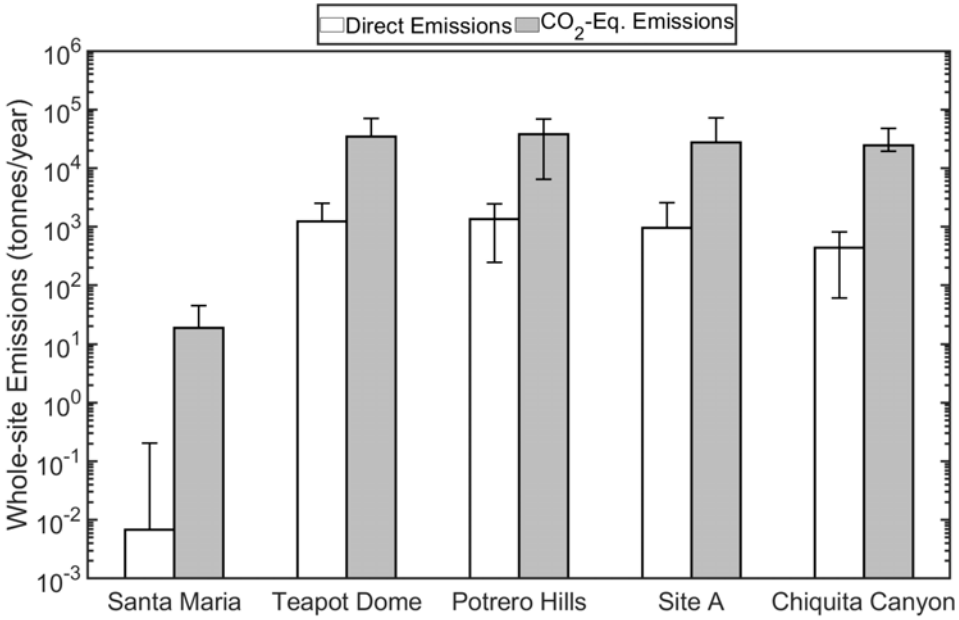
Flux Data – Effects of Tire Disposal

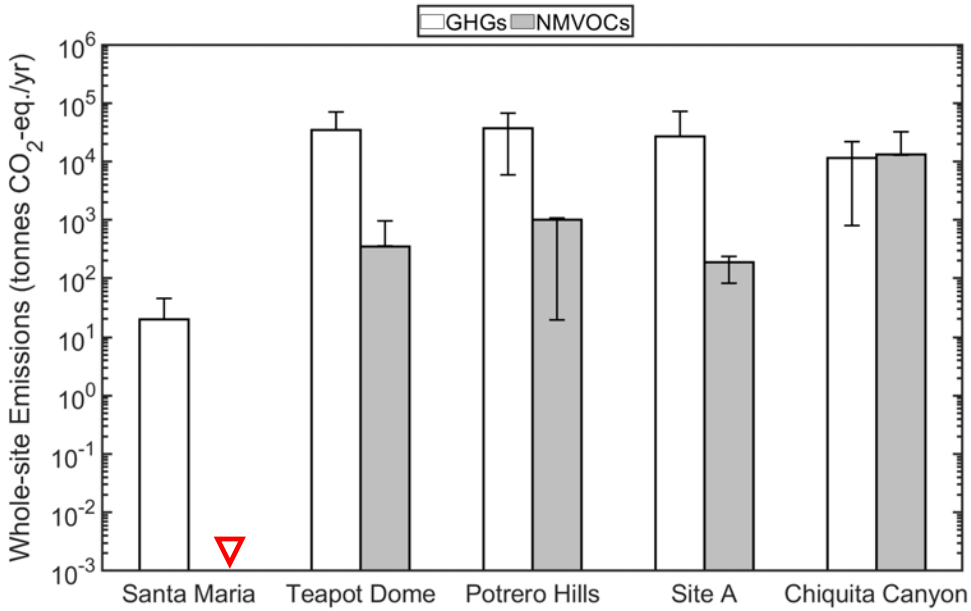


RSC: reduced sulfur compounds, Ar: Aromatic hydrocarbons

CalRecycle Contract: DRR16109 and CARB Contract: 16ISD006
Final Report and Presentation available at: *https://ww2.arb.ca.gov/resources/documents/landfill-gas-research*

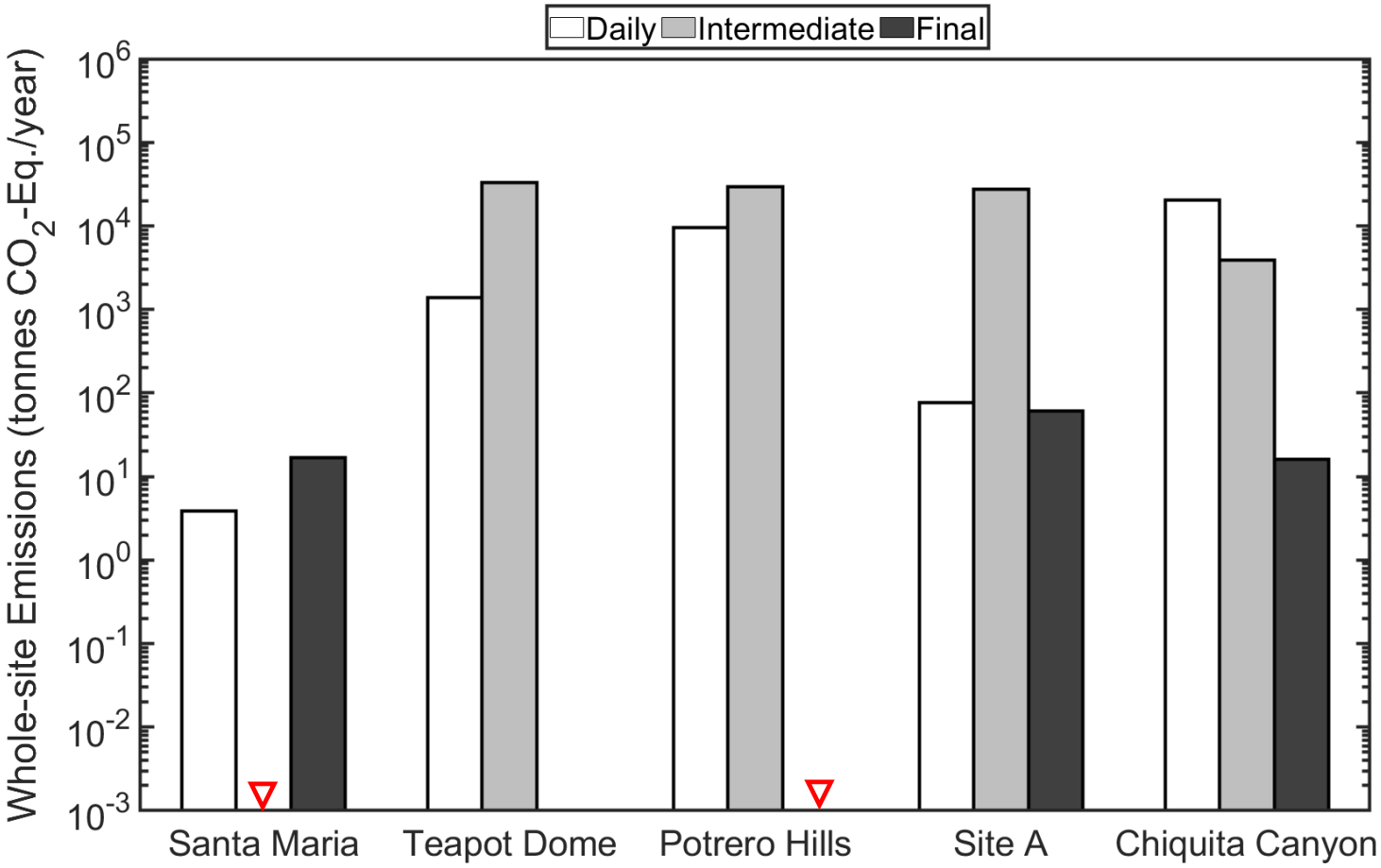
Emissions Data – Inter Landfill





CalRecycle Contract: DRR16109 and CARB Contract: 16ISD006
Final Report and Presentation available at: *https://ww2.arb.ca.gov/resources/documents/landfill-gas-research*

Emissions Data – By Cover Type



CalRecycle Contract: DRR16109 and CARB Contract: 16ISD006
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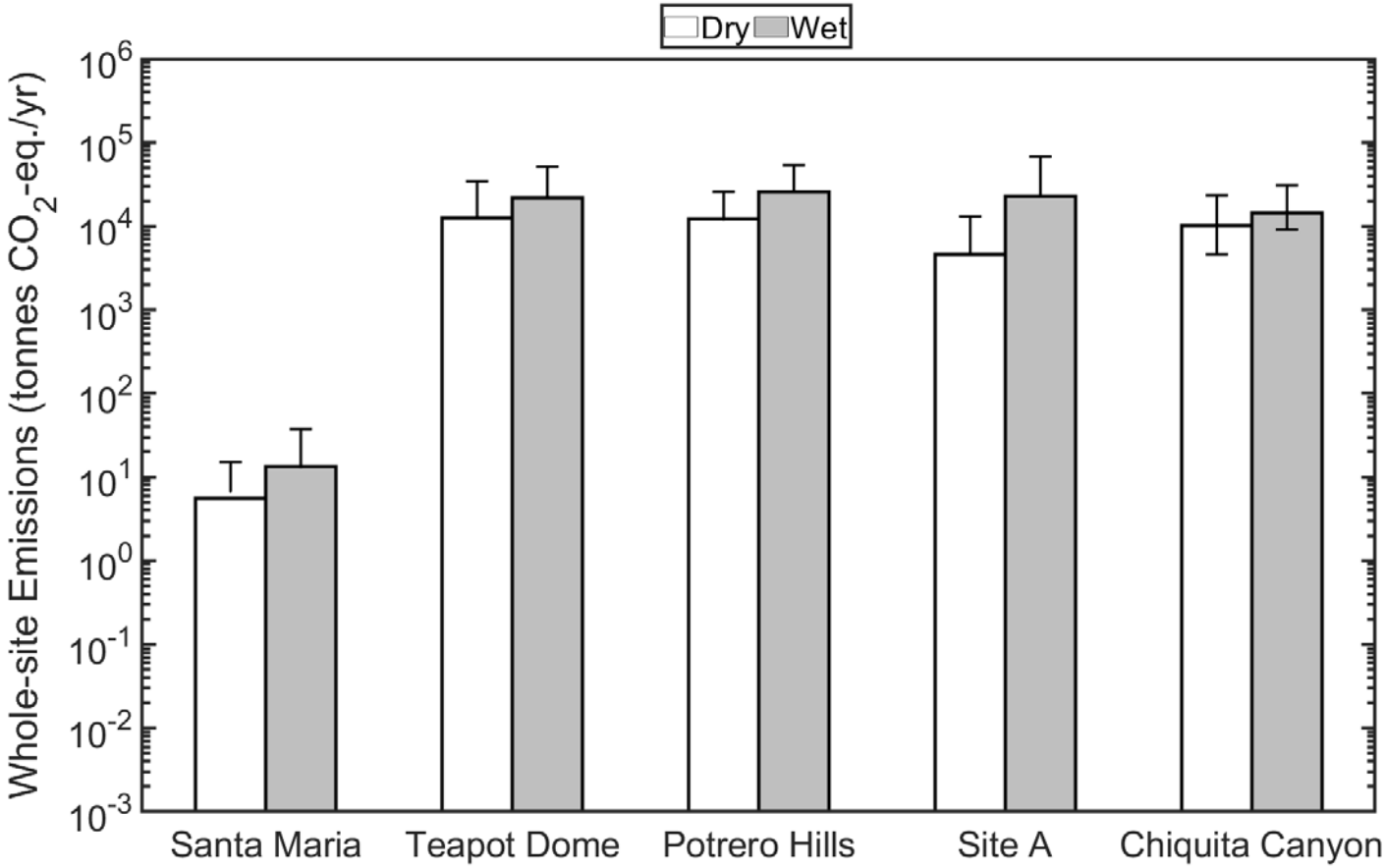
Emissions Data – Seasonal Comparison



CalRecycle Contract: DRR16109 and CARB Contract: 16ISD006
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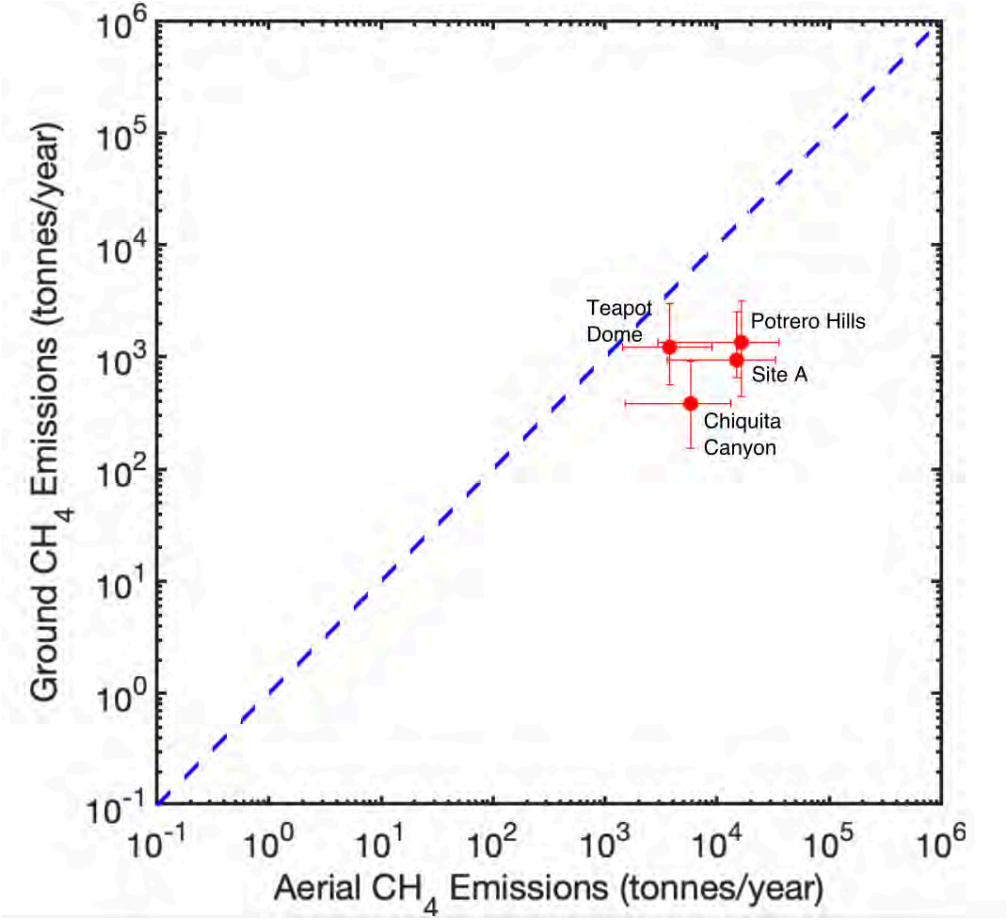
Emissions – Aerial and Ground Measurements



CalRecycle Contract: DRR16109 and CARB Contract: 16ISD006
Final Report and Presentation available at: *https://ww2.arb.ca.gov/resources/documents/landfill-gas-research*

Emissions – Aerial, Ground, Inventory Data

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)

CalRecycle Contract: DRR16109 and CARB Contract: 16ISD006
Final Report and Presentation available at: *https://ww2.arb.ca.gov/resources/documents/landfill-gas-research*

Gas Collection Efficiency

- Gas Collection Efficiency (**Measured**):

  (Gas Collection) / (Gas Emissions + Gas Collection)

  All parameters determined using site records (collection) and field test program (emissions)

- Gas Collection Efficiency (**Modeled**):

  (Gas Collection) / (Gas Generation)

  All parameters determined using site records (collection) and LandGEM (generation)

CalRecycle Contract: DRR16109 and CARB Contract: 16ISD006
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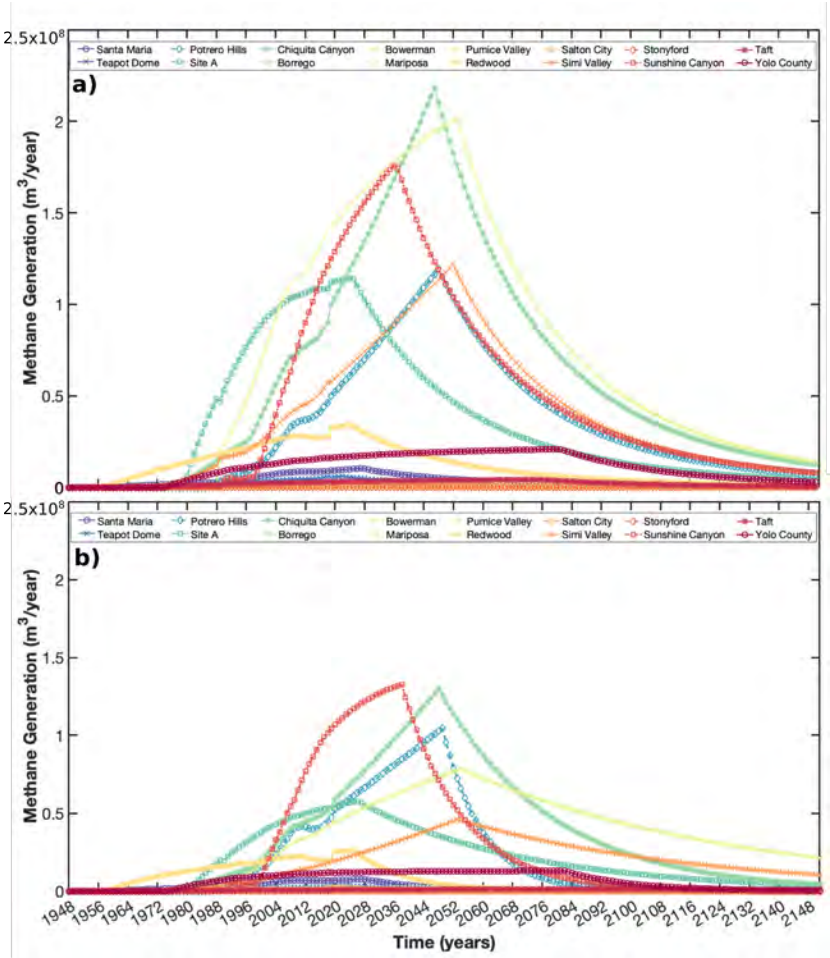
Gas Generation - LandGEM



a) Baseline: Default L_o and k values

b) Refined: Updated L_o and k values

CalRecycle Contract: DRR16109 and CARB Contract: 16ISD006
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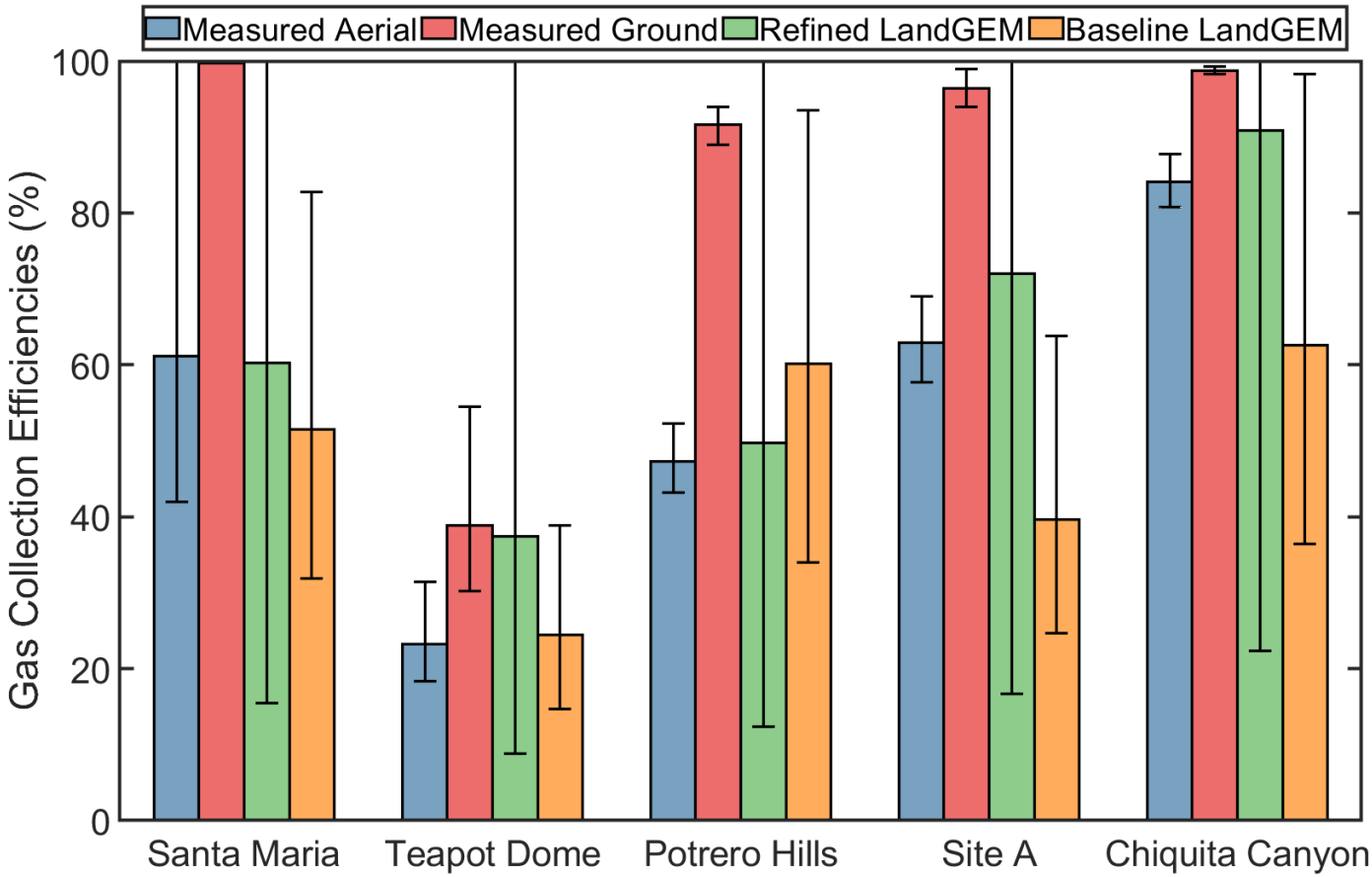
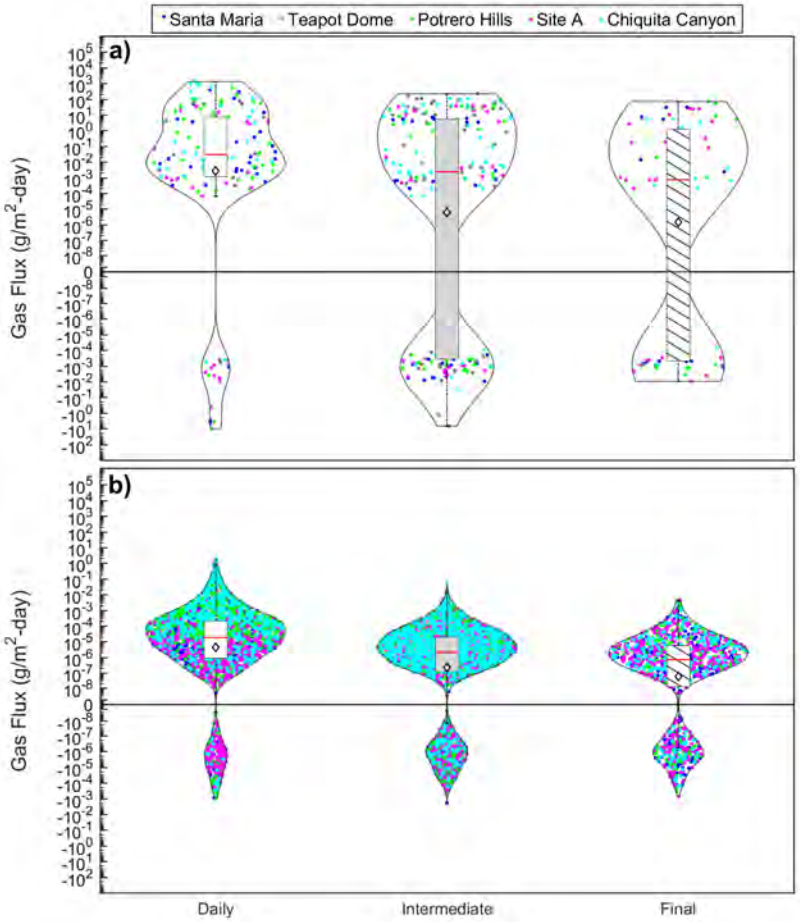
Gas Collection Efficiency



CalRecycle Contract: DRR16109 and CARB Contract: 16ISD006
Final Report and Presentation available at: *https://ww2.arb.ca.gov/resources/documents/landfill-gas-research*

Engineering Significance – Statistical Variability

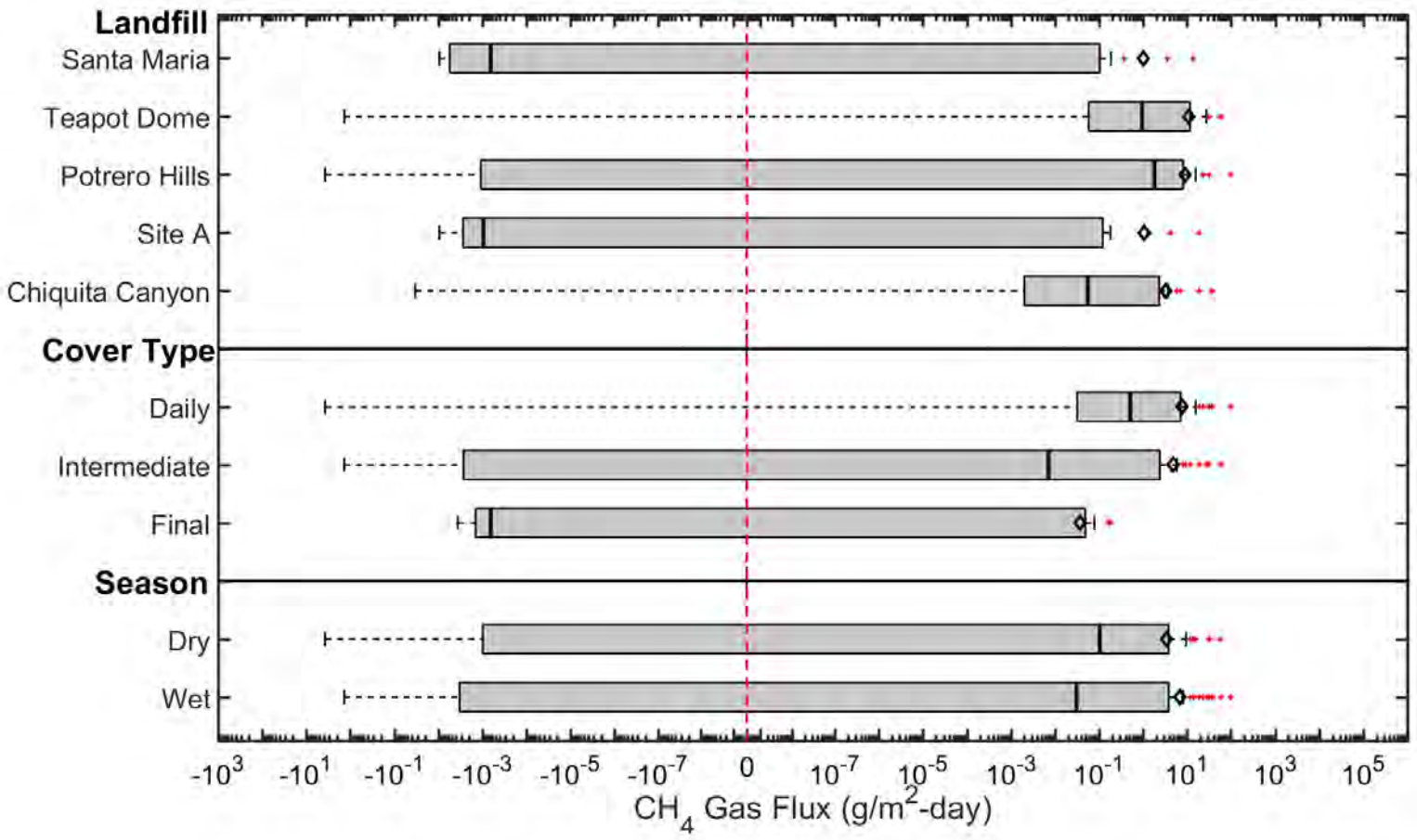


a) GHGs

b) NMVOCs

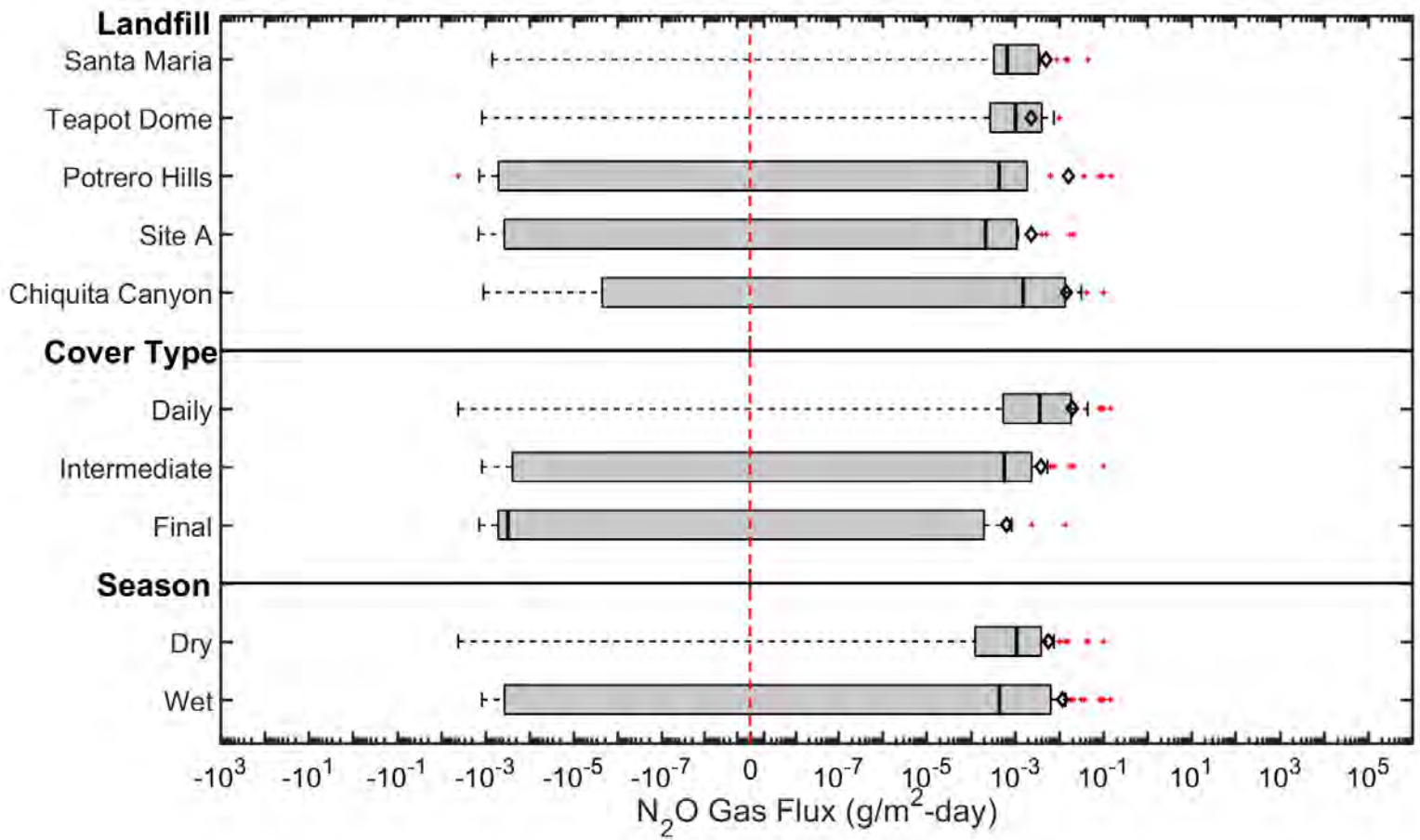
CalRecycle Contract: DRR16109 and CARB Contract: 16ISD006
Final Report and Presentation available at: *https://ww2.arb.ca.gov/resources/documents/landfill-gas-research*

Engineering Significance – Methane Flux



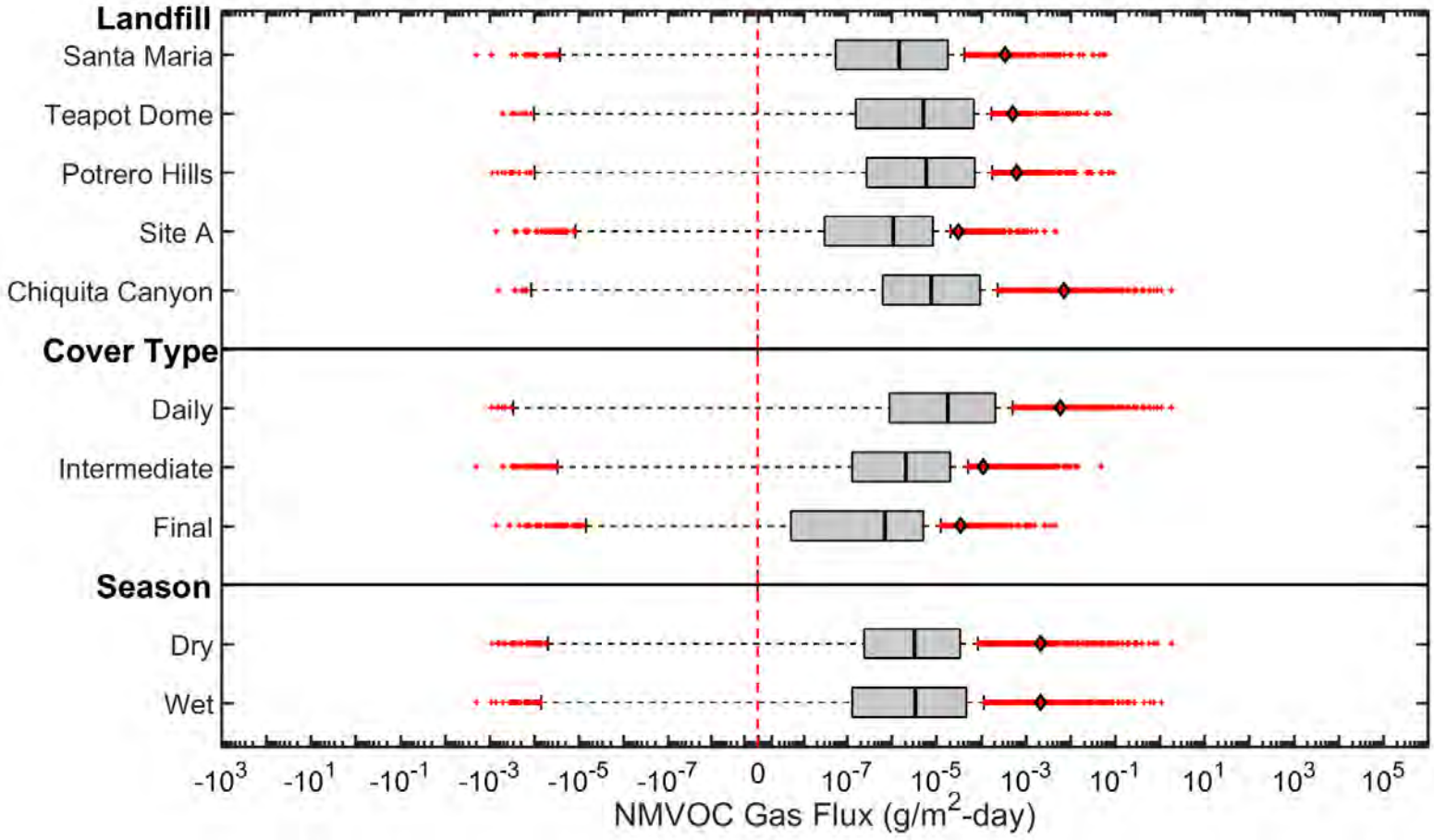
CalRecycle Contract: DRR16109 and CARB Contract: 16ISD006
Final Report and Presentation available at: *https://ww2.arb.ca.gov/resources/documents/landfill-gas-research*

Engineering Significance – Nitrous Oxide Flux



CalRecycle Contract: DRR16109 and CARB Contract: 16ISD006
Final Report and Presentation available at: *https://ww2.arb.ca.gov/resources/documents/landfill-gas-research*

Engineering Significance – NMVOC Flux



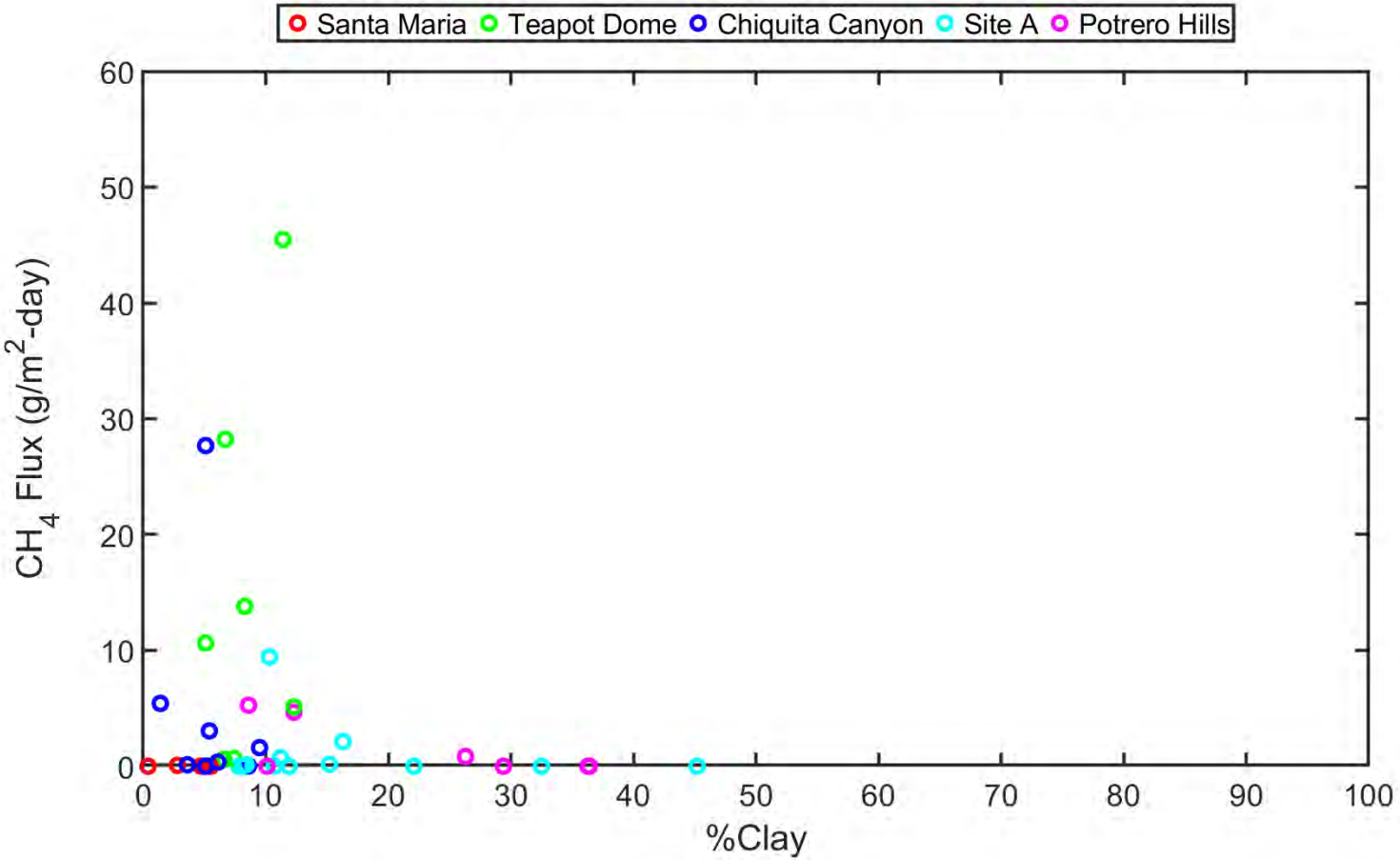
CalRecycle Contract: DRR16109 and CARB Contract: 16ISD006
Final Report and Presentation available at: *https://ww2.arb.ca.gov/resources/documents/landfill-gas-research*

Engineering Significance – Correlations

- Geotechnical Properties: Fines content, clay content, Atterberg limits, moisture content, degree of saturation, void ratio, density
- Operational Conditions: Waste in place, waste column height, average waste age, % daily cover, waste throughput, cover thickness
- Climatic Conditions: Temperature, precipitation, barometric pressure
- Physicochemical Properties: Molecular weight, vapor pressure, water solubility

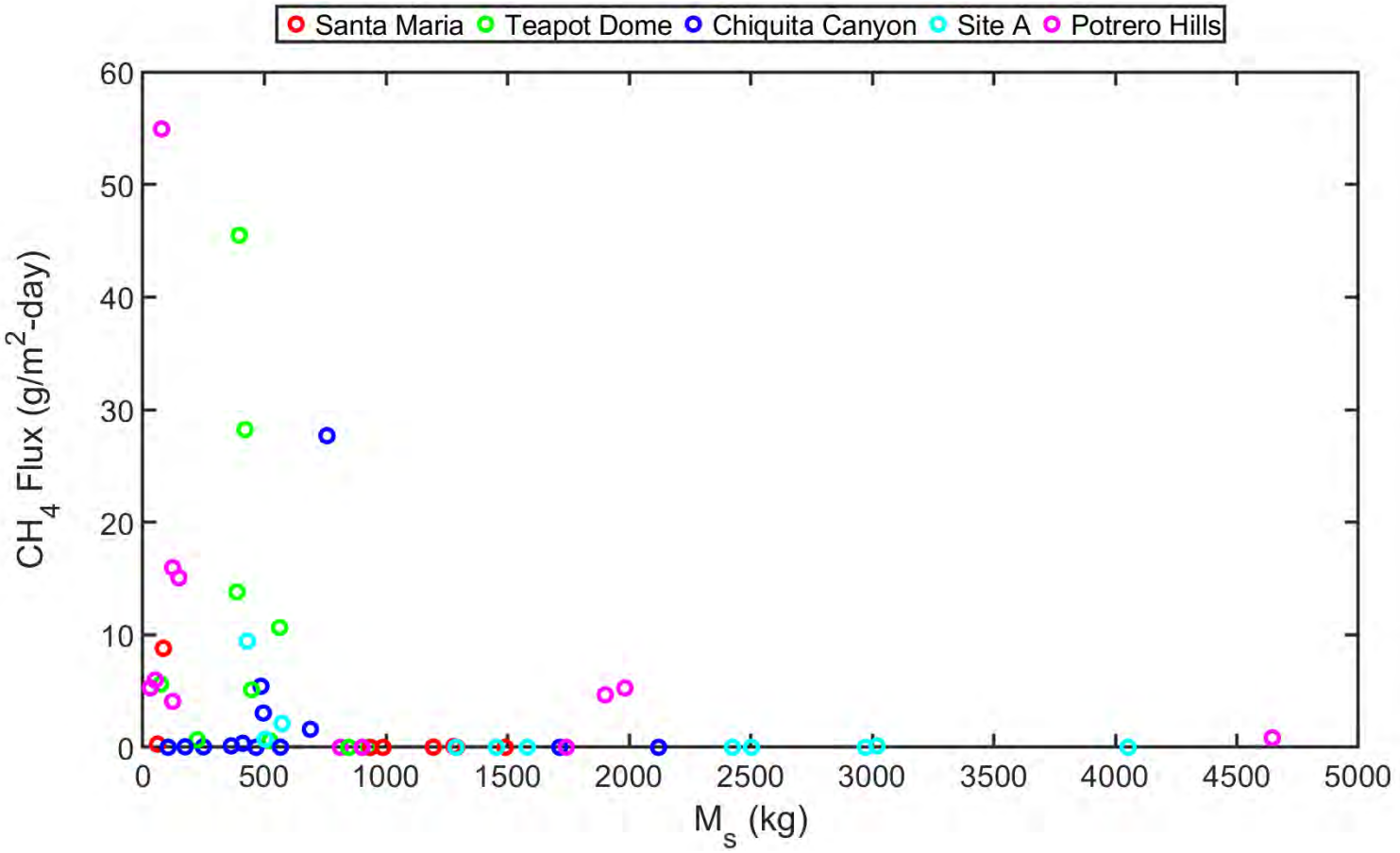
CalRecycle Contract: DRR16109 and CARB Contract: 16ISD006
Final Report and Presentation available at: *https://ww2.arb.ca.gov/resources/documents/landfill-gas-research*

Engineering Significance – Clay Content



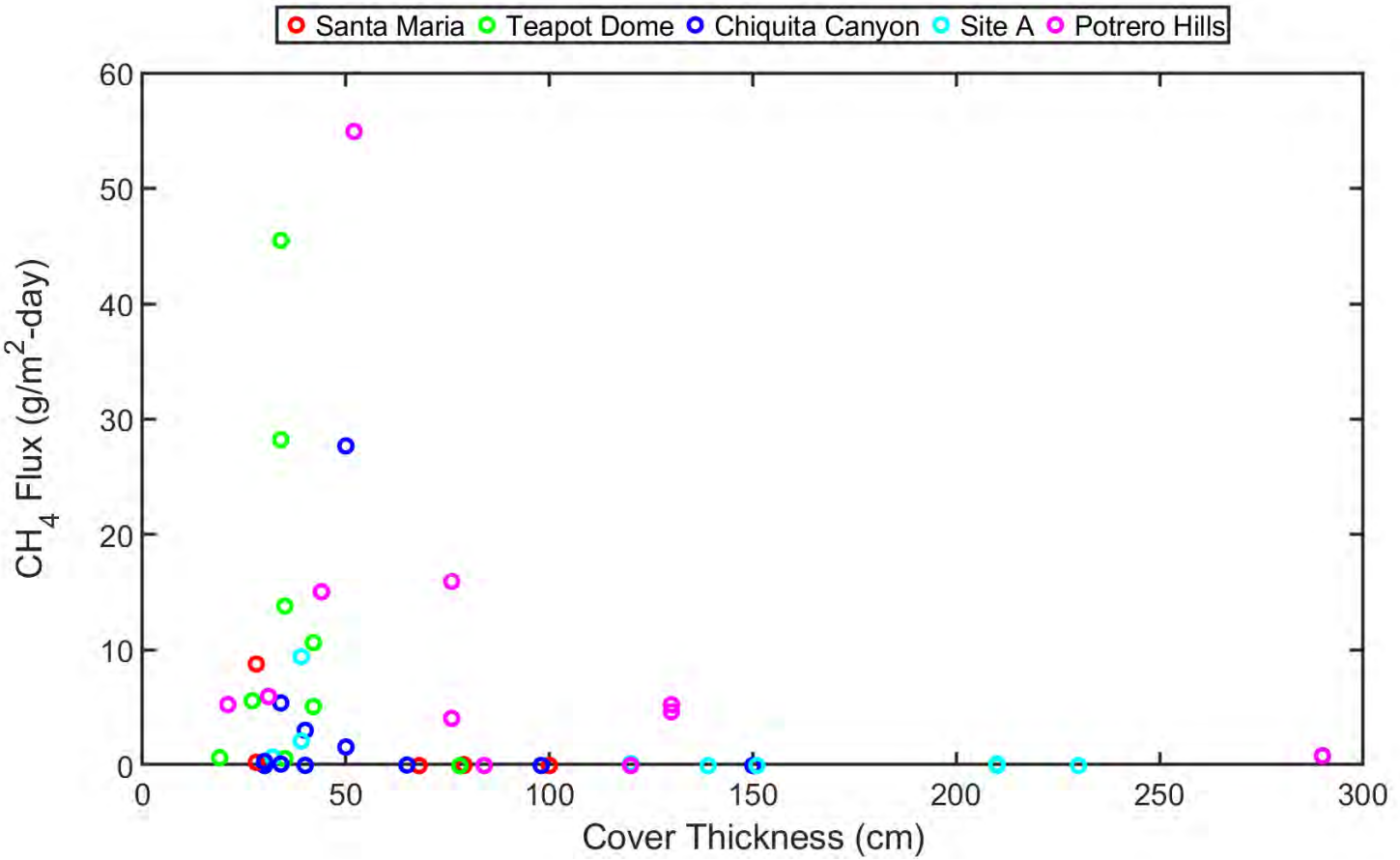
CalRecycle Contract: DRR16109 and CARB Contract: 16ISD006
Final Report and Presentation available at: *https://ww2.arb.ca.gov/resources/documents/landfill-gas-research*

Engineering Significance – Solids Mass



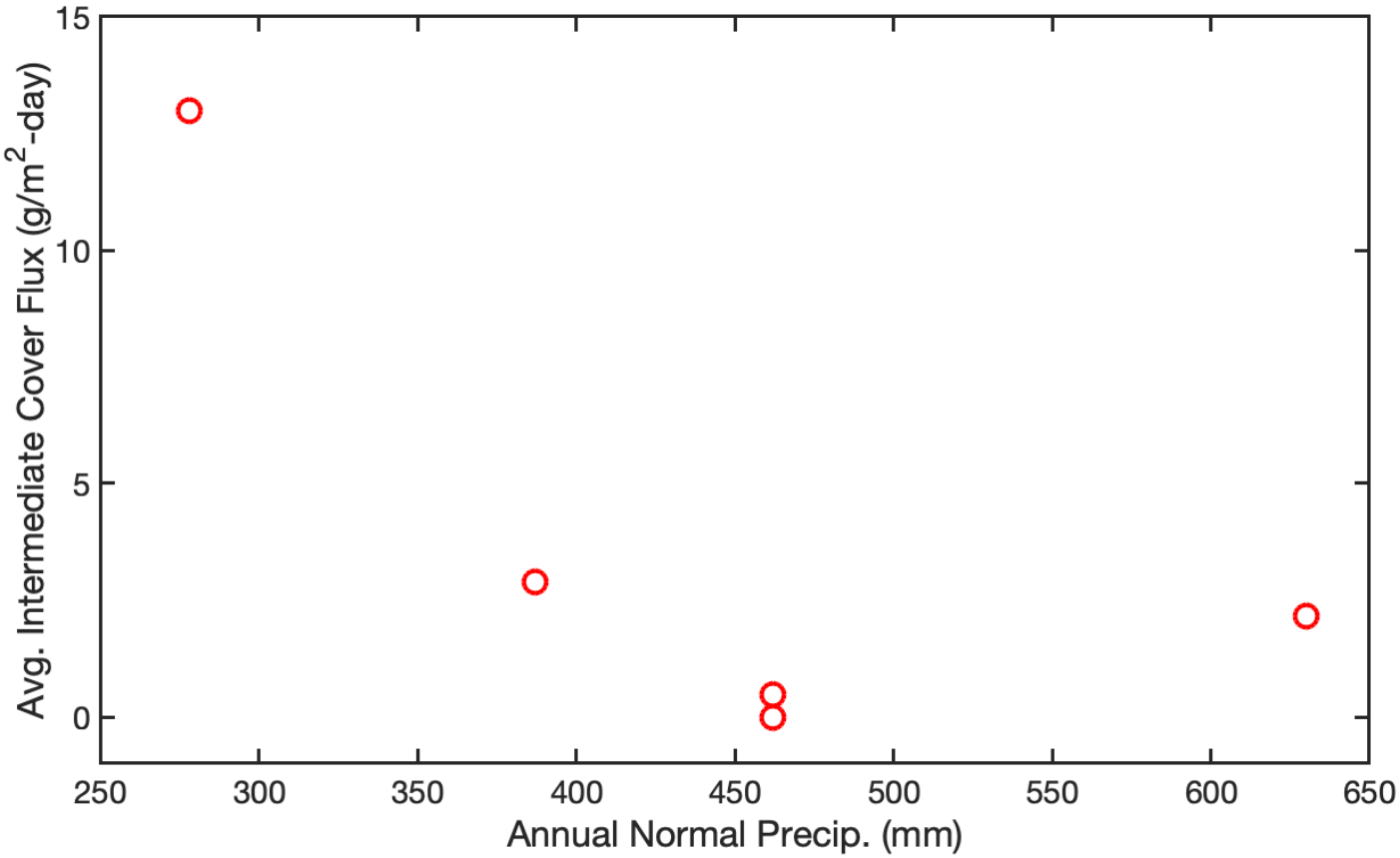
CalRecycle Contract: DRR16109 and CARB Contract: 16ISD006
Final Report and Presentation available at: *https://ww2.arb.ca.gov/resources/documents/landfill-gas-research*

Engineering Significance – Thickness



CalRecycle Contract: DRR16109 and CARB Contract: 16ISD006
Final Report and Presentation available at: *https://ww2.arb.ca.gov/resources/documents/landfill-gas-research*

Engineering Significance – Precipitation



CalRecycle Contract: DRR16109 and CARB Contract: 16ISD006
Final Report and Presentation available at: *https://ww2.arb.ca.gov/resources/documents/landfill-gas-research*

Engineering Significance – Additional Analysis

- Flux/emissions as a function of:
  - Variable Distances from Gas Well
  - Interim Cover Thickness
  - System Vacuum Pressure
  - Temporal and Diurnal Variation

- Comparison to modeling results and ground CRDS testing

- Correct understanding of landfilling operations

CalRecycle Contract: DRR16109 and CARB Contract: 16ISD006
Final Report and Presentation available at: *https://ww2.arb.ca.gov/resources/documents/landfill-gas-research*

Gas Emission Control Measures – Covers

- Soil covers generally more effective than non-soil covers
- Higher material quantity (solids mass, thickness) was effective
- Daily covers: Minimize area, duration of coverage; minimize coarse, highly porous materials and C&D wastes
- Intermediate covers: Increased effectiveness with increased thickness up to 1 m, fines content > 30%, minimize area
- Final covers: Conventional earthen covers more effective than alternative cover (methane), PI > 20, thickness > 150 cm (methane), thickness > 75 cm (NMVOCs), fines > 60%, clay content > 12%
- Geotechnical properties, engineering classification (USCS)
- Fat clays (CH soils) most effective in emissions control

CalRecycle Contract: DRR16109 and CARB Contract: 16ISD006
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Cover Regulations

27 CCR Sections 20670 et seq. for daily/intermediate cover requirements:

- **Daily cover** – 6 inches of compacted earthen material soil applied at end of operating day
  - Alternative daily cover (ADC) – as approved
  - 11 materials with specific standards (27 CCR 20690)
  - Others may be approved with demonstration project
- **Intermediate cover** (no waste for >180 days) – 12 inches compacted earthen material
  - Alternative intermediate cover (AIC) – as approved
  - May be approved with demonstration project

27 CCR Sections 21090 and 21140 for final cover requirements:

- **Final Cover**
  - Prescriptive Standard
  - 2-feet foundation layer
  - 1-foot impermeable layer at 1 x 10^{-6} cm/sec
  - Cannot be more permeable than bottom liner (i.e., no “bathtub effect”)
  - 1-foot vegetation layer
  - Alternatives may be approved

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Gas Emission Control Measures

- Robust cover over wet waste placement zones
- N_2O emissions: Avoid concentrated areas of organic sludges
- NMVOCs are trace components, yet are a significant and detectable fraction of landfill gas with net positive fluxes from all cover categories, appreciable portions of total emissions
- Gas collection efficiency not a measure of emissions
- Flux/emissions of a given chemical/chemical family cannot be used for other chemicals/chemical families (i.e., methane does not serve as a surrogate for other chemicals)
- Both top-down and bottom-up measurements provide context for methane emissions from landfills

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Acknowledgment

- Funding provided by CalRecycle and CARB
- Research Collaborators: Dr. Jean Bogner (University of Illinois-Chicago) and Dr. Don Blake (University of California-Irvine)
- Graduate Student: Alexandra Limpert
- Numerous graduate and undergraduate students
- Dr. Amro El Badawy
- Cooperation, field access, and field assistance provided by partner landfills
- Scientific Aviation

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All Done!

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