Landfills as the Final Sink

Residuals, heat, PFAS and measurement: what current research tells landfill operators

EREF Environmental Research & Education Foundation™
www.erefdn.org

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President & CEO, Environmental Research & Education Foundation (EREF)

EREF Mission

Mission

- To advance scientific research and create educational pathways that enable innovation in sustainable waste management practices.

Vision

- To light the way towards a more circular economy.

Our Role

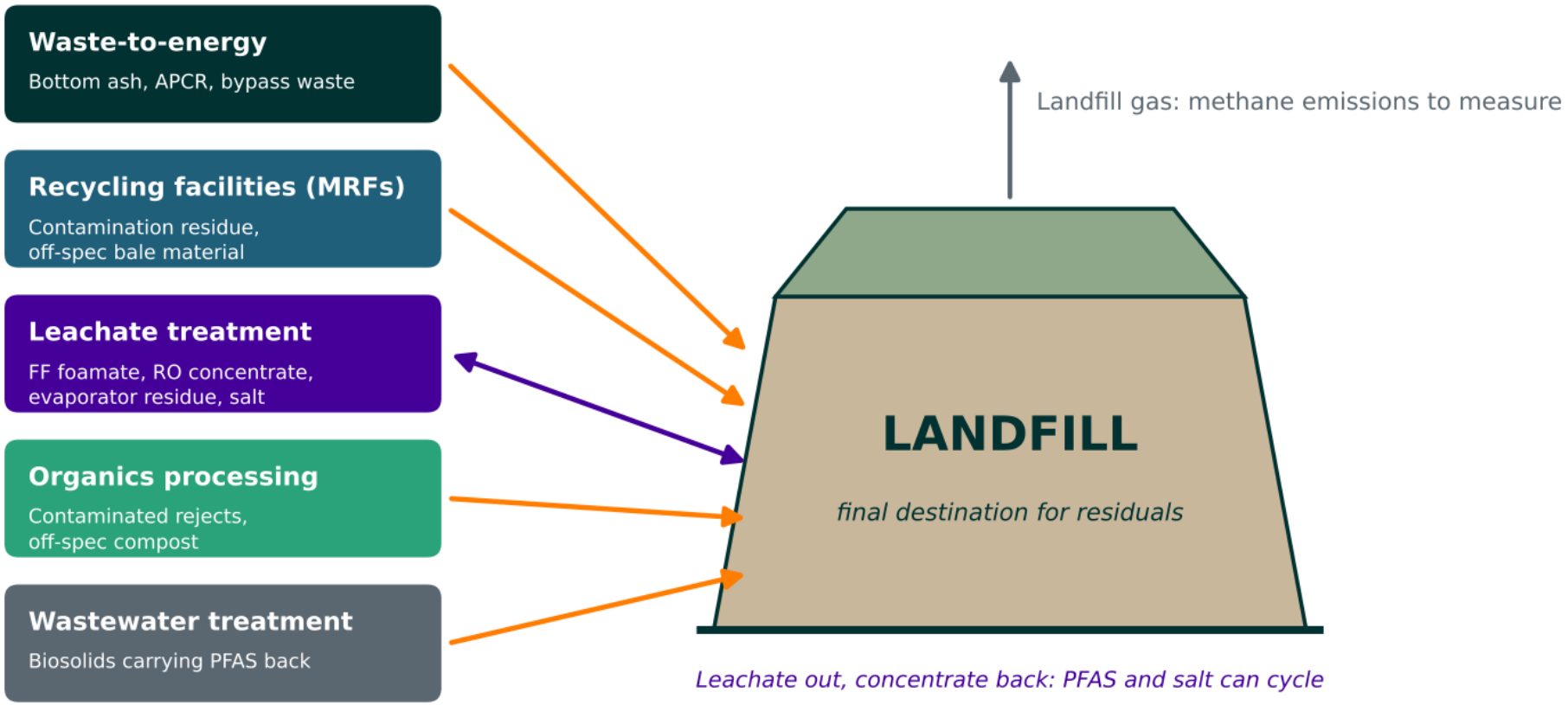
- Advance waste and sustainability science through ***credible, objective*** applied research; aggregate and translate data into actionable knowledge; develop the expertise that advances the field; and provide ***trusted*** thought leadership that informs industry, policy, and practice.

What We Do: Core Programs

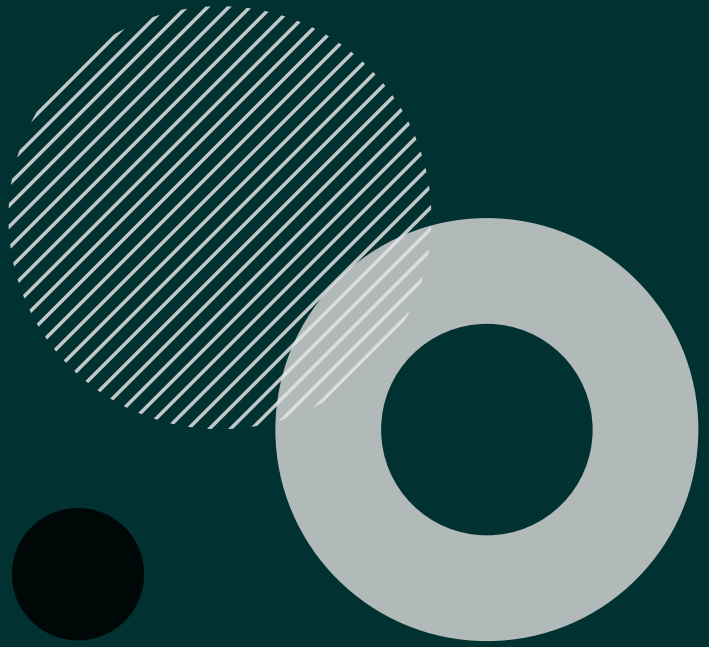
- *Research Grants*
  - 145 grant projects funded since 1998
  - 30 active projects
  - $21+ million awarded through 2026
- *Scholarships*
  - $4+ million awarded
  - 196 scholars since 1998
  - 65 active scholars
- *Data Analysis*
  - 45 Projects Completed since 2014
  - 30 Active Projects
- *Education*
  - Online content (e.g., textbook, courses)
  - Technical Meetings
  - Science Sessions

THE THEME OF THIS TALK

Every pathway sends its residuals back to the landfill



WTE



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WASTE-TO-ENERGY

Circular Economy: Why WTE and Landfills Remain Necessary

HOW CIRCULAR ARE WE?

6.9%

of materials used globally are cycled back (2025)

12.2%

EU circular material use rate (2024)

RESOURCE RECOVERY

WTE converts

- Non-recyclable combustibles to energy
- Recovers ferrous metals missed by recycling and composting
- Produces ash that still needs a landfill

REPOSITORY AND RECOVERY

Landfills hold

- Wastes not yet designed to be circular
- Ash and harmful or potentially harmful materials
- Methane captured for power, heat and renewable gas

REALITY CHECK

“Zero waste”

- A useful aspiration, limited by upstream product design
- Residues and harmful materials will always need a repository

61 stand-alone municipal waste combustors in the U.S.

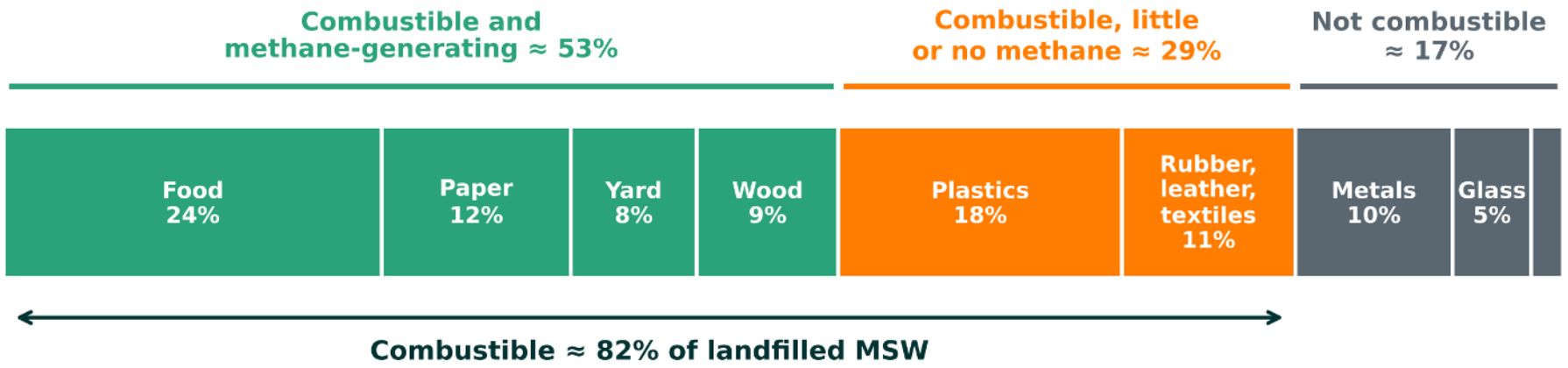
~24M U.S. tons of MSW combusted per year, alongside ~1,410 MSW landfills

Sources: EREF, Waste Generation in the US (2026, unpublished); Circle Economy, Circularity Gap Report 2025 (global circularity 6.9%); Eurostat, circular material use rate, 2024 data (EU 12.2%)

WASTE-TO-ENERGY · WHAT COULD BE DIVERTED FROM LANDFILL

WTE suits part of the waste stream, not all of it

U.S. MSW LANDFILLED, BY MATERIAL (2018, % BY WEIGHT)



Methane potential is different than combustibility

Large portion of MSW is food waste with a MC =70%, which consumes energy to evaporate the water

C&D is mostly not combustible

~600 Mt/yr in the U.S. (about 2× MSW): concrete, asphalt, brick and gypsum dominate; ~145 Mt landfilled

Industrial waste varies

Non-hazardous industrial streams have variable WTE potential depending on what they are

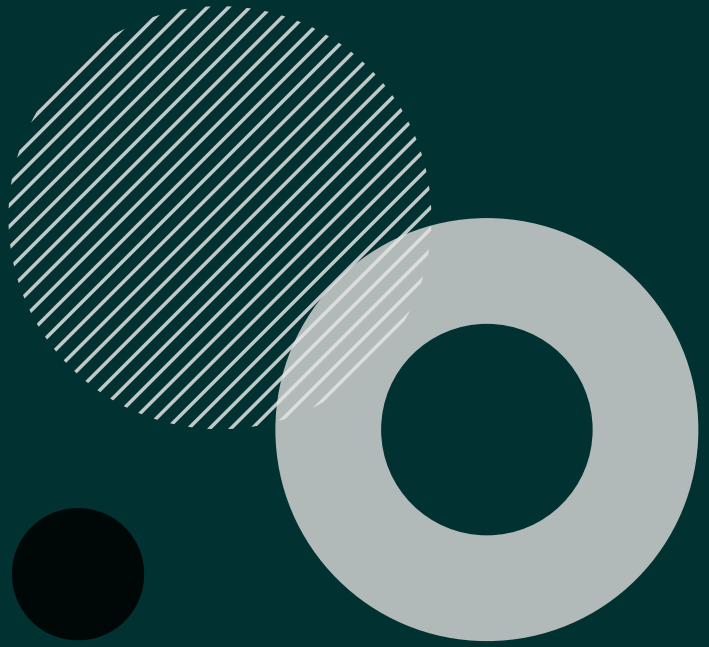
Sources: U.S. EPA, Advancing Sustainable Materials Management: Facts and Figures (2018 data); U.S. EPA, Sustainable Management of C&D Materials. Shares estimated from EPA tonnage tables

Ash effects are general; deep and wet sites amplify them

Effect	At any site	Amplified at deep or wet sites	Source
Heat release	Ash hydration, carbonation and aluminium corrosion release heat after placement	Deep: heat is retained. Wet: more water drives the reactions	Barlaz et al. 2022 (EREF final report)
Leachate collection clogging	Ash supplies calcium; with carbonate from MSW it precipitates. Co-disposal can be more clog-prone than ash monofills	Wet: more leachate flow carries more calcium to the drainage layer	Levine et al. 2005; Schert et al. 2015 (Florida)
Hydrology and leachate chemistry	Bottom-ash fills stay largely unsaturated; 5–10% of volume acts as fast flow paths. Leachate pH 7.2–9.3, salt-rich	Wet: storms dilute salts but raise some metals (Al, Cu, Cr, V, Zn)	Ingold et al. 2024
Slope stability	Ash and ash–sludge mixes can be engineered for stable co-disposal; mixing ratio matters	Deep: higher stresses. Wet: pore pressure in fine-grained layers	Benoît et al. 1999

Sources: Barlaz et al. (2022) Understanding and Predicting Temperatures in MSW Landfills, EREF final report; Levine et al. (2005) Hinkley Center; Schert et al. (2015) Hinkley Center; Ingold et al. (2024) Environ. Earth Sci. 83:180; Benoît et al. (1999) J. Geotech. Geoenviron. Eng. 125(10)

PFAS and WTE

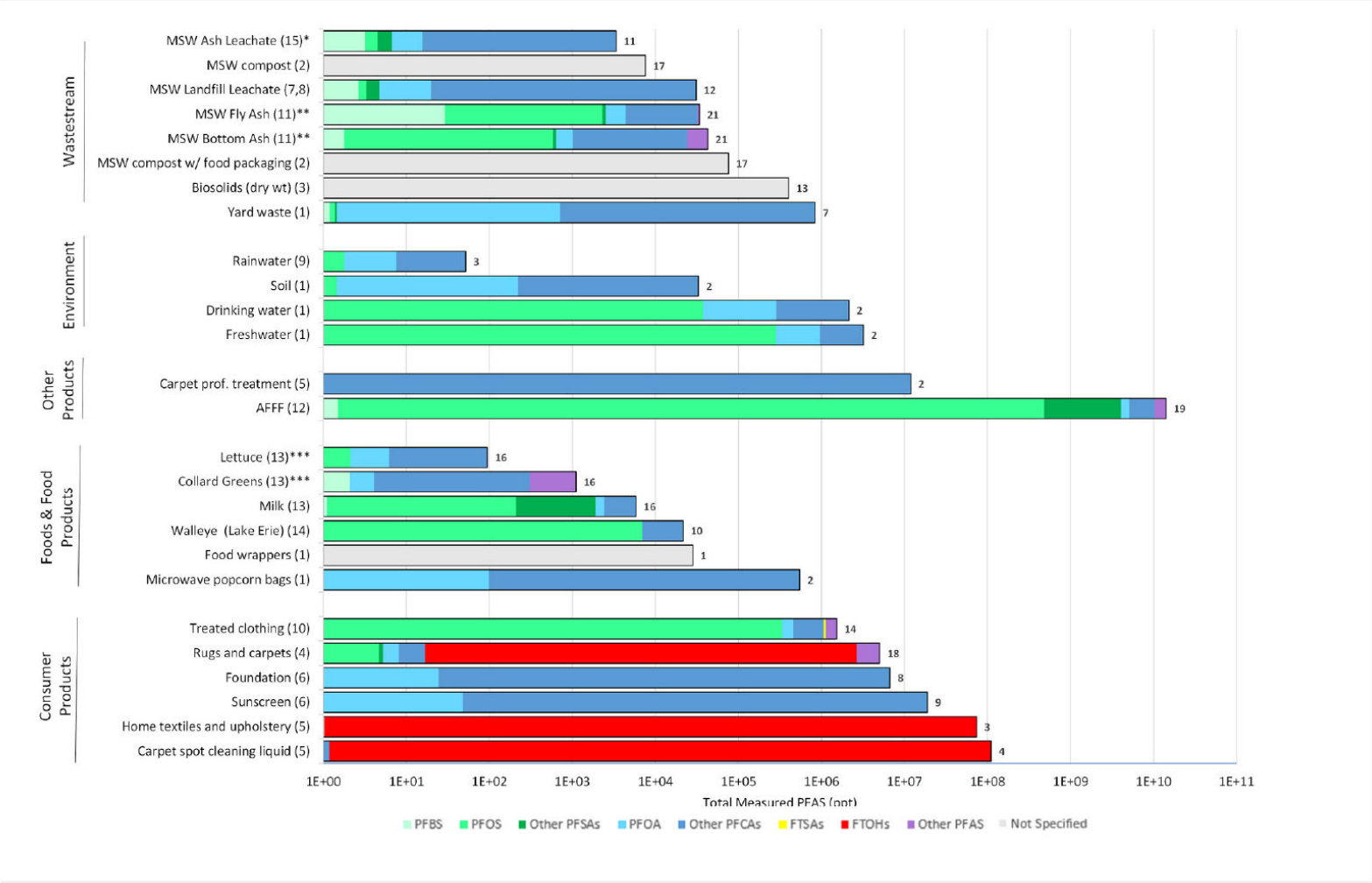


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PFAS · WHERE IT COMES FROM

PFAS enter the waste system in everyday products

HIGHEST REPORTED PFAS LEVELS (ppt, LOG SCALE)



WHERE MANAGEMENT ROUTES CARRY IT

Compost and digestate

Choi et al., 2019

Landfill gas

13 of 27 PFAS detected at three Florida sites, mostly volatile FTOHs; fluorine in gas comparable to leachate

Landfill leachate

Medians 2–100× higher than groundwater or stormwater; short-chain PFAS prevalent

WTE ash

What survives combustion ends up mostly in bottom ash

Sources: Weitz et al. (2024) Sci. Total Environ. 932:172658, Fig. 1 (reproduced); Lin et al. (2024) ES&T Letters; EREF PFAS treatment assessment (forthcoming)

PFAS · THERMAL DESTRUCTION · FULL-SCALE STACK TESTS

Two recent full-scale U.S. EPA stack tests

	Haz Waste Incinerator (Clean Harbors, Aragonite, Utah)	WTE Facility (Reworld, Lake County, Florida)
Unit	Hazardous waste incinerator: rotary kiln + afterburner	Municipal WTE: reciprocating grate mass burn (228 tpd unit)
Temperature	Kiln 950–1196 °C; afterburner >1100 °C	>1093 °C in the flame zone
Feed	AFFF concentrate plus nine spiked PFAS	Normal MSW plus permitted medical waste; PFAS content unknown
PFAS Reduction	99.95–99.9999% (nine spiked PFAS)	Not calculable
C2F6 indicator Reduction	99.99–99.9999%	98% average
Stack results	Volatile fluorinated compounds <1 ppbv; most PFAS non-detect	Each PFAS <2.6 ng/m³; ~7.8 g/yr total; PFOS not detected

SITE-SPECIFIC OBSERVATIONS

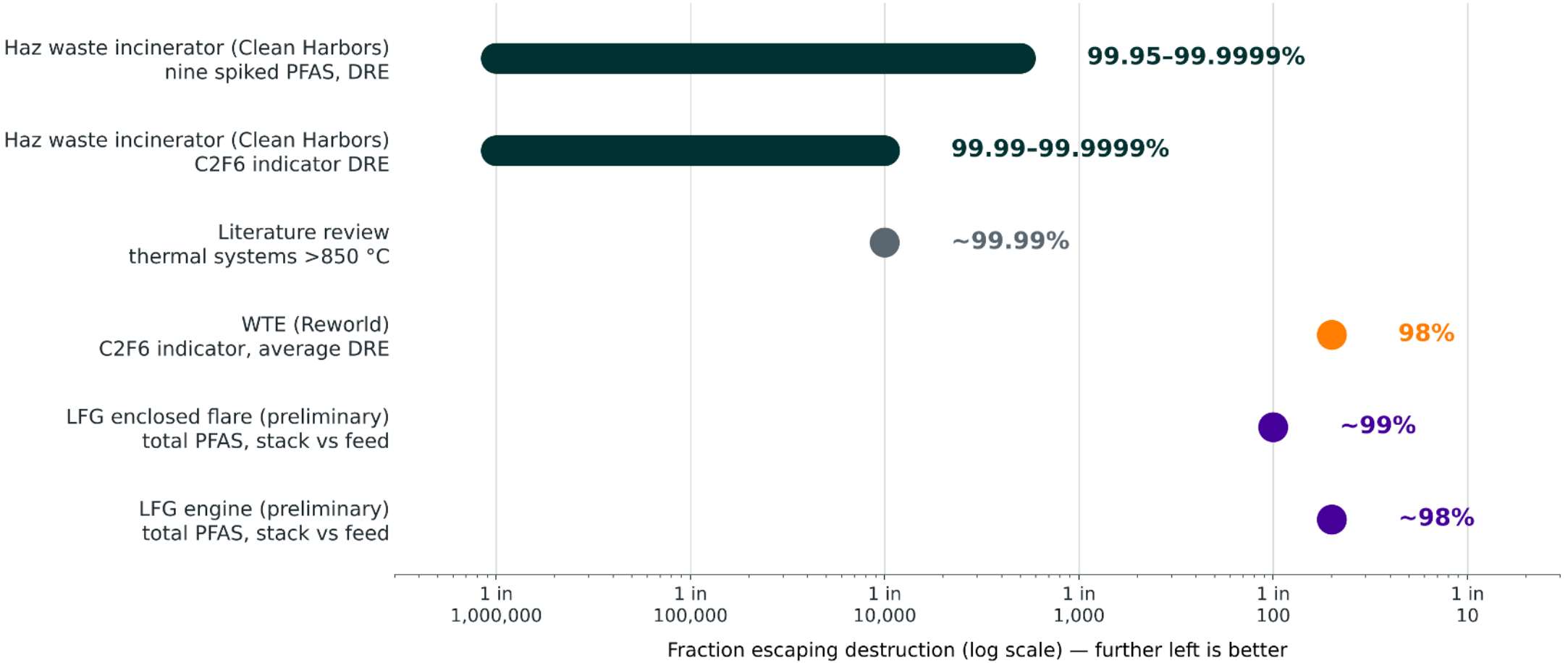
- Clean Harbors: whole-system mass balance gave destruction efficiency of 99.97–99.9999%; third test at this unit; EPA says results apply to the unit tested
- Reworld: higher-than-predicted C2F6 destruction likely reflects localised flame temperatures on the grate; air pollution control removal could not be determined
- C2F6 is harder to destroy than most PFAS, so both studies point to it as a simpler indicator for future testing

DRE (destruction and removal efficiency) = 1 − mass emitted from the stack ÷ mass fed, so it credits both destruction and capture by air pollution controls. DE (destruction efficiency) also subtracts PFAS left in ash and other residues.

Sources: U.S. EPA (2025) EPA 600/R-25/172; U.S. EPA (2026) EPA 600/R-25/273

PFAS · THERMAL DESTRUCTION

How much PFAS escapes thermal destruction?



C2F6 is harder to destroy than most PFAS, so it is a conservative indicator; WTE PFAS DRE could not be calculated (feed PFAS unknown).
LFG results are preliminary total-PFAS reductions from one engine and one enclosed flare; stack methods for volatile PFAS are ~1,000× less sensitive.

Sources: U.S. EPA (2025) EPA 600/R-25/172; U.S. EPA (2026) EPA 600/R-25/273; Weitz et al. (2024); EREF-funded LFG combustion study, preliminary results (Badireddy, Zemba et al., May 2025)

PFAS · THERMAL DESTRUCTION

PFAS that survive combustion end up mostly in bottom ash

Four Florida MSW combustors, 52 PFAS

Measure	Bottom ash	Fly ash
Mean total PFAS	2.2 ng/g	0.33 ng/g
Share of residue PFAS	89%	11%

PFAS in bottom ash tracked loss on ignition: better burnout, less PFAS. An estimated 1.2–8.6% of PFAS remained in ash.

HOW ASH REACHES LEACHATE

- Ash monofills: the ash is the main PFAS source in leachate
- Co-disposal sites: leachate PFAS reflects the unburned waste; ash leaches 10–24× less PFAS (lab tests)

Research gap: ash's share of PFAS in MSW-landfill leachate has not been quantified; it depends on ash share of waste in place and where leachate flows

BACK TO THE LANDFILL

2,820 vs 19,970 ng/L

Total PFAS in leachate from an ash monofill vs mixed-waste landfills

Whether PFAS were mineralised or converted to other compounds cannot be determined from these data

Sources: PFAS in MSWI ash, Waste Manag. (2025) doi:10.1016/j.wasman.2025.115226; Liu et al. (2022) Waste Manag. 144:49–56; Solo-Gabriele et al. (2020) as reviewed in Weitz et al. (2024)

PFAS to Landfills

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PFAS BENCHMARKING FOR LANDFILLS

Benchmarking Involves Solving for Multiple Issues

PFAS is a complex and difficult to manage chemical and many questions/challenges remain on most effective and efficient management approaches.

1 Incoming PFAS

Characterizing what actually enters the waste stream, and how it varies by specific waste components/classes (e.g. special wastes, packaging).

2 Fate, Transport and Emissions

Sequestration in the waste mass, transformations, partitioning to landfill gas and leachate.

3 Treatment Strategies

Removal/treatment efficiency targets, treatment train design, residual management, cost, etc.

4 Measurement & Detection Challenges

Detection limits, inability to detect all PFAS, conversion to other PFAS, methodological issues.

5 External PFAS Sources

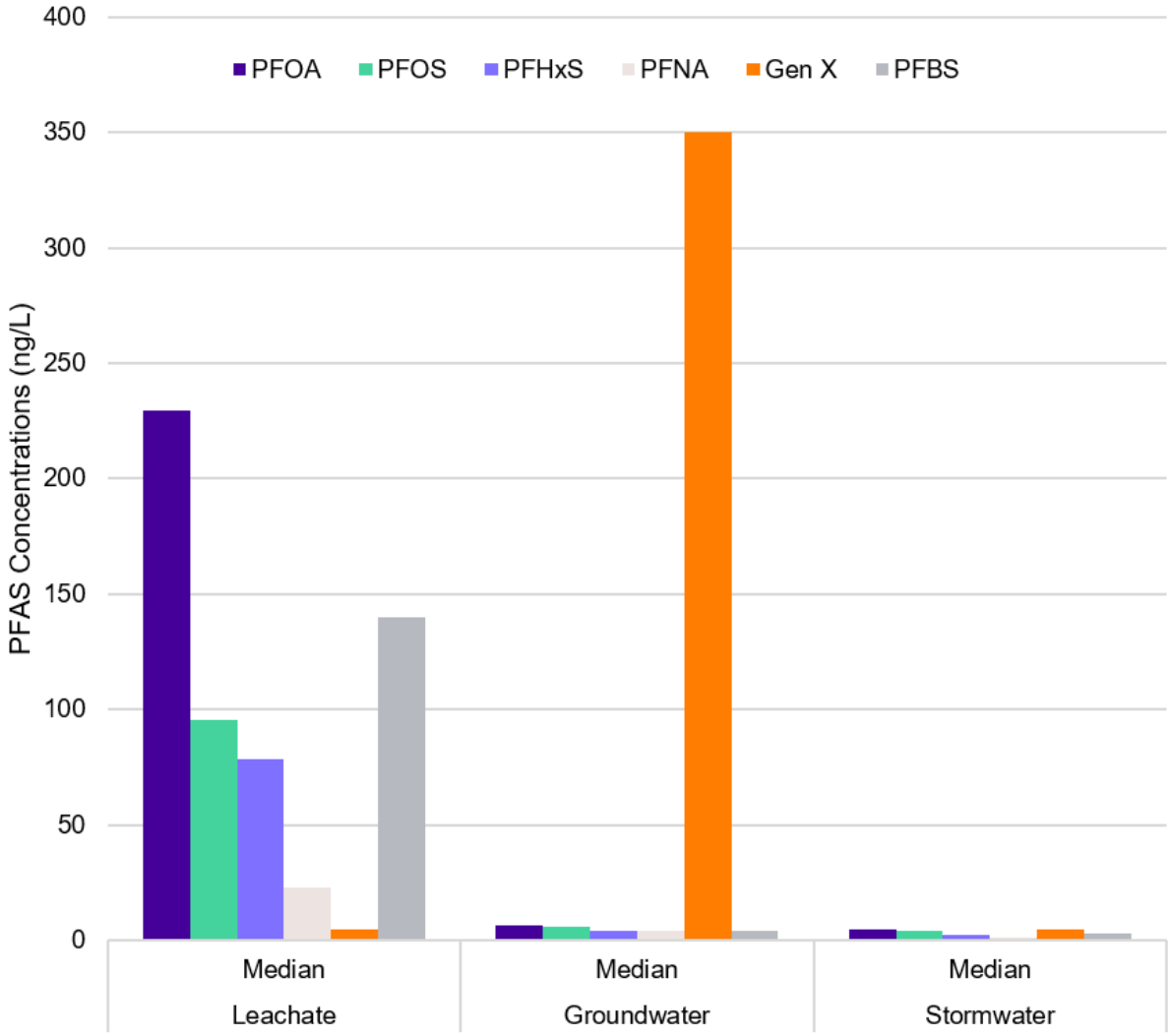
Offsite sources (e.g. manufacturing facilities), Inadvertent use of PFAS-containing materials (e.g. geotextiles, geomembranes, plastic products).

6 Operational & Risk Mitigation

Contribution to potential exposure pathways (e.g. airborne, water), Discharge planning/WWTP dynamics, permitting exposure,and liability management.

PFAS · LANDFILL LIQUIDS, GRONDWATER, STORMWATER

The liquid matters: not all treatment strategies fit best



U.S. dataset: 590 landfills, 812 groundwater and 410 surface water locations

Leachate medians 2–100× higher than groundwater and stormwater

Short-chain PFAS more prevalent in leachate

Greatest variability in leachate; national values support context, not design

Source: EREF, Current State of PFAS Treatment for Landfill Liquids (2026)

Leachate Treatment: Complex
Matrix = Complex Treatment

Leachate is difficult to treat because:

- High organic content
- High dissolved solids
- Competing contaminants
- Fouling potential
- Short-chain PFAS prevalence
- Higher PFAS concentrations

So, what works?

Foam Fractionation

- Minimal pretreatment
- Low operating costs
- Effective with high concentrations of long chain PFAS
- Low residual generation for disposal
- **60-99%+ removal**

Reverse Osmosis

- Broad PFAS removal
- Can remove other contaminants
- May require pre-treatment
- Generally, more expensive than other options
- Generates residual
- **90-99%+ removal**

Groundwater & Stormwater Treatment

Simpler Matrix = More Options

Groundwater & Stormwater are easier to treat because:

- Less PFAS present
- Lower organic content
- Less interference potential
- More predictable adsorption

So, what works?

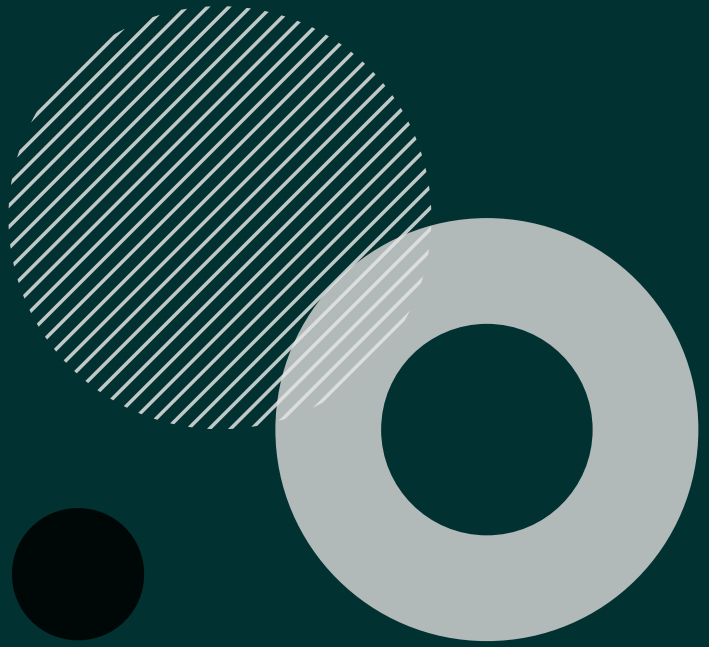
Granular Activated Carbon

- Established technology
- Simple operations
- Effective for long-chain PFAS
- Less effective for short-chain
- **70-99%+ removal**

Anion Exchange Resin

- Effective for short- and long-chain PFAS
- Smaller footprint
- Capital cost higher than GAC
- Spent resin management
- **80-99%+ removal**

Residuals Management



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Leachate evaporation in the US

PASSIVE / LOW ENERGY

Enhanced pond evaporation

- Misting systems over leachate ponds (e.g., New Waste Concepts)
- Used primarily as a volume reduction strategy
- South Carolina landfill: 2.1–2.6× natural evaporation, but only up to 7% cost savings
- Climate-limited; drift and aerosol questions

ACTIVE / LFG OR WASTE HEAT

Heated evaporators

- Fired by landfill gas or waste heat; enclosed designs (e.g., Heartland Concentrator)
- Heartland reports 25 units in 10 states
- Minnesota county pilot (2026): ~95% volume reduction

US PRACTICE

How they are used

- Mainly volume reduction where sewer discharge is restricted or hauling is costly
- Residue usually returns to the landfill
- Use as a concentration step ahead of destruction is still emerging





Sources: Drafts et al. (2023) Detritus; Heartland (2024) sponsored content; Marshall Independent (June 2026), Lyon County, MN pilot; Tang, FAMU/Hinkley Center (2023)

RESIDUALS MANAGEMENT · DECISION

Concentrate: return it to the landfill, or remove it?

CLOSE THE LOOP ON SITE

Return to the landfill

- Lowest cost; simplest logistics
- PFAS, chloride, ammonia and dissolved solids cycle back into the next leachate
- Calcium-rich residue adds clogging risk in the drainage layer
- Leachate strength can rise over time

TAKE IT OFF SITE

Remove and dispose

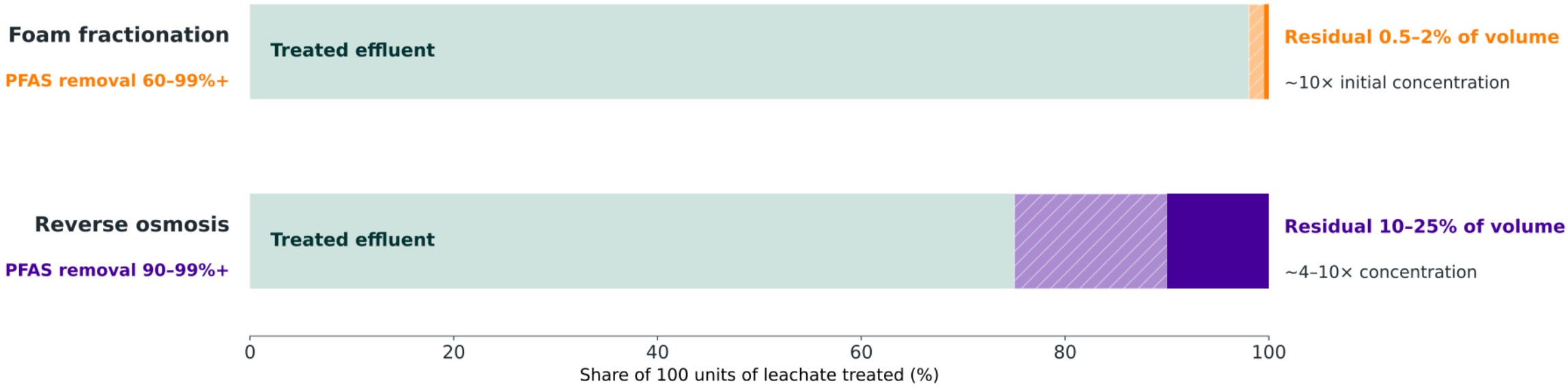
- Breaks the recycle loop
- Options: deep-well injection, incineration, stabilisation and off-site disposal, destruction (EC oxidation, SCWO)
- Higher cost; availability and regulator acceptance vary by jurisdiction

WHAT DECIDES IT

Site mass balance · residual volume (foam fractionation 0.5–2% of flow; RO 10–25%) · contaminants of concern such as PFAS · regulator acceptance · cost

Sources: EREF, Current State of PFAS Treatment for Landfill Liquids (forthcoming), Table 4-1; de Almeida et al. (2022) Waste Manag. Res. (membrane concentrate review)

Treatment concentrates PFAS into a smaller residual stream



Management options

Solidification and encapsulation · deep well injection · incineration · third-party disposal

Destruction

EC oxidation and SCWO suit small, concentrated volumes; high energy and O&M; limited availability

Source: EREF, Current State of PFAS Treatment for Landfill Liquids (forthcoming), Table 4-1

Electrochemical oxidation: practical considerations

1

Where it fits

Best matched to small, concentrated streams such as foam fractionation foamate or RO concentrate, rather than whole leachate volumes

2

What drives performance

pH, temperature, electrode material and reaction conditions; leachate organics and dissolved solids compete for oxidation capacity

3

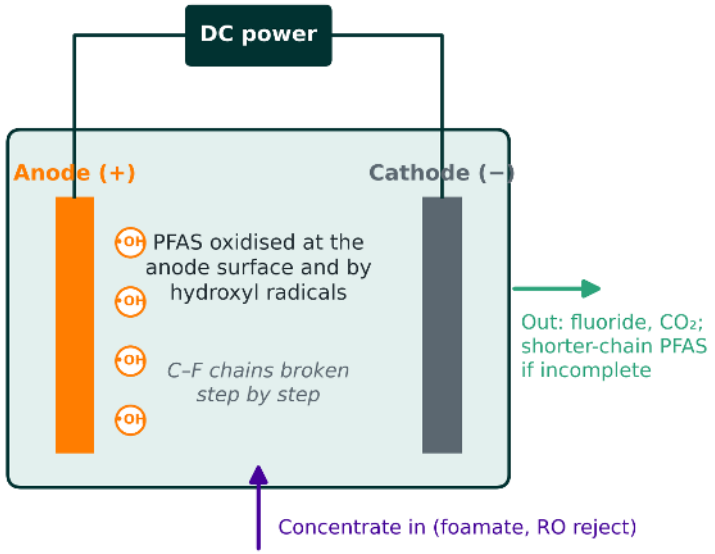
Watch-outs

Partial destruction can leave shorter-chain PFAS; chloride-rich streams can form chlorate and perchlorate; electrodes can scale and foul

4

Status

High PFAS destruction is achievable, but energy and O&M demands are high and commercial application at landfills is still limited



HOW IT WORKS

A direct current drives oxidation at the anode, often boron-doped diamond. PFAS are attacked at the anode surface and by hydroxyl radicals, breaking toward fluoride and CO_2.

Source: EREF, Current State of PFAS Treatment for Landfill Liquids (forthcoming); byproduct and fouling points from the wider EC oxidation literature

Landfill Emissions

US methane rules: a federal floor; states go further

FEDERAL FLOOR

Federal (Clean Air Act)

- 2016 landfill standards: sites ≥2.5 million Mg and 2.5 million m³ capacity install gas collection once NMOC reaches 34 Mg/yr
- Quarterly surface monitoring at 500 ppm; 98% NMOC destruction
- Methane is controlled as a co-benefit of NMOC limits, so the Feb 2026 endangerment-finding repeal did not change these rules
- GHG reporting above 25,000 tCO_2e/yr; EPA proposed ending it (Sept 2025), not final; 2025 reports due 30 Oct 2026
- The federal methane fee (IRA 'Waste Emissions Charge', $1,500/t CH_4) applies only to large oil and gas facilities; its start is now delayed to 2034

State	What is different
California	Methane-based trigger (2010). 2025 amendments (in force 2027): collection under working face at 15 ft depth; drones for steep areas; must respond to satellite and aerial plumes; repairs start within 3 days
Maryland	Methane-based trigger and 200 ppmv threshold (2023)
Oregon, Washington	Rules modelled on California
Colorado	Collection above 664 t CH_4/yr; open flares phased out; drones allowed; satellite-flagged leaks checked within 15 days (Dec 2025)

Sources: 40 CFR 60 Subparts XXX/Cf; Federal Register (16 Sept 2025); Gable Gotwals (Sept 2026); CARB LMR fact sheet (Feb 2026); MDE; Waste Dive (Dec 2025)

METHANE · US INCENTIVES

What else drives landfill gas capture in the US

PAY FOR CAPTURE

Market incentives

- Federal renewable fuel credits (RFS D3 RINs) for landfill gas used as vehicle fuel
- State low-carbon fuel standards: California, Oregon, Washington
- Federal 45Z clean fuel production tax credit, extended through 2029
- Voluntary carbon offsets, only for landfills not already required to collect gas

REDUCE OR CONTROL BY OTHER MEANS

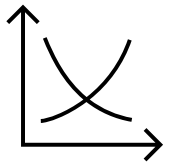
Indirect regulation

- Federal hazardous air pollutant standard for landfills (2020): wellhead and operating requirements
- Organics diversion mandates: California SB 1383 targets a 75% cut in organics disposal (2025 vs 2014); food-waste bans in other states
- EPA enforcement alerts on gas collection operation and maintenance (2024)
- Public satellite and aerial plume data adding reputational pressure

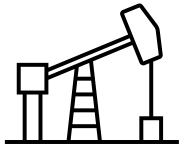
Much US landfill methane control is driven by markets for gas and by rules written for other pollutants.

Sources: EPA LMOP; Waga Energy (2026) incentive summary; CalRecycle SB 1383; Harvard EELP regulatory tracker

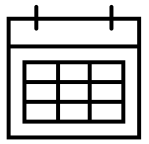
Landfill Emissions Monitoring



New technologies are emerging to monitor these emissions – can go beyond models



How effective are these technologies are in a landfill setting?



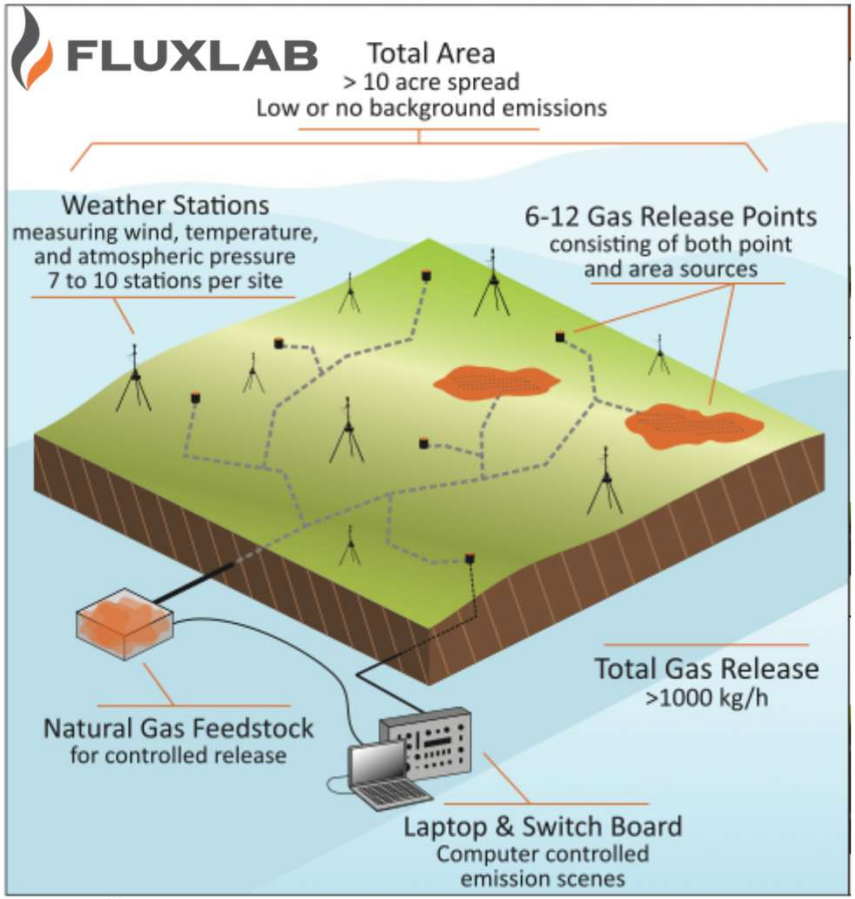
Most measurements at discrete timepoints – how can these be expanded to an annual emissions value

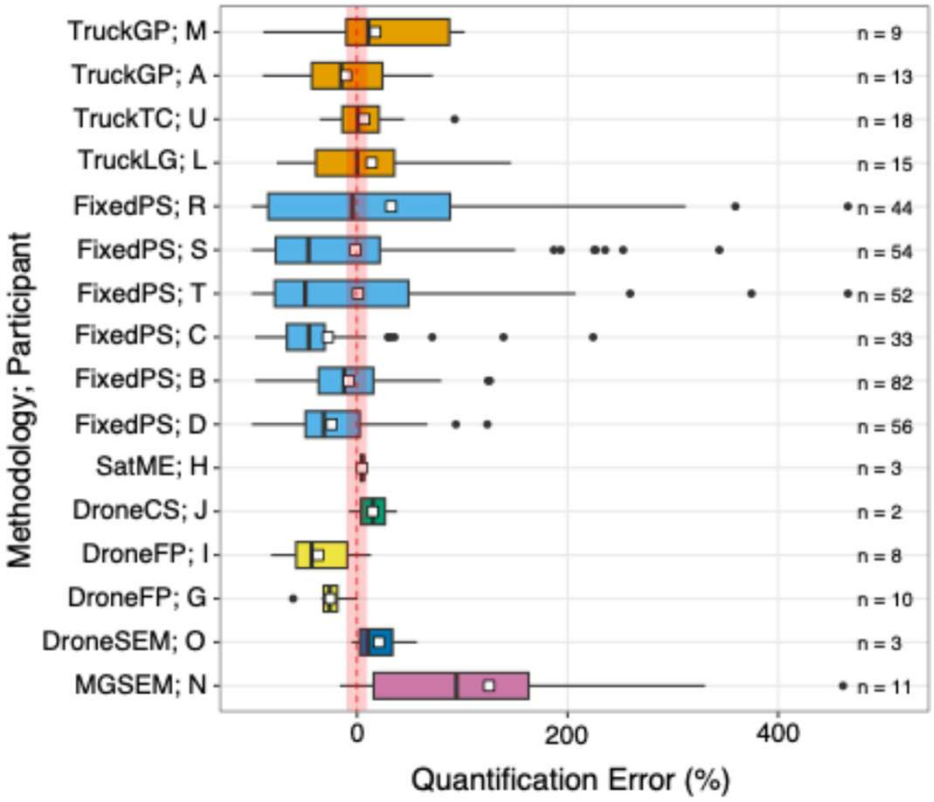


Standard Methods need to be developed

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EREF Controlled Releases





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Three Rivers Solid Waste Authority (TRSWA)

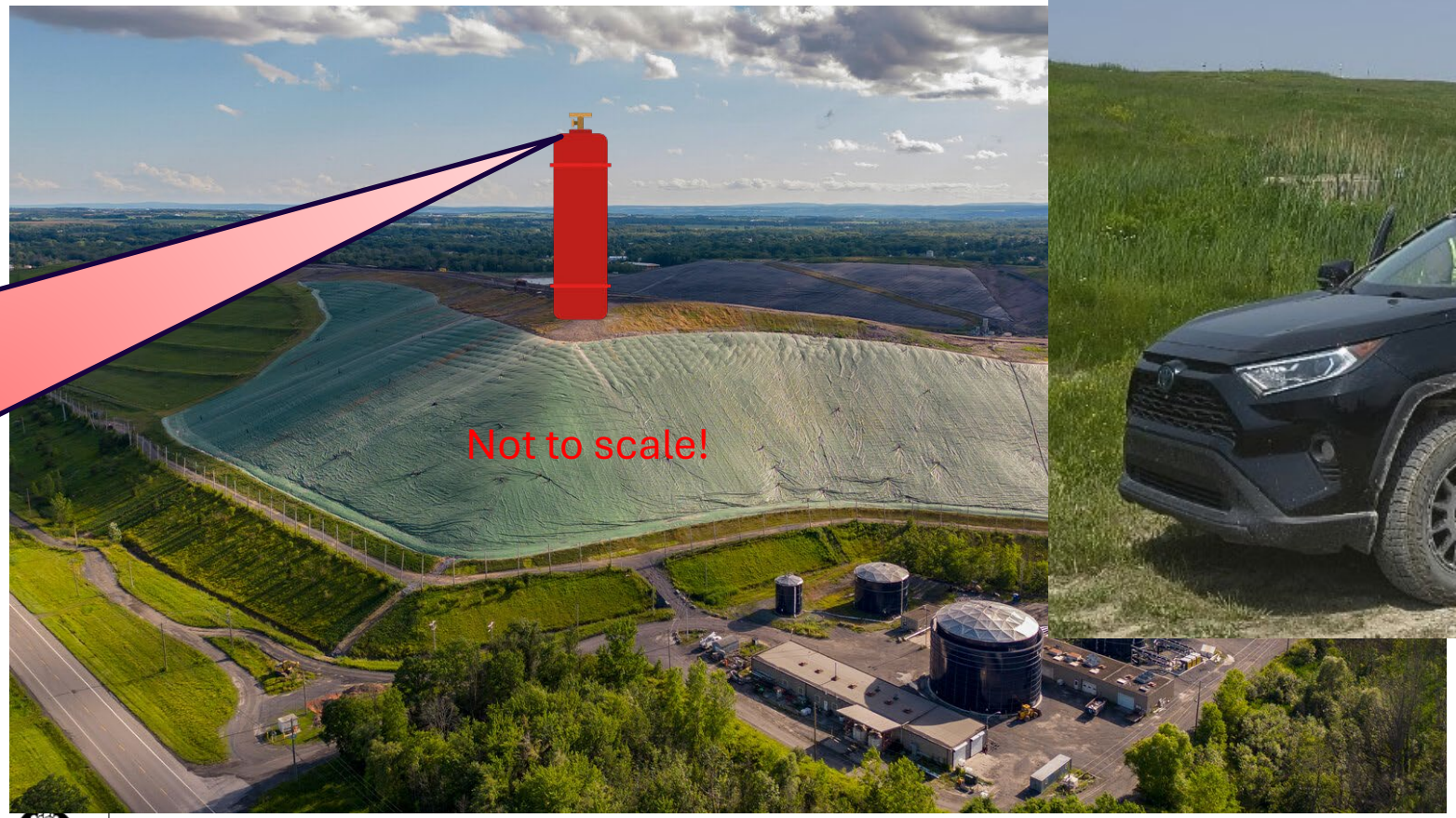


- Near SC/GA border
- Opened 1998
- Consortium of 9 counties
- Located on the US DOE's Savannah River Site
  - Obligation to spend portion of tip fees to fund research
- New RNG plant

Landfill Emissions Frequency of Monitoring

- Accuracy of discrete measurements
- Frequency of measurement needed for annual calculations
  - Temporal effects
- Technologies included in protocol:
  - Tracer Correlation Method
  - Continuous Sensors
  - Satellite
  - ~~UAV~~
  - SEM (?)
  - GCCS Data

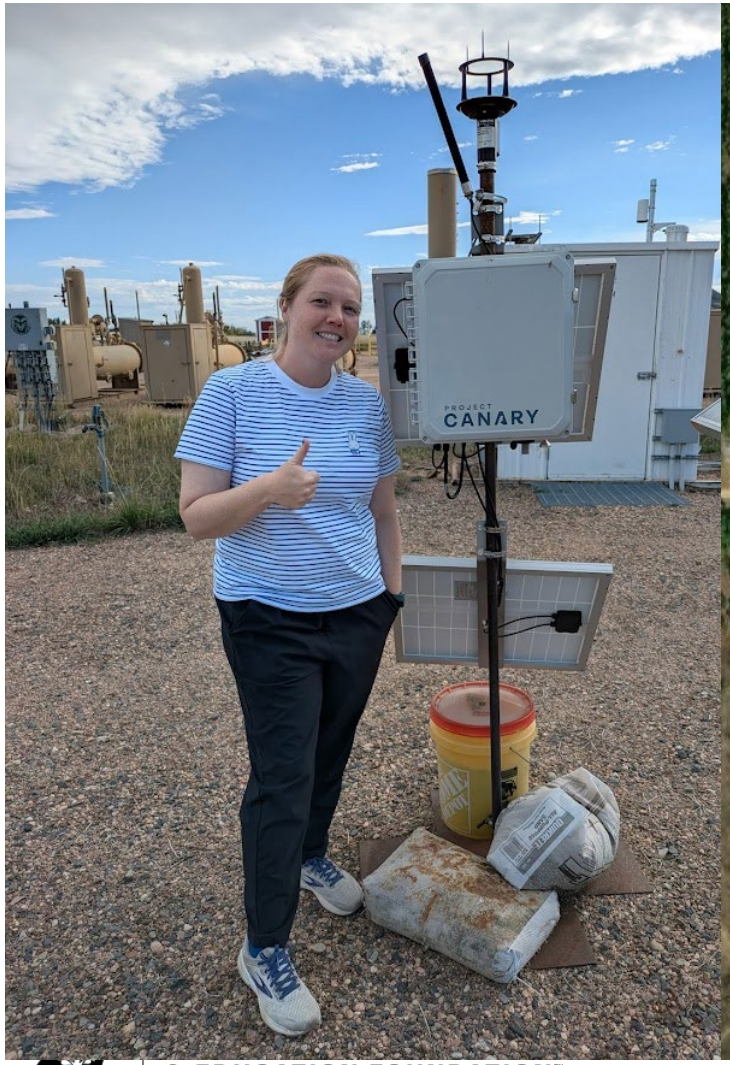
Tracer Correlation Method



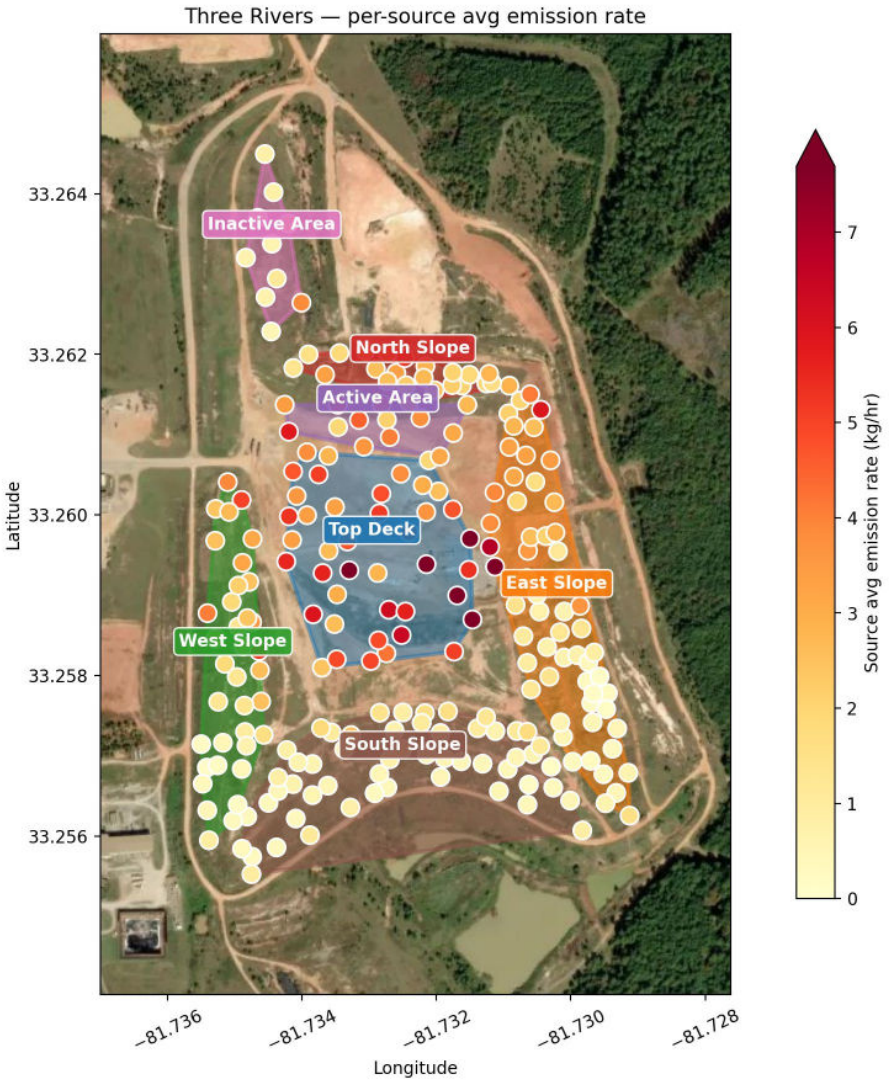




Continuous Sensor

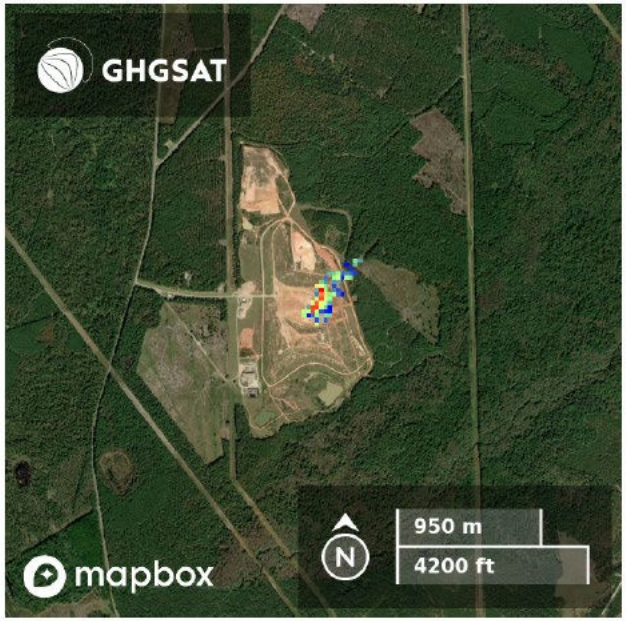






Satellites (and Aircraft)





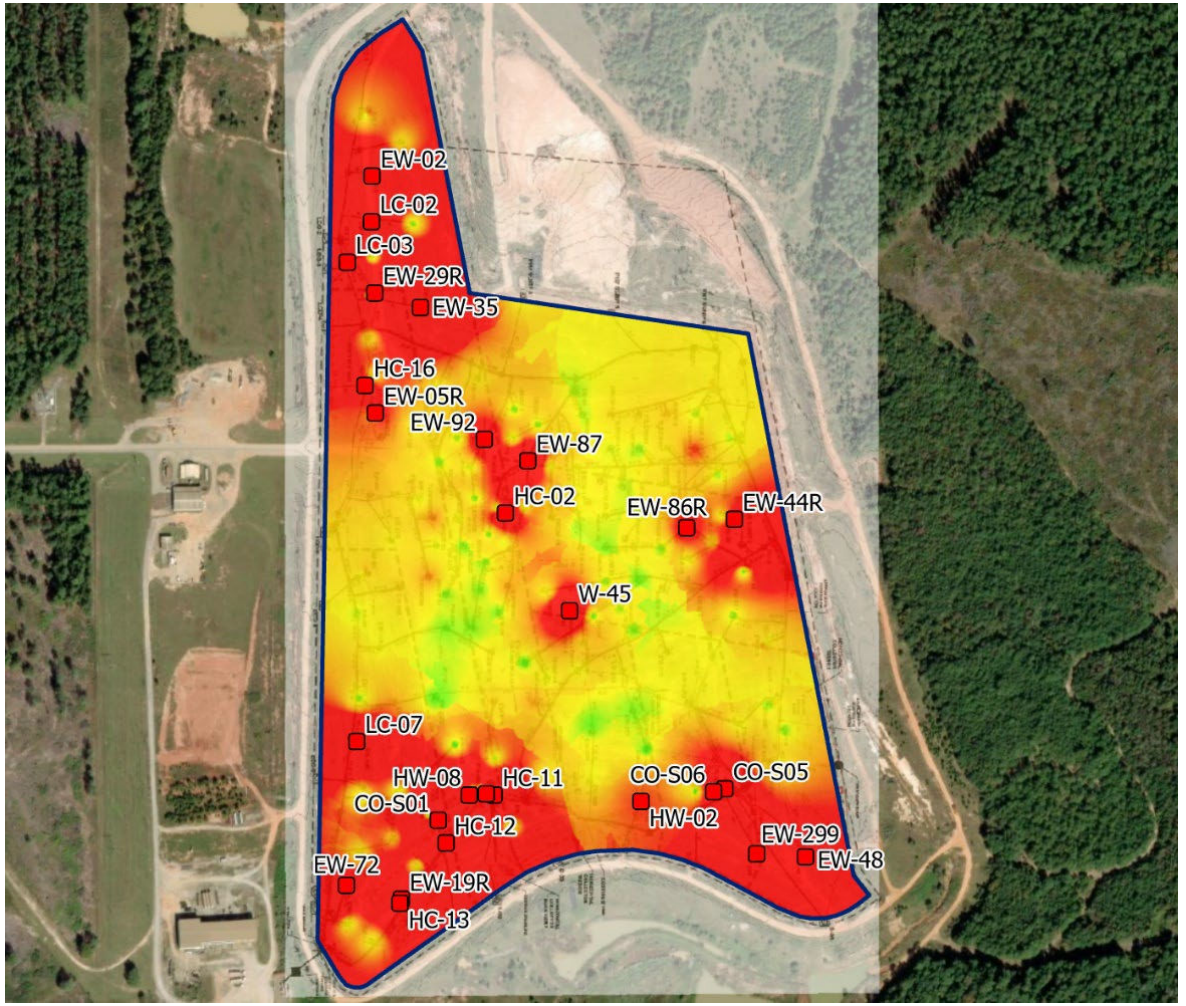




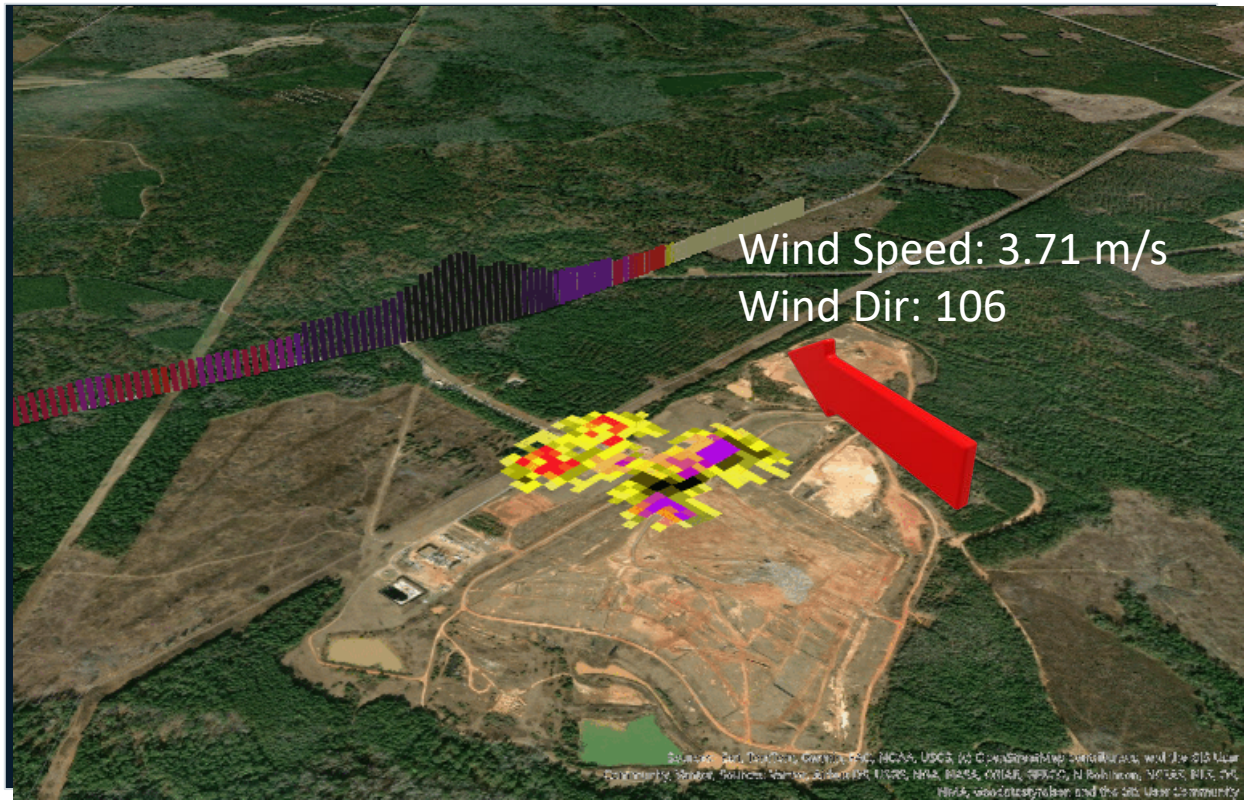
Emission Detection	Date (YYYY-MM-DD)	Latitude (°)	Longitude (°)	Wind (m/s)	Source Rate (kg/hr)	Source Rate Error (%)
YES	2026-02-12 20:46:50 UTC	33.2598	-81.7321	1.31	340	41

Surface Emissions Monitoring: Handheld and UAV





Preliminary results: Concurrent TCM & Satellite



Concurrent GHGSat and TCM

April 10, 2026 · GHGSat pass, concurrent with the TCM ground transect

3.3% ERD	**2.8** SNR	**5.16** SNR (C_2H_2)
0.874 R^2	**Gold** Plume Category	**30** MA (15-min)

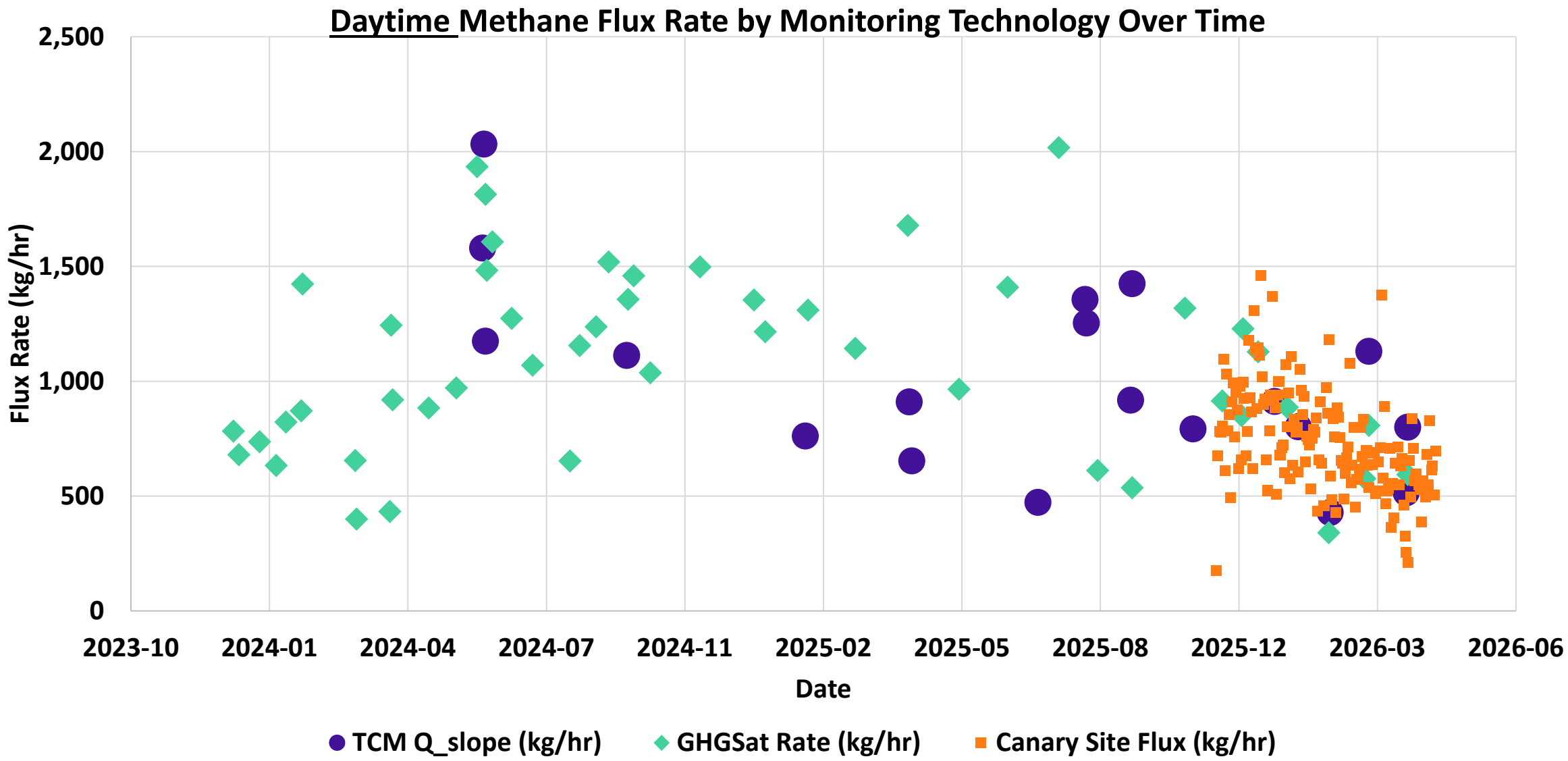
Flux quantification (TCM):

526 kg/h Q Slope Flux	**528 kg/h** Q Area Flux

Flux quantification Satellite

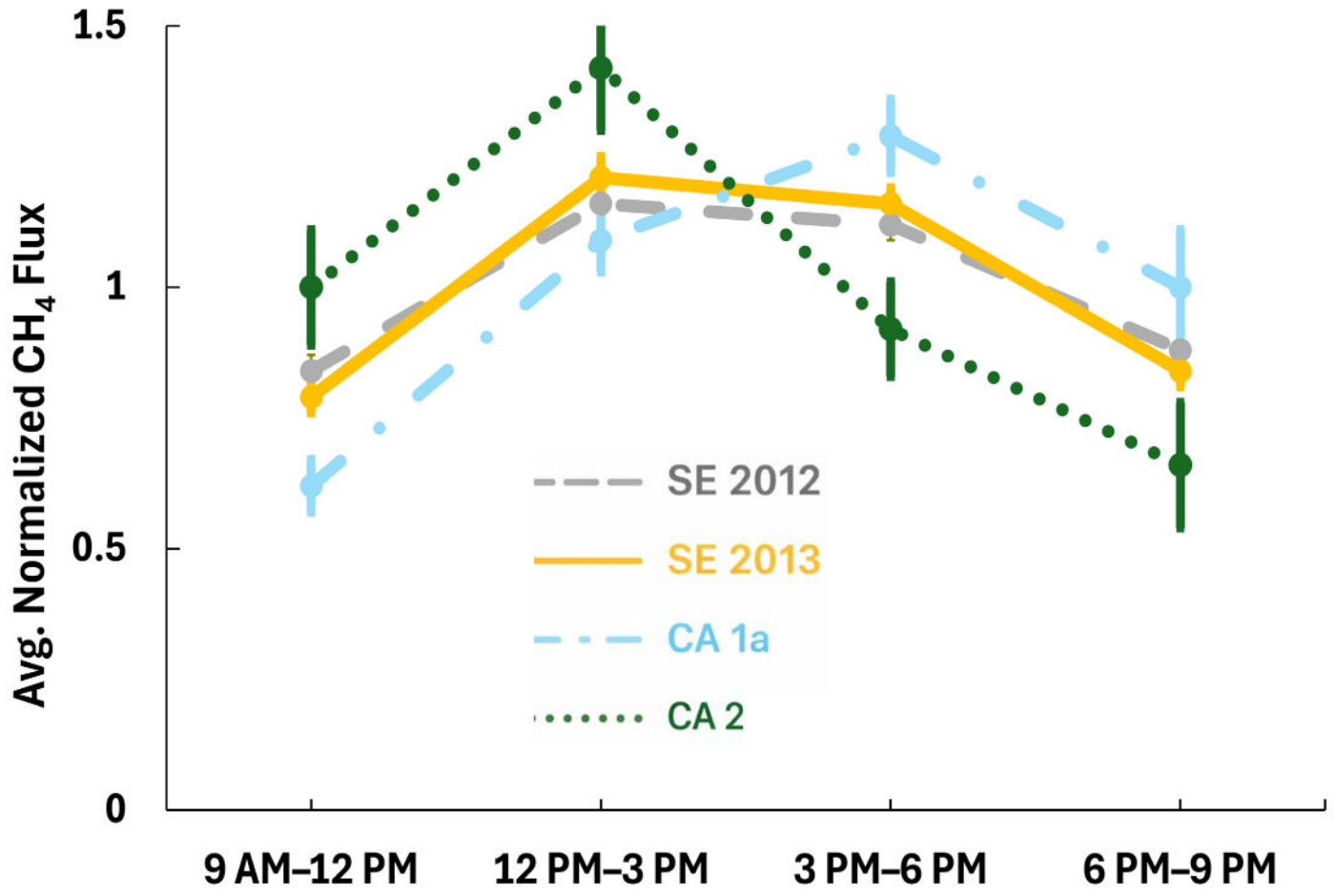
593 kg/h Flux	**13 % Higher**

Flux Estimates with Different Technologies



EREF

CH_4 Flux - Diurnal Variability (U. Delaware Study)



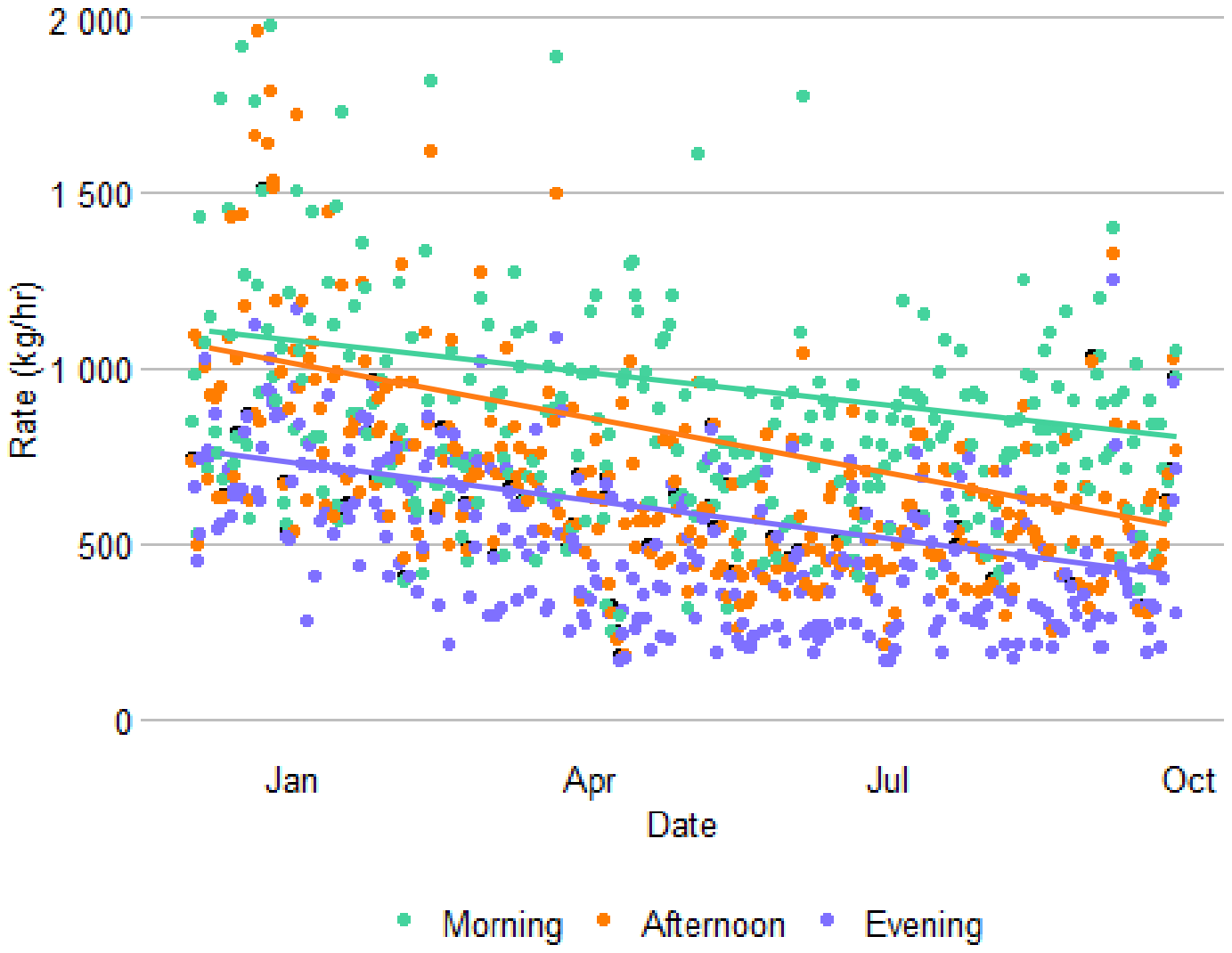
- Diurnal patterns were **consistent** regardless of cover type or GCCS presence.
- Emissions varied up to **2x** in a day and often reached **peaks between 12-6 PM**.
- **Measurement timing could significantly influence extrapolated annual estimates.**

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Project Partners: Univ. of Delaware, UC-Davis

Continuous Sensor Preliminary Data (SC Site)

- Similar diurnal pattern identified in Delaware study observed at SC site
- Morning emissions > Afternoon emissions > Evening Emissions
- Pattern holds even as overall emissions are dropping



Rethinking EPA Method 21 Surface Emissions Monitoring: Quantifying Performance Limits for Methane Detection at Municipal Solid Waste Landfills

David Risk[a], Nadia Tarakki[a], Karen Marsh[b], Lindelwa Coyle[a], Martin Lavoie[a], Rafee Hossain[a], Pylyp Buntov[a], Yurii Dudak[a], Khalil El Hachem[a], Chelsie Hall[a], Tarek Abichou[c]

[A]
Department of Earth and Environmental Sciences, St. Francis Xavier University, Antigonish, NS, Canada
[b]Lumina Sky Consulting PC, Holly Springs, NC, USA
[c]Department of Civil and Environmental Engineering, Florida State University, Tallahassee, FL, USA

Evaluating EPA M21 SEM

01
The Regulation

EPA Method 21 SEM is the standard compliance tool for landfill gas monitoring

Incorporates

- 30 m grid
- 500 ppm action trigger

Sensitivity and reliability was never established

02
What Was Tested

Simulations and

SIMFLEX-LF controlled-release site in Petrolia ON

90%-Probability of Detection (POD) Minimum Detection Limit (MDL)

3 spacings: 30, 15, 7.5 m

3 triggers: 500, 200, 50 ppm

03
What Was Found

98 kg/h

Regulatory MDL
30 m / 500 ppmv

13 kg/h

Enhanced MDL (Colorado etc)
7.5 m / 200 ppmv

Most modern tools out-compete even an Enhanced version

Elementa paper: Tarakki, N., Marsh, K., Coyle, L., Lavoie, M., Hossain, R., Buntov, P., Dudak, Y., El Hachem, K., Hall, C., Abichou, T., Risk, D., 2026. Rethinking EPA Method 21 Surface Emissions Monitoring: Quantifying performance limits for methane detection at municipal solid waste landfills. Elementa: Science of the Anthropocene 14, 00133. https://doi.org/10.1525/elementa.2025.00133

SEM versus Alternatives

Method	90%-POD	% Sources Detected
SEM - 30 m / 500 ppm	98 kg/h	< 10%
SEM - 7.5 m / 200 ppm	13 kg/h	9 – 54%
UAS TDLAS or tube (OTM51)	~6 kg/h	20 – 54%
Aerial LiDAR	~1 kg/h	70 – 90%

Source Detection Comparison

Source distributions from detailed surveys at 8 landfills in Canada:

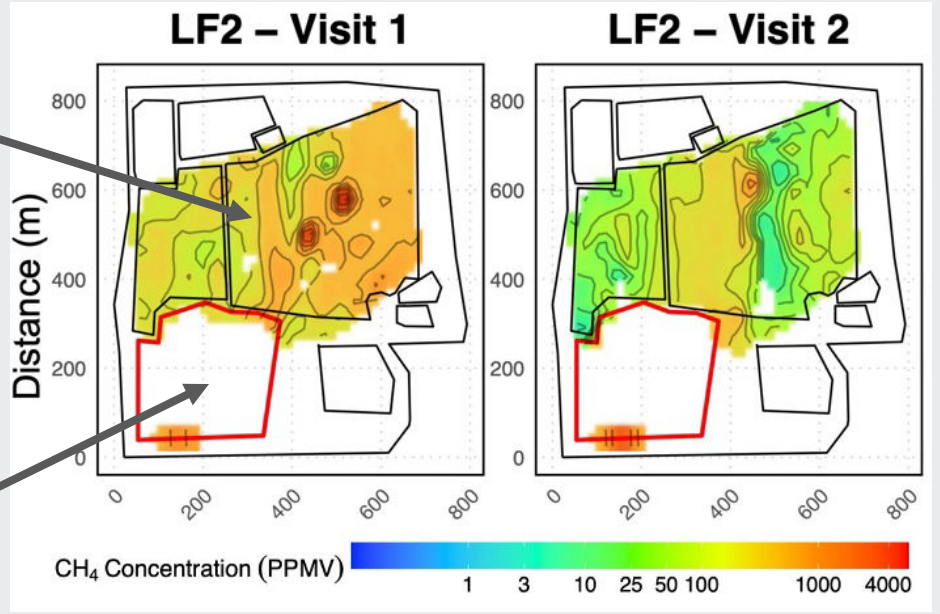
- SEM applicable areas only
- ~15-35 sources per site
- ~1-100 kg/hr (most smaller)

EPA M21 SEM detected very few sources, higher cost.

Source Coverage Comparison

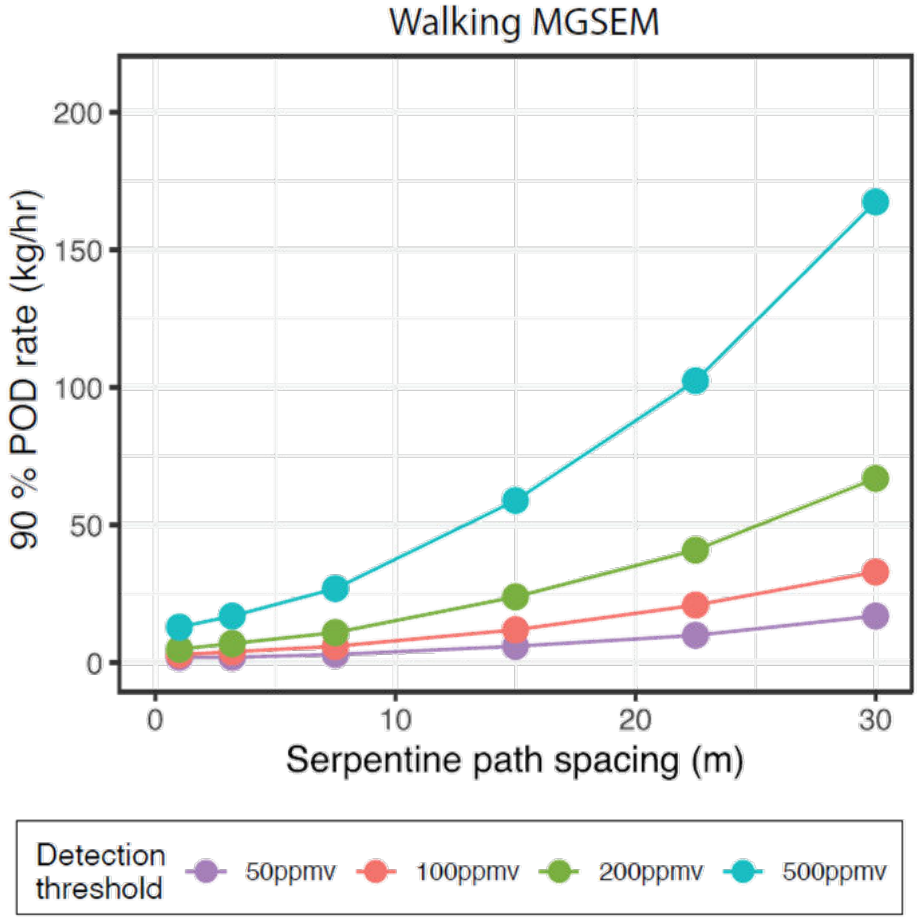
Source distributions from same 8 landfills:

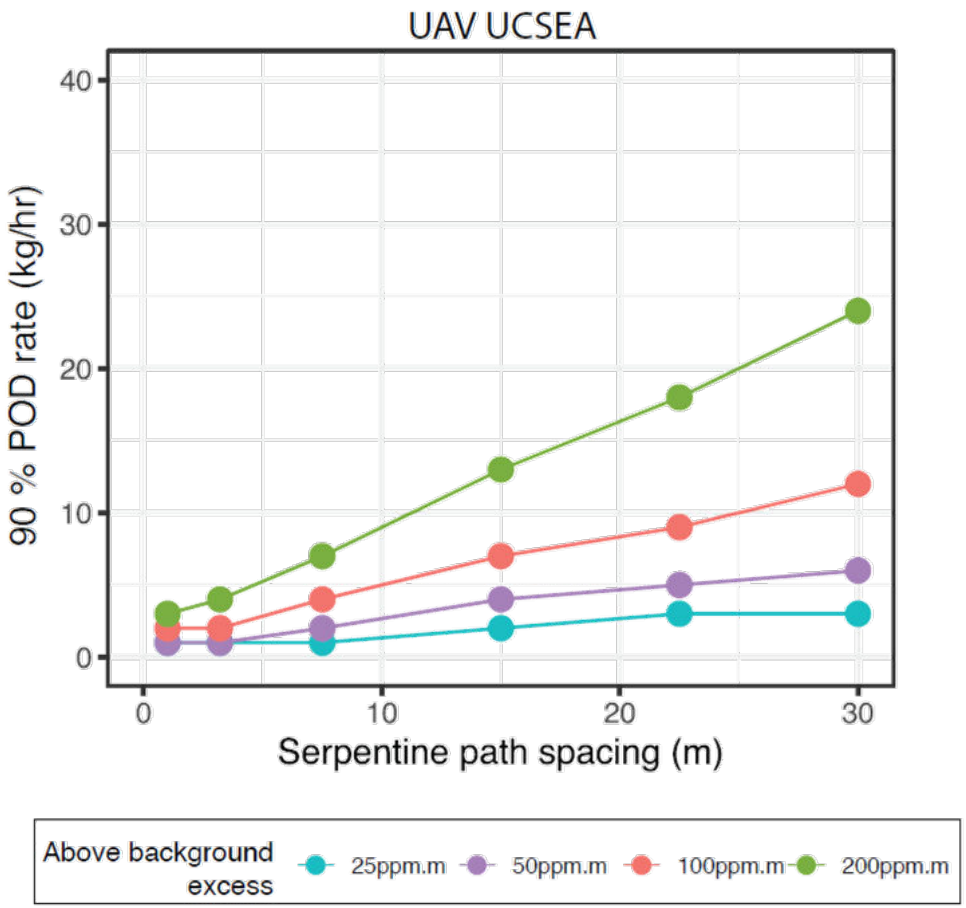
- Hired professional SEM service provider
- Highest emitting portions not walkable (red outline)
- SEM coverage (heat maps) was only 17% of total
- Most alternative techs can cover all sources



Omidi, A., Bourlon, E., Khaleghi, A., Tarakki, N., Martino, R., Stuart, J., Risk, D., 2025. Most landfill methane emissions Escape detection in EPA21 surface emission monitoring surveys. Waste Management 207, 115104. https://doi.org/10.1016/j.wasman.2025.115104

Surface Emissions Monitoring (SEM) EPA Method 21 Detection Sensitivity





EPA Method 21 SEM is inconsistent and has low detection sensitivity, especially at larger path spacings.

Utilizing drones enhance detection rate and sensitivity

LOOKING AHEAD · AI

AI in landfill management: now and next

IN USE OR IN PILOT

Now

- Gas wellfield: automated wellhead tuning with AI-generated action plans (LoCI Controls)
- Equipment: remote-operated dozer in service, autonomous compactor next (WM with Caterpillar, Arizona)
- Airspace: drones and equipment GPS track density and remaining capacity
- Emissions: sensor accuracy gains from algorithms alone; satellite plume detection
- Hazards: AI detection of batteries at tipping floors (MRFs and transfer stations; landfill use emerging)

WHERE IT IS HEADING

Next

- “Digital twins” combining gas, temperature, leachate and survey data
- Early warning of heat build-up, subsurface reactions and fires
- Autonomous compaction tuned for density and cover use
- Continuous monitoring accepted by regulators in place of quarterly surveys
- Better emissions estimates from models trained on measurements

Sources: Waste Dive (2026) LoCI Controls; Waste Dive (Aug 2026) WM autonomous equipment; Waste360; EREF 2025 controlled-release report; Waste Advantage (2026)

Thank you

EREF is a resource for you.

Bryan Staley, Ph.D.

bstaley@erefdn.org · erefdn.org

Backup slides

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PFAS · THERMAL DESTRUCTION · STUDY 2

Municipal WTE: Reworld Lake County, Florida

98%

Average C2F6 DRE, higher than predicted at typical WTE temperatures

< 2.6 ng/m³

Each individual PFAS in stack gas; PFOS not detected

7.8 g/yr

Estimated annual air emissions, all detected PFAS; PFOA < 0.5 g/yr

Conditions

Reciprocating grate mass burn, 228 tpd unit; above 1093 °C in the flame zone; normal MSW plus permitted medical waste

What could not be determined

PFAS DRE (feed PFAS content unknown) and air pollution control removal (stack levels near detection limits)

Source: U.S. EPA (2026) Characterization of PFAS in the Emissions from a Municipal WTE Facility and the Destruction of Hexafluoroethane, EPA 600/R-25/273

TAKEAWAYS

The landfill receives what treatment leaves behind

Ash and APCR

Test reactivity; set monofill or mixing rules for slope stability and heat

Thermal destruction

High destruction at full scale; what survives goes mostly to bottom ash

Leachate PFAS

Foam fractionation and RO suit leachate; plan for the residual before choosing

Methane

SEM misses most sources; method, timing and analytics drive accuracy

Research gaps relevant to Australia: deep and wet sites, salt and PFAS in returned residues, satellite validation for landfills.

METHANE · SURFACE EMISSIONS MONITORING

Walking SEM detects only the largest leaks

~65 kg/h

Leak size detected 90% of the time at the regulatory setup (30 m spacing, 500 ppmv)

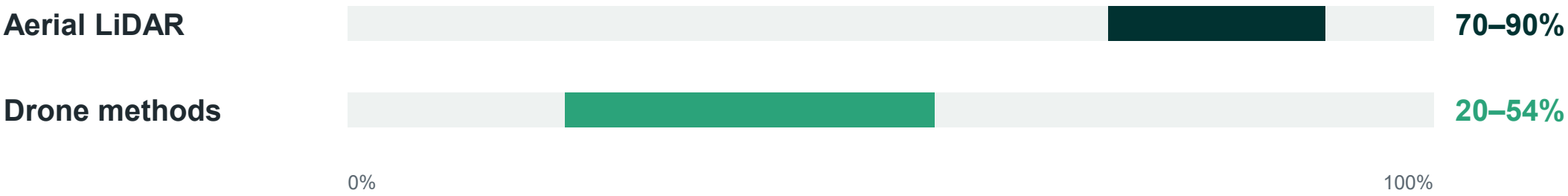
≤ ~10%

Share of individual sources detected at real landfills, because most emit less than 65 kg/h

~13 kg/h

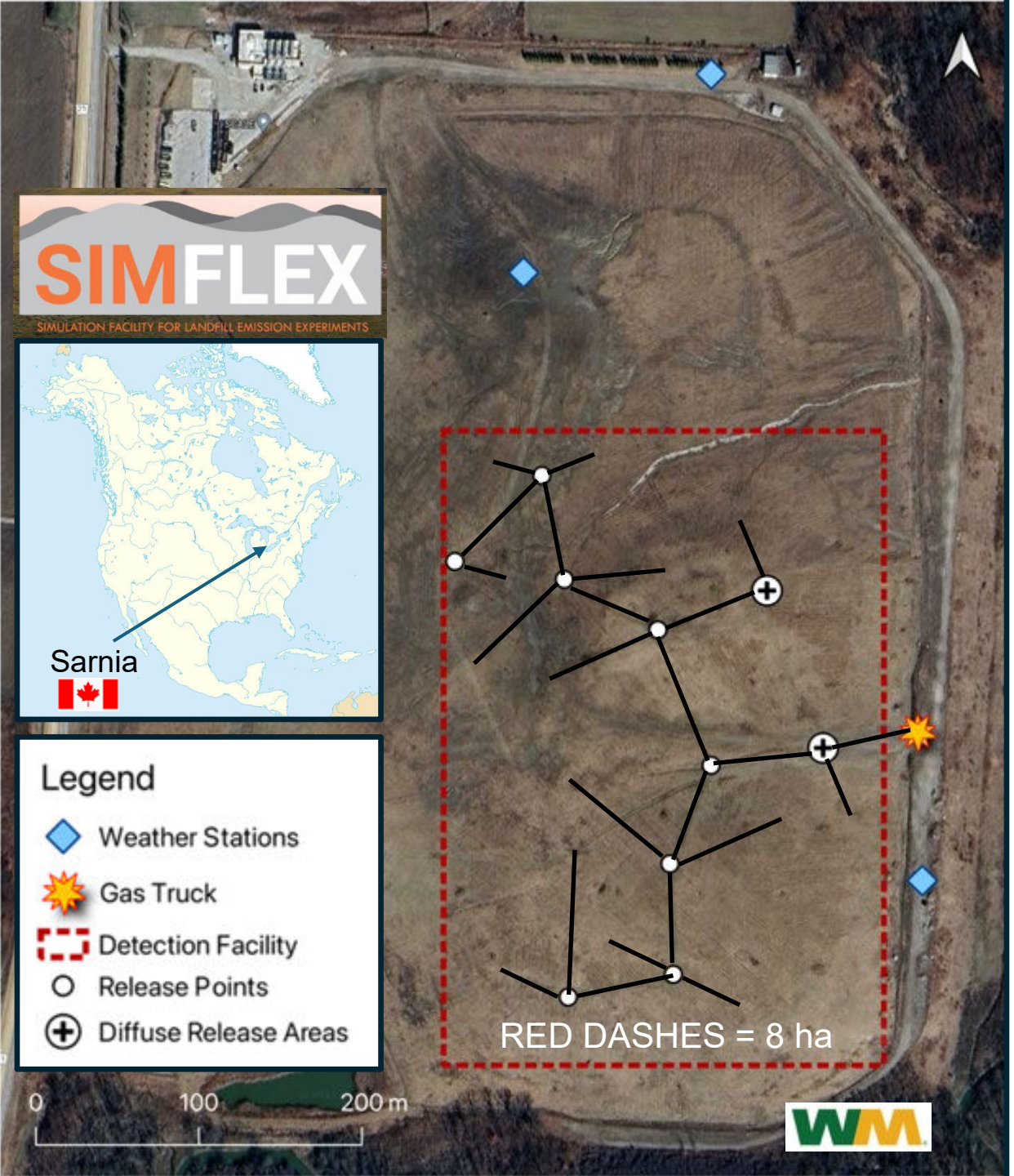
With 7.5 m spacing and 200 ppmv, at the cost of more survey effort and false positives

SHARE OF TOTAL EMISSIONS DETECTED, EIGHT CANADIAN LANDFILLS



Even optimised SEM detects a smaller share than either, and finds less methane per dollar spent.

Source: Tarakki et al., Rethinking EPA Method 21 Surface Emissions Monitoring (St. Francis Xavier University; manuscript)



Controlled Releases

- **World's largest test facility for landfill emissions measurement**
- Operated for **EREF**, representing US/CAN landfill industry, and hosted by **WM**
- Closed landfill with gas collection
- For testing ALL measurement methods
- >12 release areas (point, small area, large area)
- Over 200 blind experiments
  - Over 30 participants from 8 countries thus far

EREF Environmental Research & Education Foundation
Lighting the way towards a more circular economy
NSERC CRSNG
FLUX LAB gas detection measurement

THE EREF VALUE MODEL

Where Research Creates Business Value

SEE ACROSS THE INDUSTRY

Reveal patterns no single company can see from its own operations.

TEST INDEPENDENTLY

Validate technologies, assumptions and anecdotal observations without commercial bias.

SHARE THE COST OF LEARNING

Investigate common problems more efficiently than having every company solve them independently.

CREATE CREDIBLE EVIDENCE

Establish a factual baseline useful to companies, regulators, policymakers, technology providers and other stakeholders.

INVESTIGATION → EVIDENCE → OPTIONS → INFORMED ACTION → MEASURED PERFORMANCE

EREF helps companies answer important questions they cannot answer alone, should not have to answer alone, or would be less credible answering alone.

Research reduces uncertainty around decisions that affect cost, revenue, risk, asset value and strategic flexibility.

WASTE-TO-ENERGY

Diverting combustibles changes how the landfill behaves

Landfill property	Expected direction	Open questions
Gas generation	Lower and earlier decline as degradable carbon leaves	Viability of gas collection and energy projects
Leachate	More inorganic: salts, metals, alkalinity from ash	Treatment systems designed for organic leachate
Waste mass	Denser, finer, more reactive fraction (ash, APCR)	Slope stability, heat release, permeability
Special wastes	Larger share of what is placed	Mixing ratios and placement rules

Much of this is still the subject of ongoing research; directions are qualitative and site-specific.

Directions summarised from EREF research and industry experience; see also GHD, “Future proofing Australia’s engineered landfills”

ORGANICS MANAGEMENT · EREF-FUNDED RESEARCH

Tracing PFAS and Microplastics from Organics to Farmland

The extent and impact of PFAS and microplastics in compost and digestate remain largely unknown as land application of diverted organics increases.

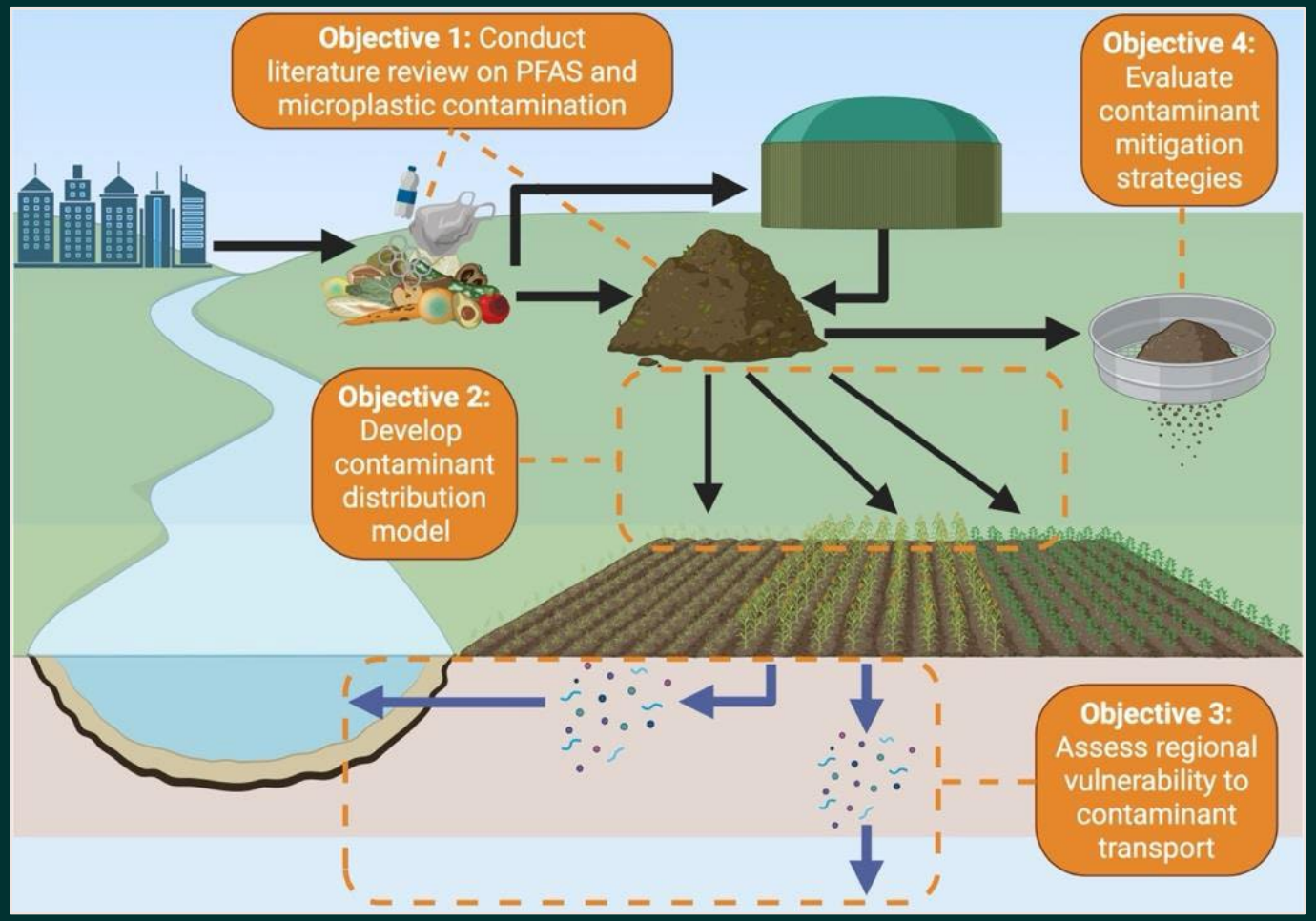


Figure: C. Scown, UC Berkeley (EREF-funded project proposal)

WHAT THE RESEARCH CONTRIBUTES

- **Evidence base (Obj. 1):** the most complete open dataset of PFAS and microplastic concentrations in organic feedstocks, composts and digestates.
- **National model (Obj. 2):** open-source, so operators and agencies can run their own inputs and assumptions.
- **Regional view (Obj. 3):** identifies potential hotspots and informs where land application is suitable.
- **Mitigation options (Obj. 4):** tests source control, sorting, thermal treatment, regulation and source separation, including greenhouse gas tradeoffs.
- **Industry input:** an advisory board of industry, trade group, research and regulatory participants reviews methods and results.

EREF Support

EREF does not have members, and as a result, there are no membership dues.

Support comes *solely* from:

- Fundraisers
  - Charitable Auction ($28+ million since 2015)
  - Fall Classic ($3.5+ million since 2015)
- Philanthropic Giving
  - Major Gifts (corporate/individual)
  - Program-Based Revenue
    - Educational sponsorships
    - Directed research funding



All of EREF's operating costs are covered by fundraisers – 100% of philanthropic giving goes directly to our programs.



EREF has raised over $23MM in philanthropic funding over the past five years (2020-present).

PFAS Treatment Technologies

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PFAS Treatment: Technology State of Practice

- 15 technologies evaluated
  - Many technologies exist at different stages of development
  - Study focused on established, commercial technologies

- Effectiveness depends on liquid quantity, type and concentration of PFAS, presence of other contaminants, removal target.

Separation / Concentration

- Granular Activated Carbon (GAC) & Powdered Activated Carbon (PAC)
- Novel Sorbents
- Anion Exchange Resin (AER)
- Precipitation/Coagulation/Flocculation
- Foam Fractionation
- High-Pressure Membrane Systems
- Aqueous Electrostatic Concentrator (AEC)

Destruction / Transformation

- Electrochemical Oxidation (EO)
- Supercritical Water Oxidation (SCWO)
- Incineration
- Photodegradation
- Hydrothermal Alkaline Treatment (HALT)
- Plasma
- Sonolysis

What is the cost of treatment?

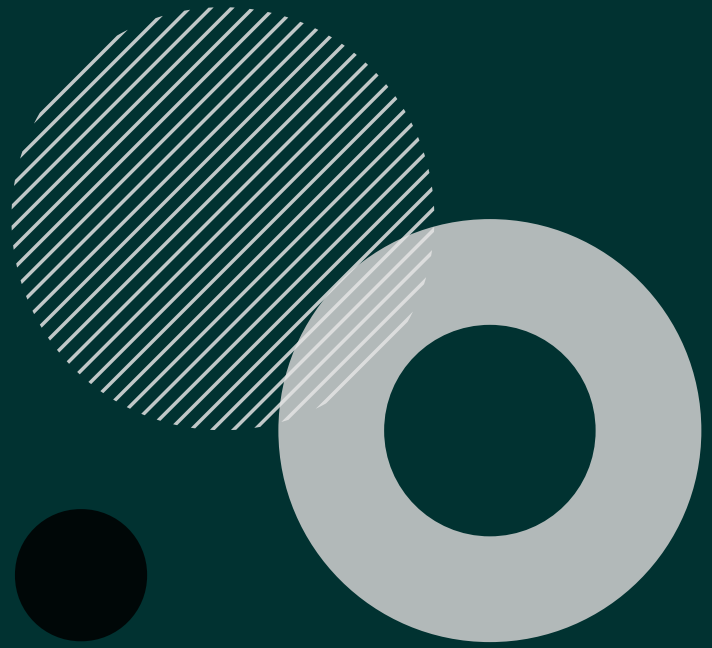
- Estimates only – will depend on system design and liquid characteristics.

	FOAM FRAC	REV OSM	GAC	ANION X RES
Typical PFAS removal	~60–95%	~90–99%+	~70–95% long-chain	~80-99%
CapEx*	$1.8–2.8M	$3.3–4.9M	$0.3–0.4M	$0.2-0.5M
OpEx*	$0.004–0.02/gal	$0.02–0.07/gal	$0.002–0.007/gal	$0.002-0.009/gal
Energy	Low	High	Low	Low
Pretreatment	Minimal	Variable	Important for leachate	Important for leachate
Primary fit	Leachate	Broad	GW/SW	GW/SW

*Capital estimates are for a 100,000-gpd PFAS treatment system and are March 2025 dollars.

Evaluating direct measurement technologies for landfill emissions

University Partner: St. Francis Xavier University (Fluxlab)



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Emissions Measurement Tech

Vendors and R&D participants, by Method

- Find and Fix
  - Walking SEM
  - UAV SEM OTM 51
  - UAV TDLAS
- Quantification
  - Aircraft mass balance
  - UAV concentration sensor / flux plane
  - Mobile/Truck Tracer Correlation
- Find and Fix and Quantification
  - Satellite
  - Aircraft LiDaR imaging
  - Truck Inverse Gaussian Dispersion/Lagrangian R&D
  - Fixed Sensor R&D Basis
  - Other R&D - StFX and ECCC

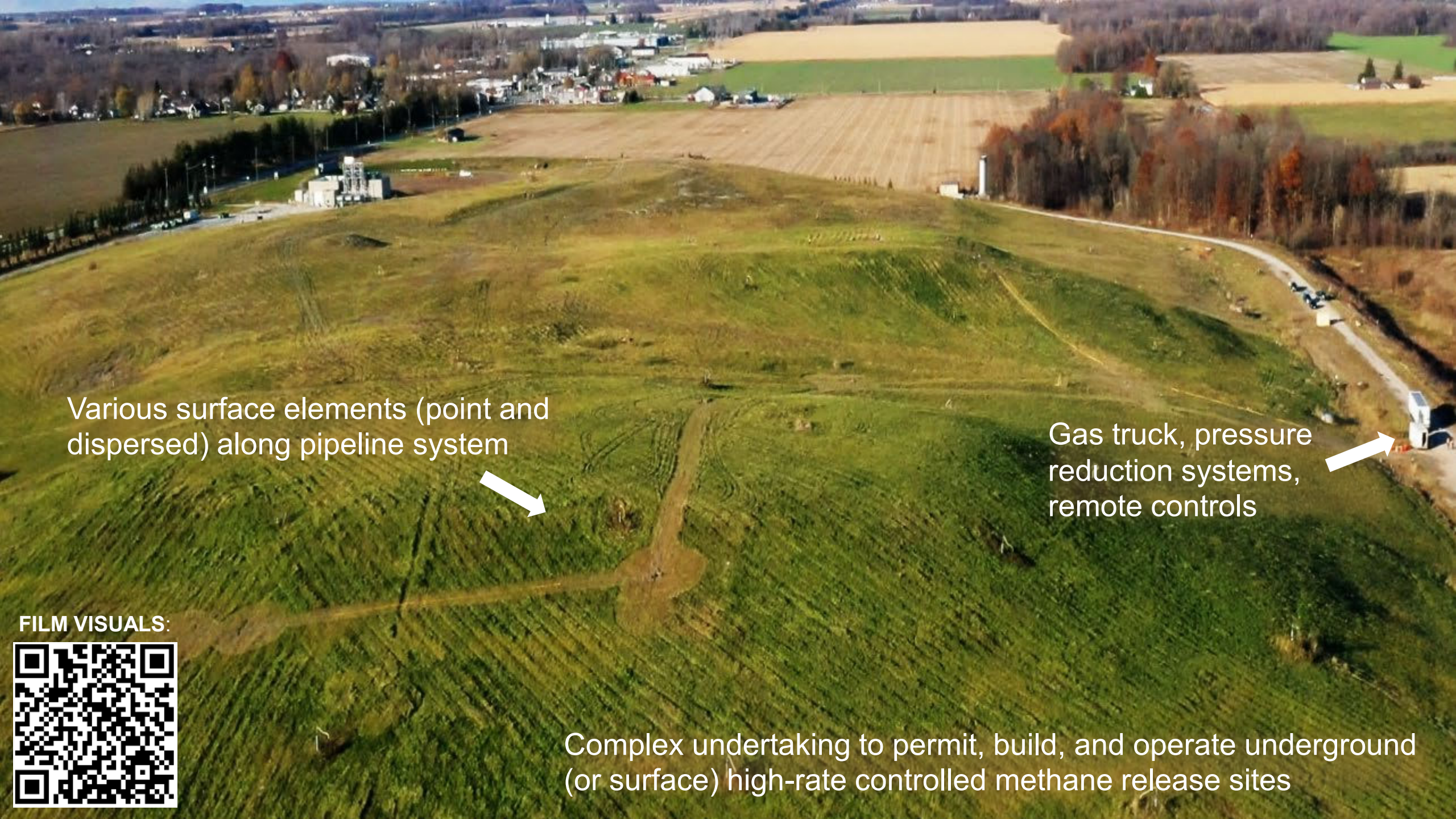











Various surface elements (point and dispersed) along pipeline system
Gas truck, pressure reduction systems, remote controls
FILM VISUALS:
Complex undertaking to permit, build, and operate underground (or surface) high-rate controlled methane release sites

Key Outcomes: Landfill Emissions

- **Model evaluation**
  - SWICS model updated; use case established; enhancements underway
  - Gas collection efficiency identified as limitation for EPA models (e.g. HH6/HH8)

- **Direct measurement technology evaluation**
  - Controlled release landfill emissions test site established (world's largest)
  - 17 technologies/methods evaluated for accuracy (e.g. satellite, aircraft, drone, ground) → found 20% to over 1000% error
  - Technology innovated (e.g. drone, fixed sensor) → 80% error to <10% error
  - SEM technique (EPA Method 21) limitations identified, drone approaches are more sensitive

- **Emissions Inventory Estimates & Operational Impacts**
  - Diurnal variation shows 2x emissions variation based on time of day
  - Measuring emissions from different operating zones (e.g. working face, temp. cover)
  - Measurement frequency can significant impact on annual estimates

CONTEXT

Australian issues and where EREF can help

Topic	What we are hearing	Relevant EREF work
Energy from waste	Facilities new and few; strong policy interest. Ash and APCR to landfill; special wastes at deep or wet sites	Ash reactivity and heat-generation research
PFAS	Leachate disposal approvals harder to obtain; compost from diverted organics under scrutiny	Landfill liquids treatment assessment; PFAS in organics
Leachate residues	Evaporators, RO and foam fractionation filling the gap; concentrate and salt return to landfill	Residuals options in treatment assessment
Methane	SEM-dominated, drones emerging; coal seam gas measurement expertise not yet applied to waste	Controlled-release test facility; SEM evaluation

WASTE-TO-ENERGY · ASH AND APCR

Current practice: test reactivity, then decide placement

STEP 1

Test reactivity

Heat release on wetting; hydration and carbonation potential; metallic aluminium content

→

STEP 2

Choose placement

Monofill, or **co-dispose** with MSW at an established mixing ratio

→

OBJECTIVES

Two outcomes

1. Slope stability
2. Lower heat-generating potential after placement

Heat sources identified in EREF-funded work: ash hydration and carbonation, and aluminium corrosion.

WASTE-TO-ENERGY · ASH AND APCR

Research tools that support placement decisions

Measure heat potential

Lab method using a quasi-adiabatic reactor to measure heat from ash and special wastes under landfill-relevant conditions, then predict temperature rise

Model placement

Heat models compare ash segregated in the centre, in a corner, or mixed with MSW; pre-hydrating ash before burial removes the heat of hydration

Watch for early signs

Rising wellhead temperatures, a falling CH_4/CO_2 ratio, and elevated H_2 indicate heat building in the waste mass

The outcome these practices aim to prevent is an elevated temperature landfill (ETLF): sustained temperatures above 80 °C with gas, leachate and settlement problems.

Sources: EREF (2022) Understanding & Predicting Temperatures in MSW Landfills; “Measurement and Temperature Prediction from Ash Disposed in Landfills…” ACS ES&T Engineering (2024) 4(2):310–17; EREF ETLF resources

PFAS · THERMAL PROCESSES AT THE LANDFILL

Flares, engines, evaporators: known and unknown

Process	What we know	What we don't know yet
Landfill gas (the source)	PFAS leave in gas: 13 of 27 PFAS detected at three Florida sites, mostly volatile FTOHs; fluorine in gas comparable to leachate, ~3× at one site. Gas condensate averaged ~19,000 ng/L total PFAS, rich in precursors	How much reaches control devices versus escaping as fugitive emissions
Flares and engines	Most collected gas is combusted; temperature and residence time vary widely by device	No full-scale PFAS destruction data yet. EREF-funded study (UVM, Sanborn Head, Weston, NC State) is measuring PFAS in and out at two landfills with EPA stack methods
Evaporators	Ionic PFAS stay with the residue: 0.1–7% to condensate in lab tests. Vendor mass balance: feed ≈ residue for nine regulated PFAS	Where volatile precursors go: >99.9% of FTOHs leave the liquid, to air or through combustion depending on design. Few field air measurements

Sources: Lin et al. (2024) ES&T Letters; Smallwood et al. (2023) J. Hazard. Mater.; EREF-funded LFG combustion study; Tang, FAMU/Hinkley Center (2023); Heartland/HDR (vendor data)

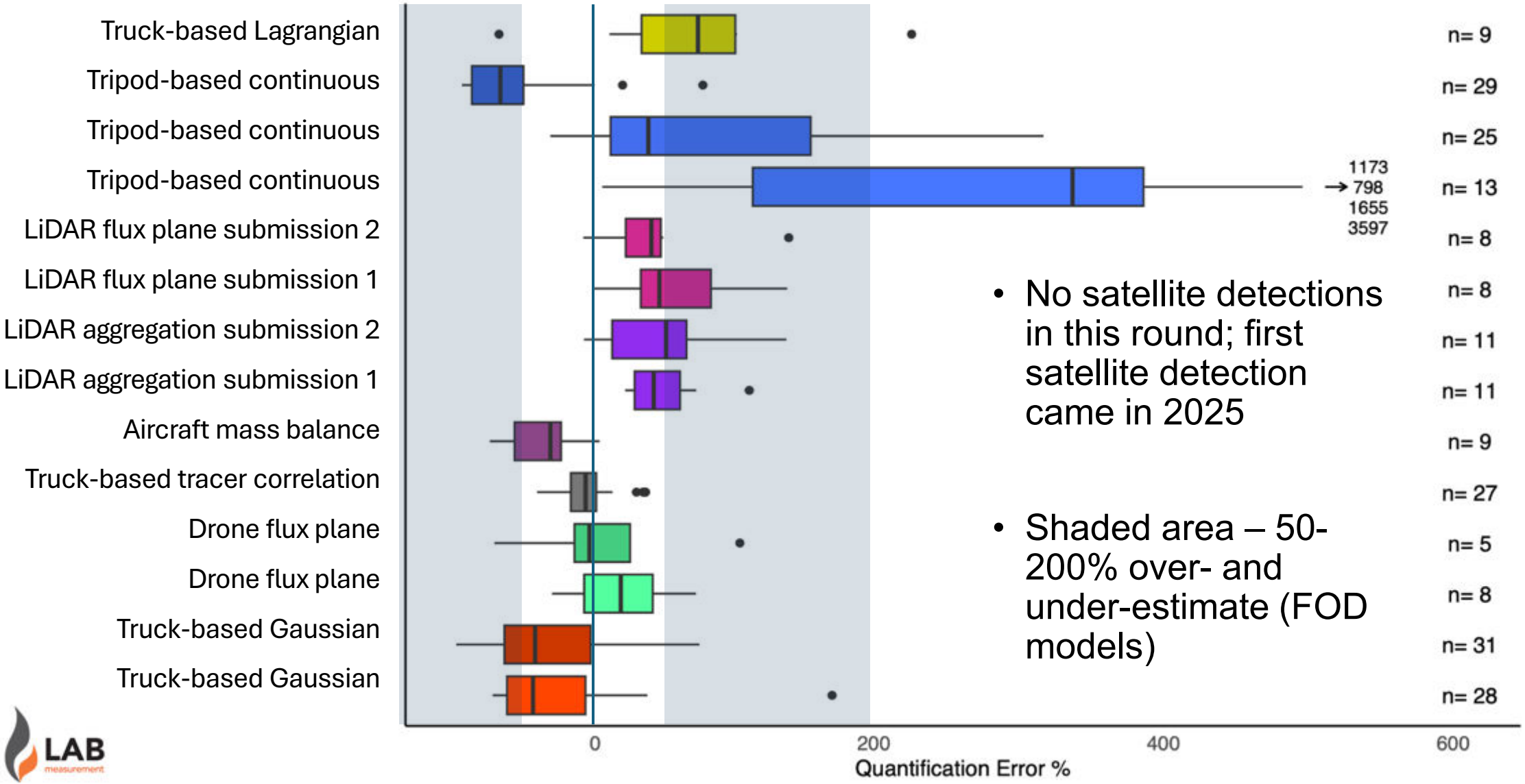
PLACEHOLDER · PFAS AND ORGANICS

PFAS in compost and digestate: University of Waterloo

[Insert from Parker / University of Waterloo slides]

Organics diversion to compost is a live PFAS issue for the organisers

Quantification Performance

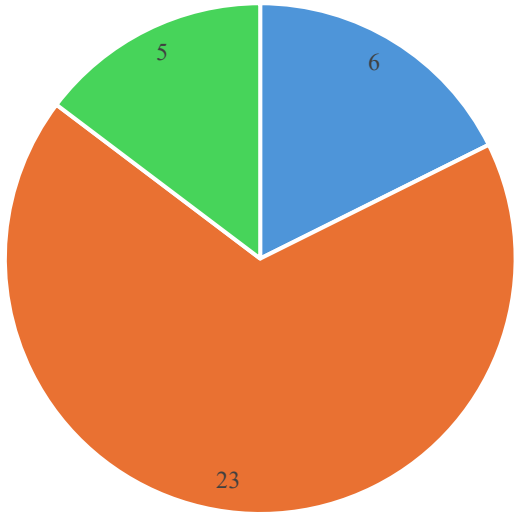


- No satellite detections in this round; first satellite detection came in 2025
- Shaded area – 50-200% over- and under-estimate (FOD models)

FLUX LAB
gas detection measurement

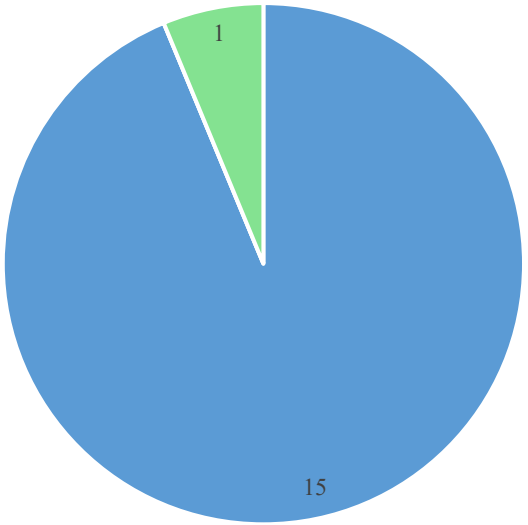
Accelerated Progress Through Testing

Vendor x - **2023**

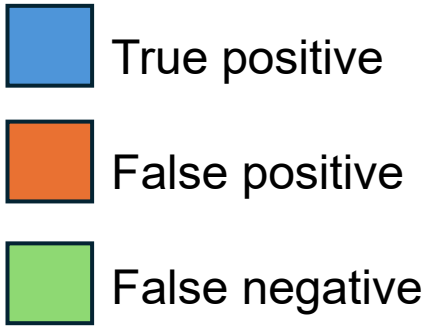


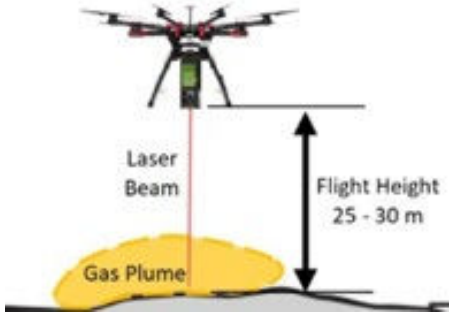
<20% POD
MDL: ~80 kg/hr

Vendor x - **2024**



>90% POD
MDL: ~12 kg/hr





KEY OUTCOMES:

- Different conditions can significantly affect ability to measure and accuracy
- CH_4 detection varied from 0% - 85% FALSE readings; some technologies improved substantially from 1st phase

FLUX LAB
gas detection measurement

METHANE · CONTROLLED-RELEASE TESTING

2025: 21 teams and the first satellite detection

SATELLITES AT THE TEST SITE

2023
Not validated: releases too small and dispersed to detect

2024
No detection: cloud cover and dispersed emissions

2025
First detection of controlled releases; results depended heavily on wind data

WHAT ELSE THE 2025 ROUND SHOWED

Truck tracer correlation
Remained the most reliable whole-site method

Fixed sensors
Improved sharply through software and algorithms alone

Aircraft hyperspectral
Imaged individual emission sources from the air

Drones
Gains came from flight strategy and data interpretation

Source: EREF third controlled-release study, closed landfill in Ontario, Canada (field work May–June 2025), with St. Francis Xavier University