The Latest and Greatest on Surface Emissions Monitoring for Methane at Landfills

Tarek Abichou, Ph.D. P.E.

FAMU-FSU College of Engineering

Hinkley Center for Solid and Hazardous Waste Management

RIDER

WASTE MANAGEMENT

Motivations

Making more use of SEMs

- Ambient air CH4 concentration measurements are already frequently obtained and monitored in many municipal solid waste landfills.
- Can we beneficially use the quarterly **SEMs** or **Enhanced SEMs** to provide an estimate of **Landfill Total Emissions** ?

Surface Methane Emission (SEM) monitoring is already used as part of New Source Performance Standards (NSPS), Title 40 Code of Federal Regulations Section 60.755(c) and (d). **Four (4) times per year**

Applications: What else can we use them for?

- Determine **Total Landfill Emissions Estimates**
- Identify high emissions **point sources**
- Identify high emissions **areas sources**
- Test different **remedial actions**
  - **Estimate emissions reduction after remediation (Fixing the exceedances, placing more cover, adding more wells, increasing vacuum, etc…)**

ppm → Kg/hr

SEM2Flux Tool

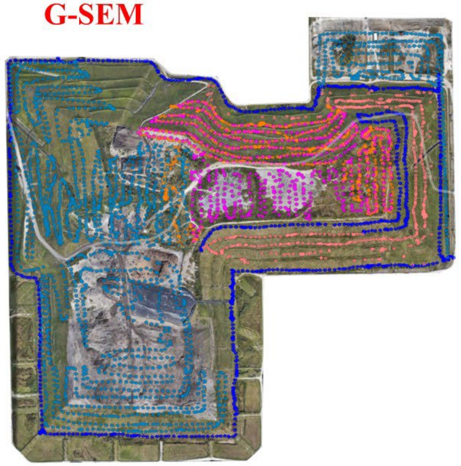
Assume measurement locations as ***receptors***, affected by emissions from adjacent area on the landfill: ***sources*** of emissions.

These ***sources*** are considered point sources and are responsible for the concentrations measured at the ***receptors***.

(Hicks 2017)

Landfill with Ground, Drone, and TCM Measurements

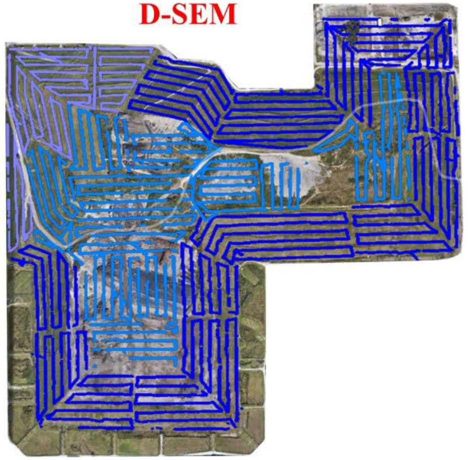
G-SEM



4,894 readings
Equivalent **27 readings per hectare**.
Measured concentrations **21 exceeding 500 ppm**.

Not Statistically Different

D-SEM

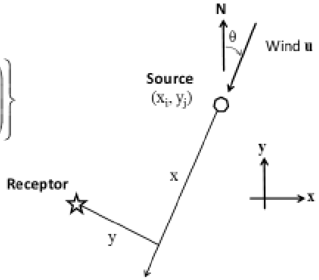


51,867 readings
Equivalent **285 readings per hectare**.
Measured concentrations **7 exceeding 500 ppm**.

SEM2Flux Tool

Gaussian Dispersion Equation

$$C(x,y,z,H)=\frac{Q}{2\pi u\sigma_y\sigma_z}\exp\left(-\frac{1}{2}\frac{y^2}{\sigma_y^2}\right)\left\{\exp\left(-\frac{1}{2}\frac{(z-H)^2}{\sigma_z^2}\right)+\exp\left(-\frac{1}{2}\frac{(z+H)^2}{\sigma_z^2}\right)\right\}$$



For ground-level sources and receptors ($z = 0$ and $H = 0$)

$$C=\frac{Q}{\pi\mu\sigma_y\sigma_z}\exp\left[-\frac{1}{2}\frac{y^2}{\sigma_y^2}\right]$$

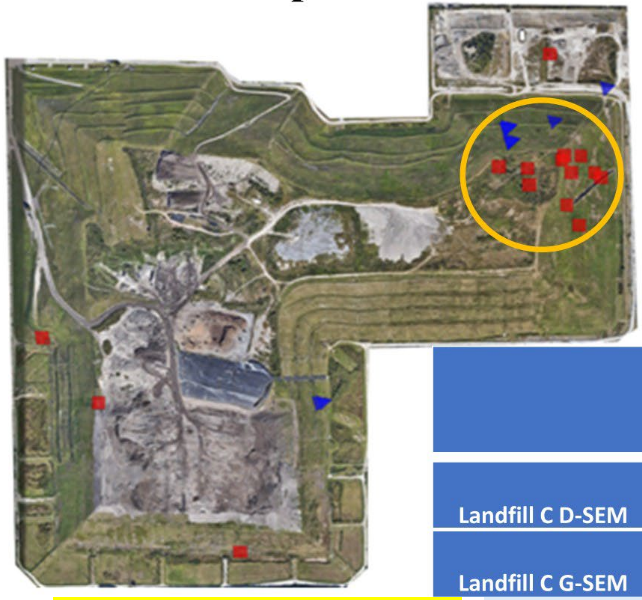
The predicted methane concentration in a receptor point i ($C_{i,\,predicted}$) is calculated through summing up all contributions (C_{ij}) of assumed source points j ($j=1,..,n$).

$$C_{i,predicted}=\sum_{j=1}^{n}C_{i,j}$$

Calculating predicted concentration for all receptor points ($i=1, .., m$) results in a vector of predicted concentration ($C_{predicted}$).

Search for the ***best-fit source configuration*** is formulated as an optimization problem that consists of residual minimization under bound constraints.

SEM2Flux Output - Results



SEM2Flux D-SEM Data Major Source Locations
SEM2Flux G-SEM Data Major Source Locations

Confirmation of GCS Construction activities (trenching into waste. Etc..)

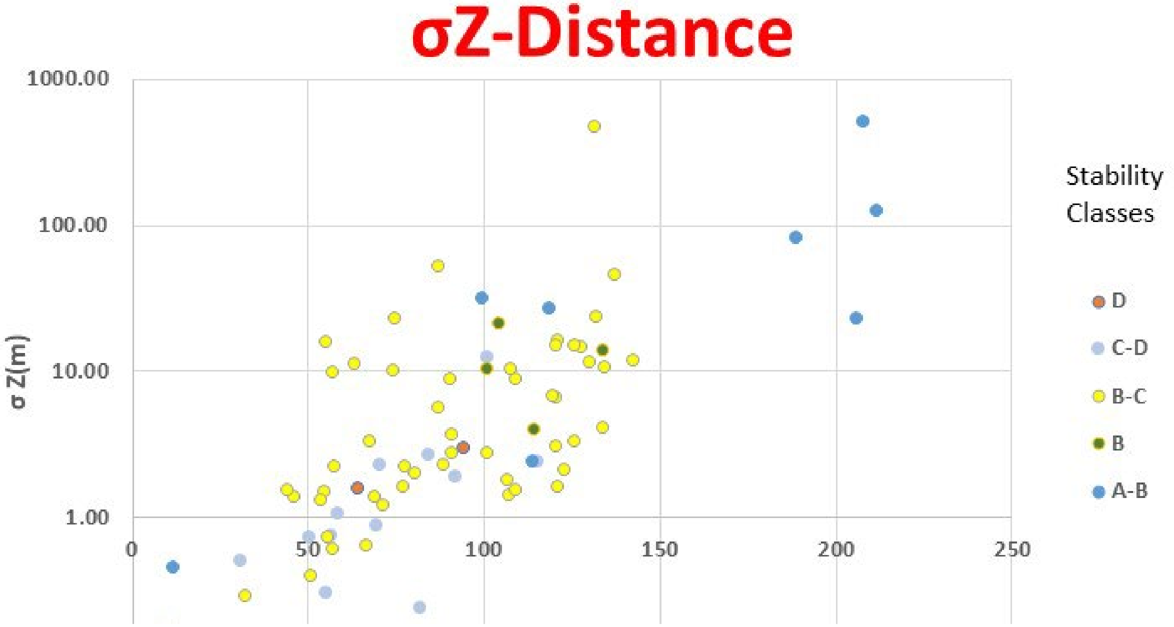
Carbon Mapper Flight Confirmed No Detection 4/14/2022 -4/16/2022

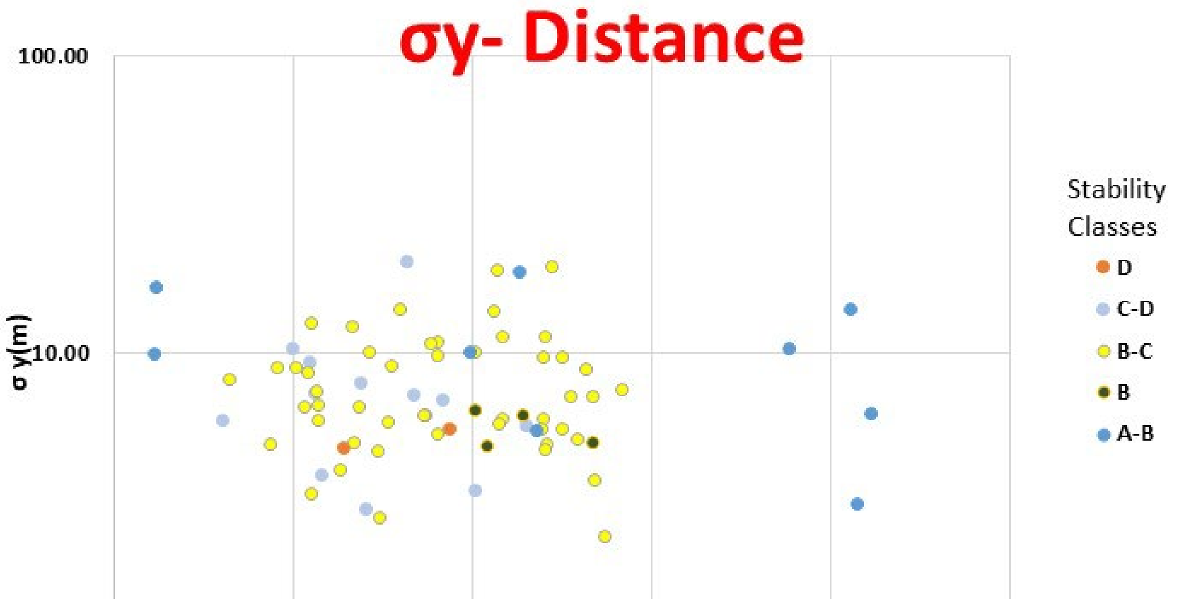
	Date	N. Major Sources	Total Fugitive Emissions (Kg/hr)	StDev (Kg/hr)
Landfill C D-SEM	4/14/2022	15	657	214
Landfill C G-SEM	4/14-4/16 2022	12	573	99

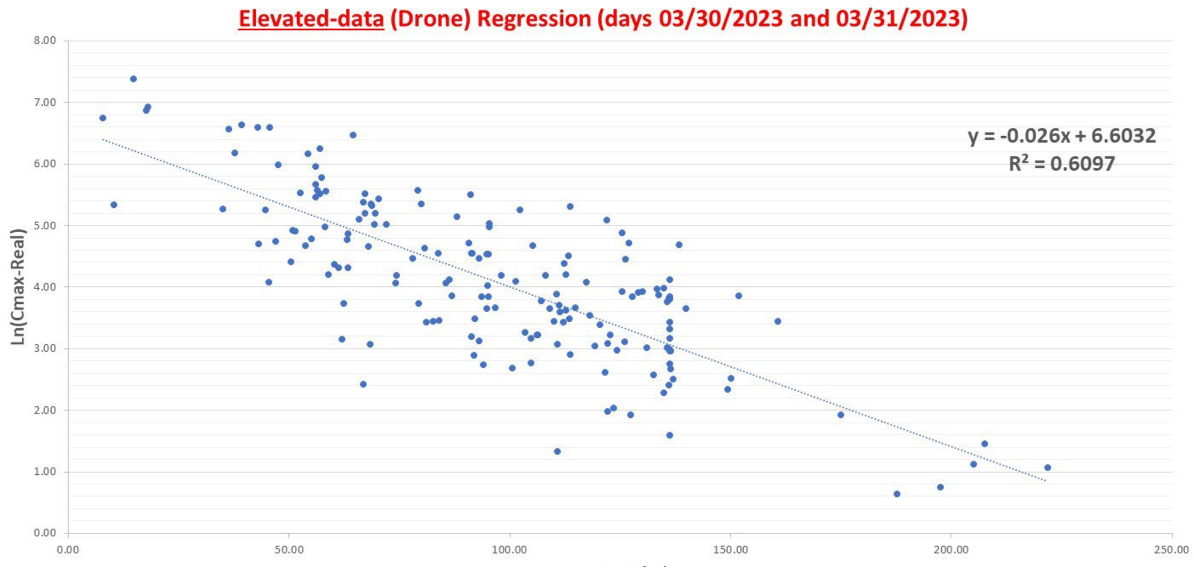
Controlled Releases at Leon County Landfill

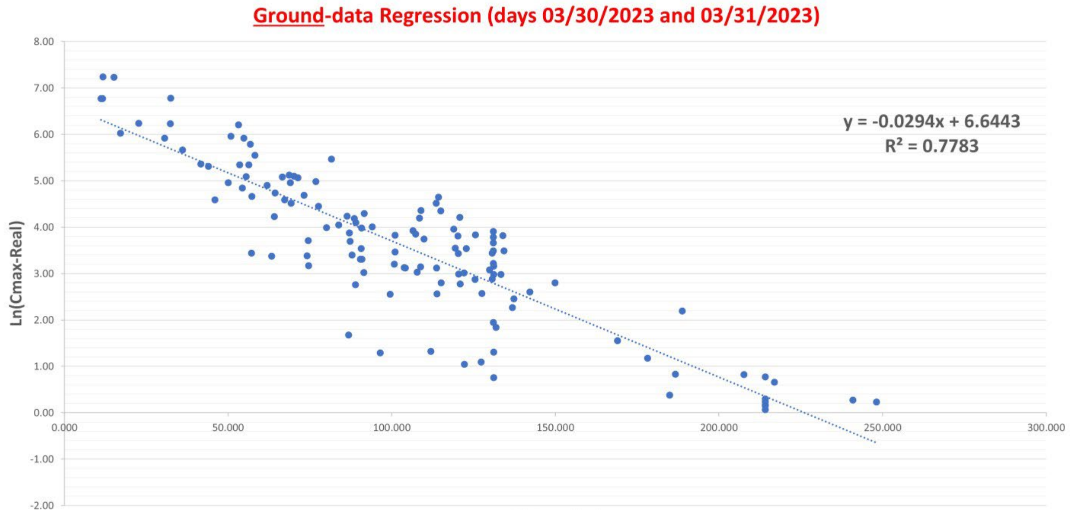
Develop near-field dispersion equations

Controlled Releases at Leon County Landfill: Calibration of Dispersion Coefficients

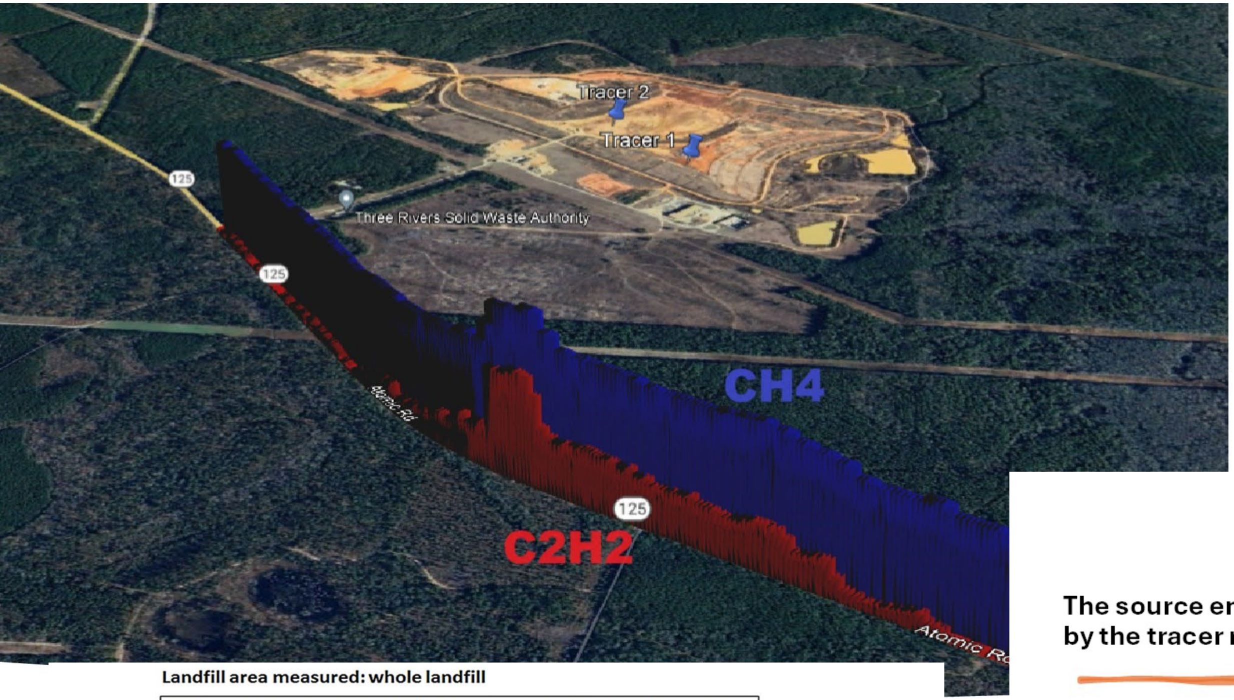


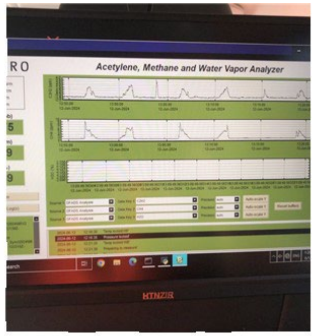




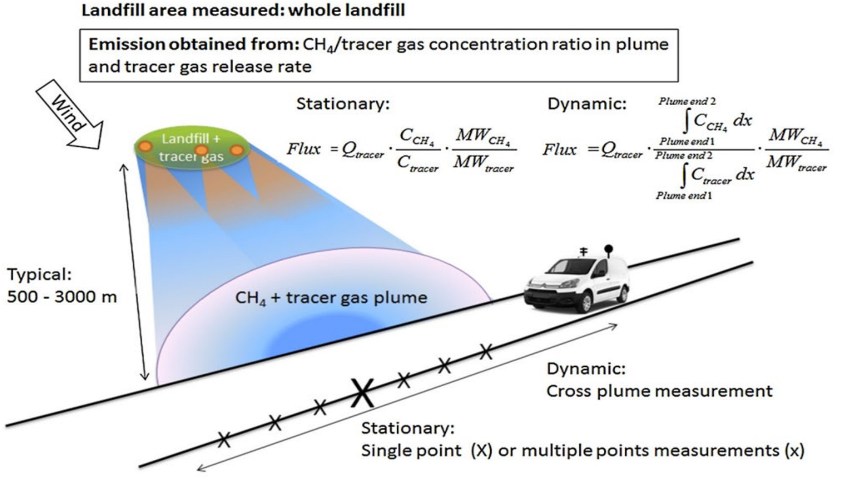


Ground Truthing: Performed Tracer Correlation Method (TCM) tests to obtain "most likely estimate" of true total emissions from the landfill





Trained, Calibrated, and Verified Approach



$$Flux = Q_{tracer} \cdot \frac{C_{CH_4}}{C_{tracer}} \cdot \frac{MW_{CH_4}}{MW_{tracer}}$$

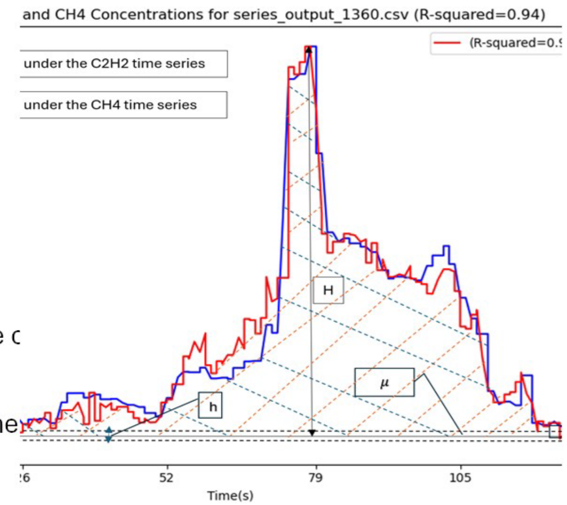
$$Flux = Q_{tracer} \cdot \frac{\int_{Plume\ end\ 1}^{Plume\ end\ 2} C_{CH_4}\, dx}{\int_{Plume\ end\ 1}^{Plume\ end\ 2} C_{tracer}\, dx} \cdot \frac{MW_{CH_4}}{MW_{tracer}}$$

(Green et al. 2009, Mønster et al. 20

The source emission rate is calculated for each transect using the ratio (ν) of CH4 and C2H2 areas, multiplied by the tracer release rate (Q_t) and the ratio of the molecular weights of CH4 (M_{CH4}) and C2H2 (M_{C2H2}).

$$Q_{CH_4,\nu} = (\nu) Q_t \frac{M_{CH_4}}{M_{C_2H_2}}$$

- $Q_{CH_4,\nu}$: the source emission rate
- Q_t : the tracer release rate
- M_{CH_4} : molecular weights of CH4
- $M_{C_2H_2}$: molecular weights of C2H2
- $\nu = \frac{\int_{t_0}^{t_f} (y(t)-\mu_y)\, dt}{\int_{t_0}^{t_f} (x(t)-\mu_x)\, dt}$
- $y(t)$: CH4 respective time series (t_0 is the start time, t_f is the end time c
- μ_y : background concentrations for CH4
- $x(t)$: C2H2 respective time series (t_0 is the start time, t_f is the end time
- μ_x : background concentrations for C2H2



Project Output

Two versions:

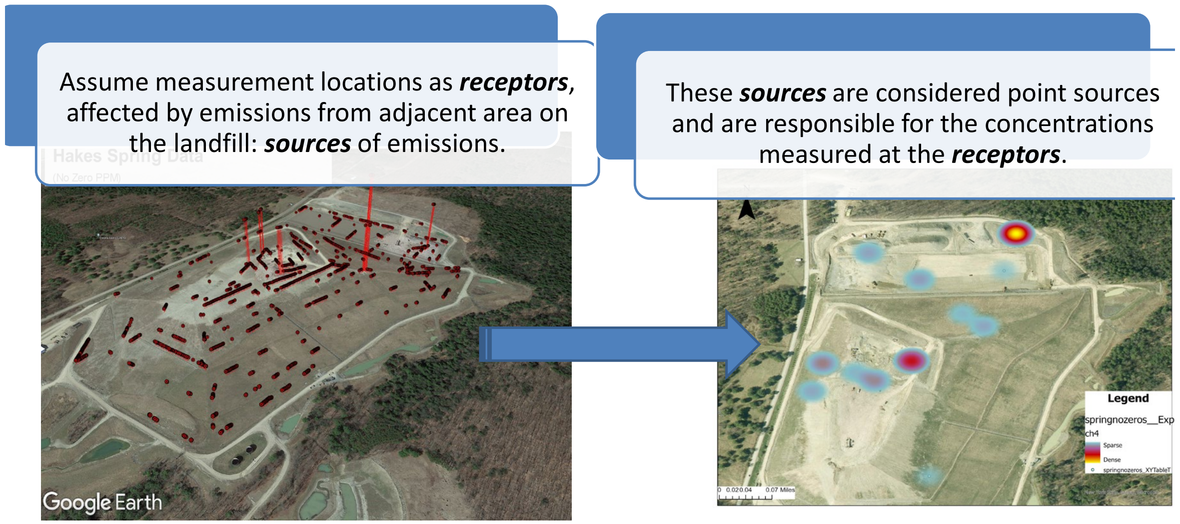
Version 1: uses SEM locations as receptors, affected by emissions from a set of adjacent sources on the landfill using wind direction. **(Focus on Large <u>Point Sources</u>)**

Version 2: uses SEMs and develop a geospatial approach to estimate area flux (g/m^2/d) for all areas under waste. **(Focus on Area Emissions Flux)**

Applications:

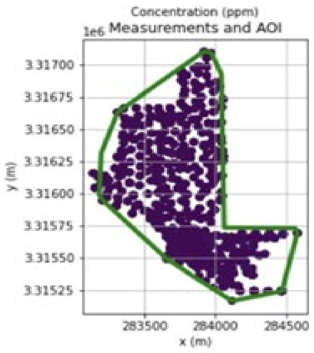
- Can we assign an emission reduction in mass/time to an improvement in LFG management practices
- Can we update the emissions **Flux** estimates once remediation are performed (Fixing the exceedances, placing more cover, adding more wells, increasing vacuum, etc…)

PPM → **SEM2Flux** → **Kg/hr**

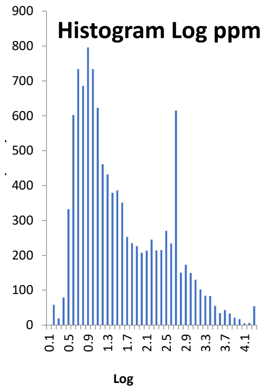


PPM → **SEM2Flux** → **g/m^2/d Kg/hr**

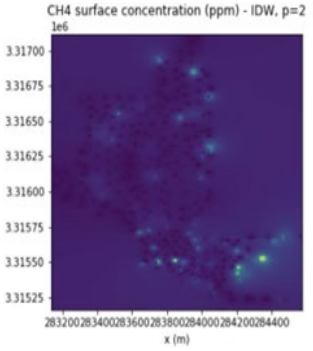
SEM Data Ground or Drone



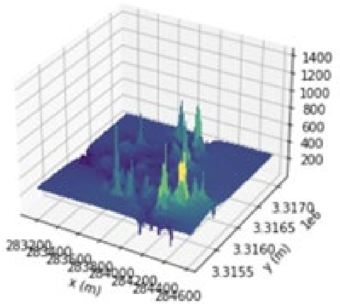
Log Transformation of SEM Data



Using Inverse Distance Weighing (IDW) to predict Local Log(ppmv)



Use Simple ppm to g/m^2/d Correlation to Predict Area Flux



methane

SEM2Flux Approach 1: Inverse Modeling

MDPI

Article

Using Ground- and Drone-Based Surface Emission Monitoring (SEM) Data to Locate and Infer Landfill Methane Emissions

Tarek Abichou [1,*], Nizar Bel Hadj Ali [2], Sakina Amankwah [1], Roger Green [3] and Eric S. Howarth [4]

SEM2Flux Tool – Point Source Locating

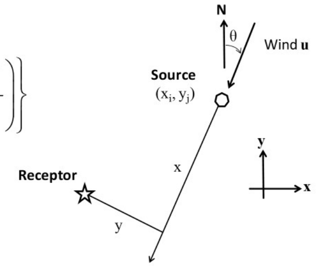
Assume measurement locations as ***receptors***, affected by emissions from adjacent area on the landfill: ***sources*** of emissions.

These ***sources*** are considered point sources and are responsible for the concentrations measured at the ***receptors***.

SEM2Flux Tool

Gaussian Dispersion Equation

$$C(x,y,z,H)=\frac{Q}{2\pi u\sigma_y\sigma_z}\exp\left(-\frac{1}{2}\frac{y^2}{\sigma_y^2}\right)\left\{\exp\left(-\frac{1}{2}\frac{(z-H)^2}{\sigma_z^2}\right)+\exp\left(-\frac{1}{2}\frac{(z+H)^2}{\sigma_z^2}\right)\right\}$$



For ground-level sources and receptors (*z = 0* and *H = 0*)

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The predicted methane concentration in a receptor point *i* ($C_{i,\ predicted}$) is calculated through summing up all contributions (C_{ij}) of assumed source points *j* (*j=1,.., n*).

$$C_{i,predicted}=\sum_{j=1}^{n}C_{i,j}$$

Calculating predicted concentration for all receptor points (*i=1, .., m*) results in a vector of predicted concentration ($C_{predicted}$).

Search for the ***best-fit source configuration*** is formulated as an optimization problem that consists of residual minimization under bound constraints.

Focus on Localization

SEM2Flux Source Localization (Timeline)

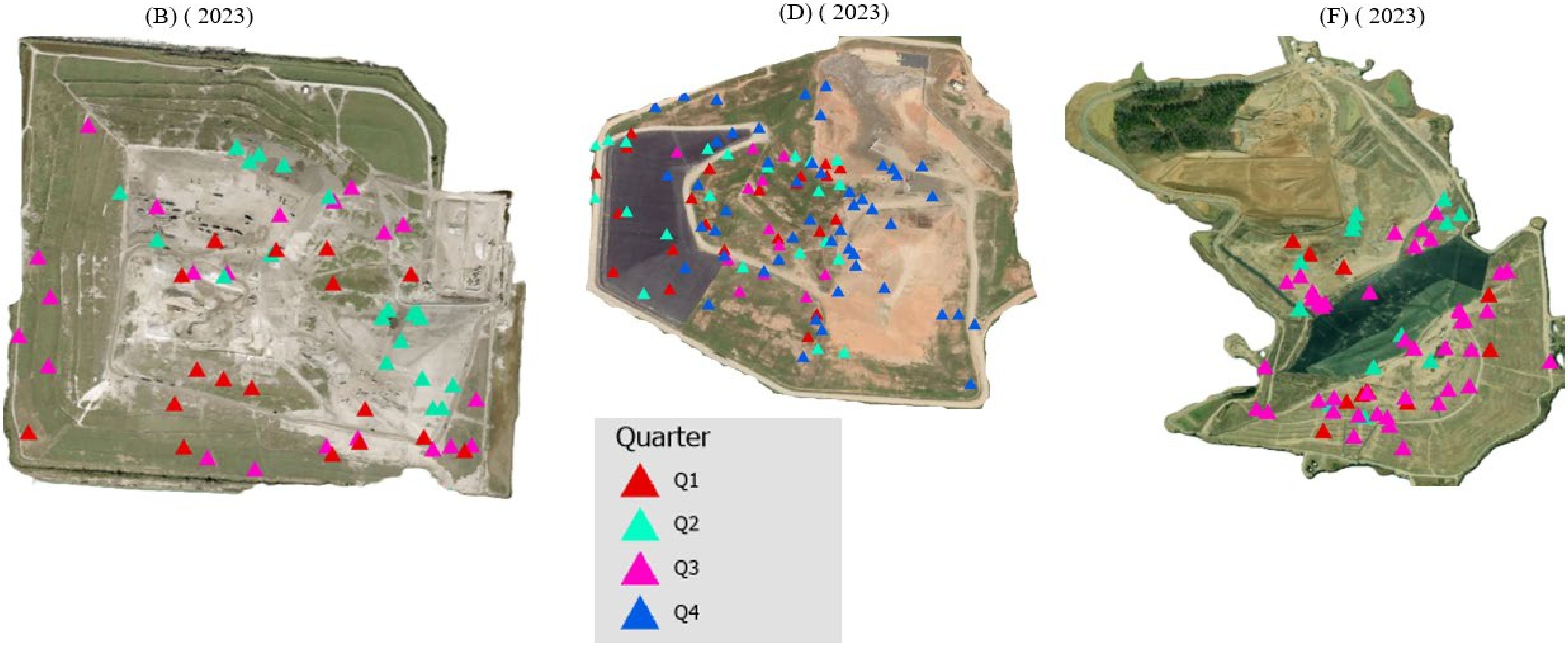
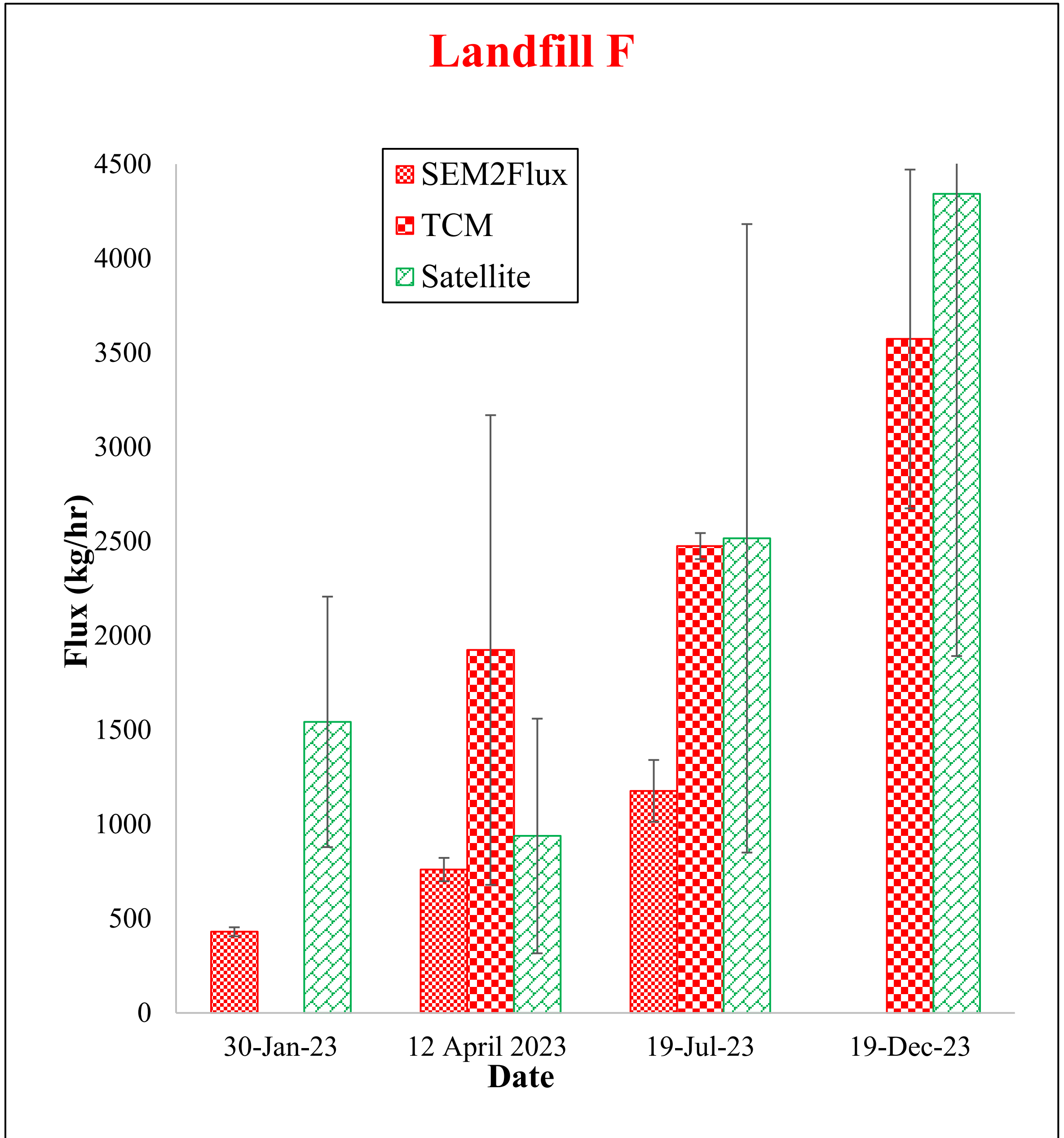
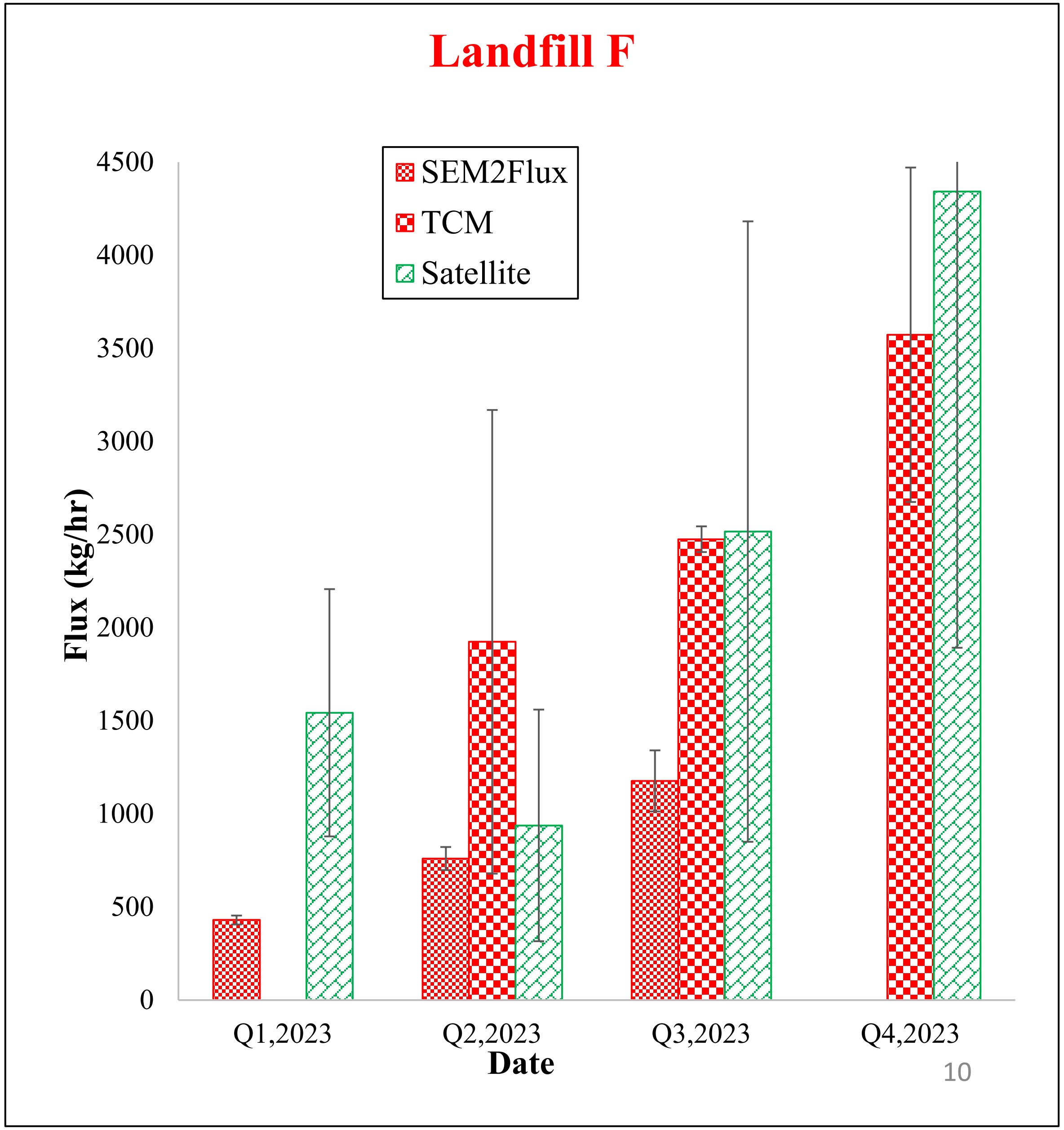


Figure A Methane emission source location from G-SEM SEM2Flux simulation.(B, D, F) are Landfills B, D and F respectively

Total Landfill Emissions Estimation





SEM2Flux Approach 2: Geospatial

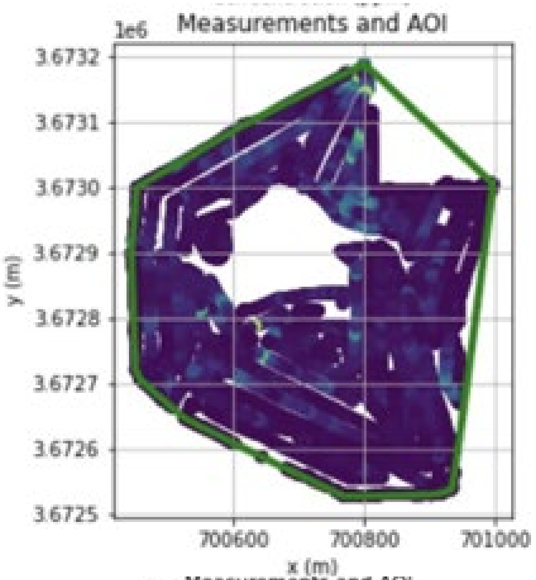
Developed Geospatial Approach to Transform SEM Data to Local Emissions Flux

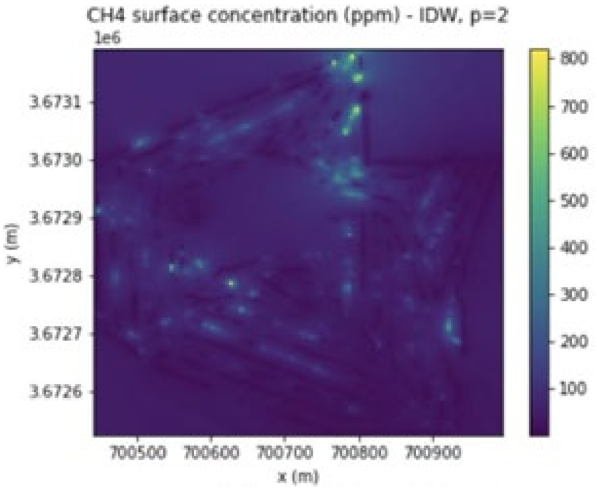
Estimation of total landfill surface methane emissions using geospatial approach combined with measured surface ambient air methane concentrations

SEM Data Ground or Drone

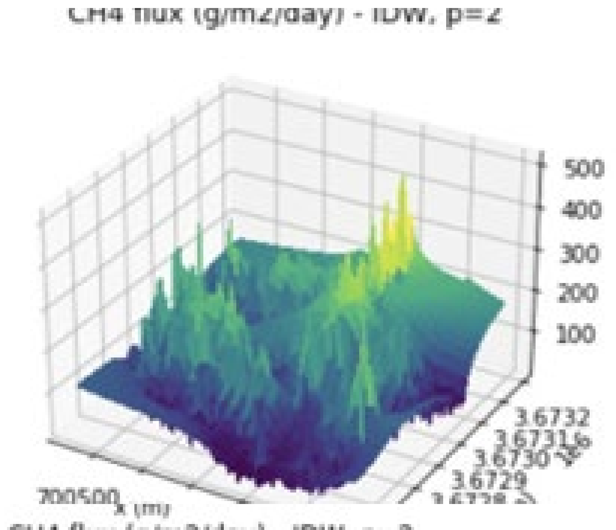
Log Transformation of SEM Data

Using Inverse Distance Weighing (IDW) to predict Local Log(ppmv)





Use Simple ppm to $g/m^2/d$ Correlation to Predict Area Flux

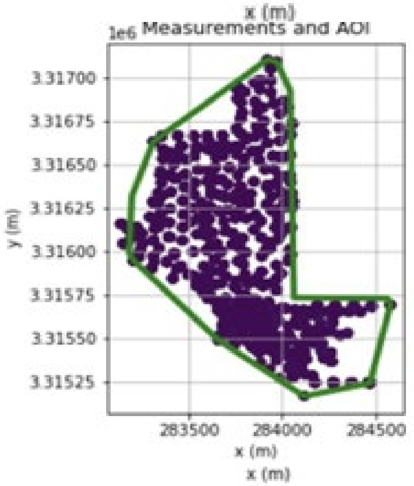


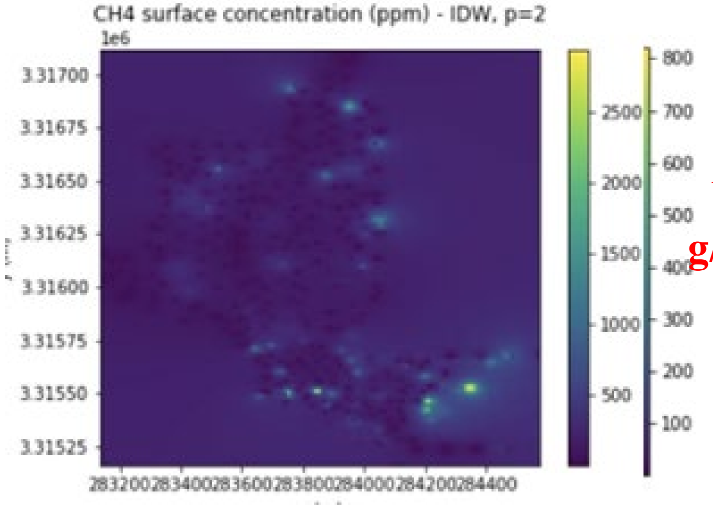
CH4 flux (g/m2/day) - IDW, p=2

Focus on area emissions flux, and total landfill emissions

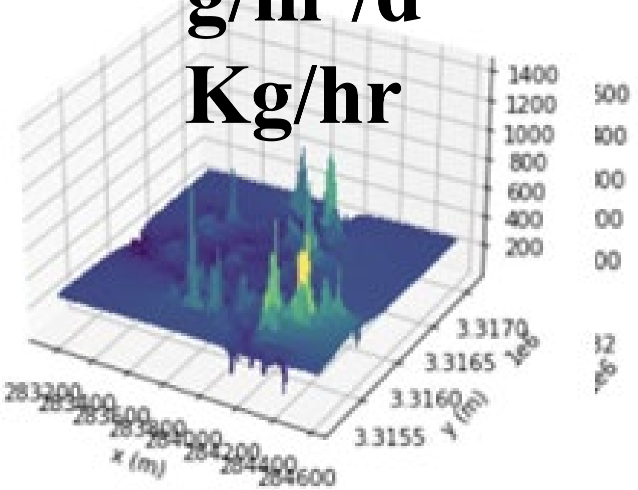
$g/m^2/d$

Kg/hr



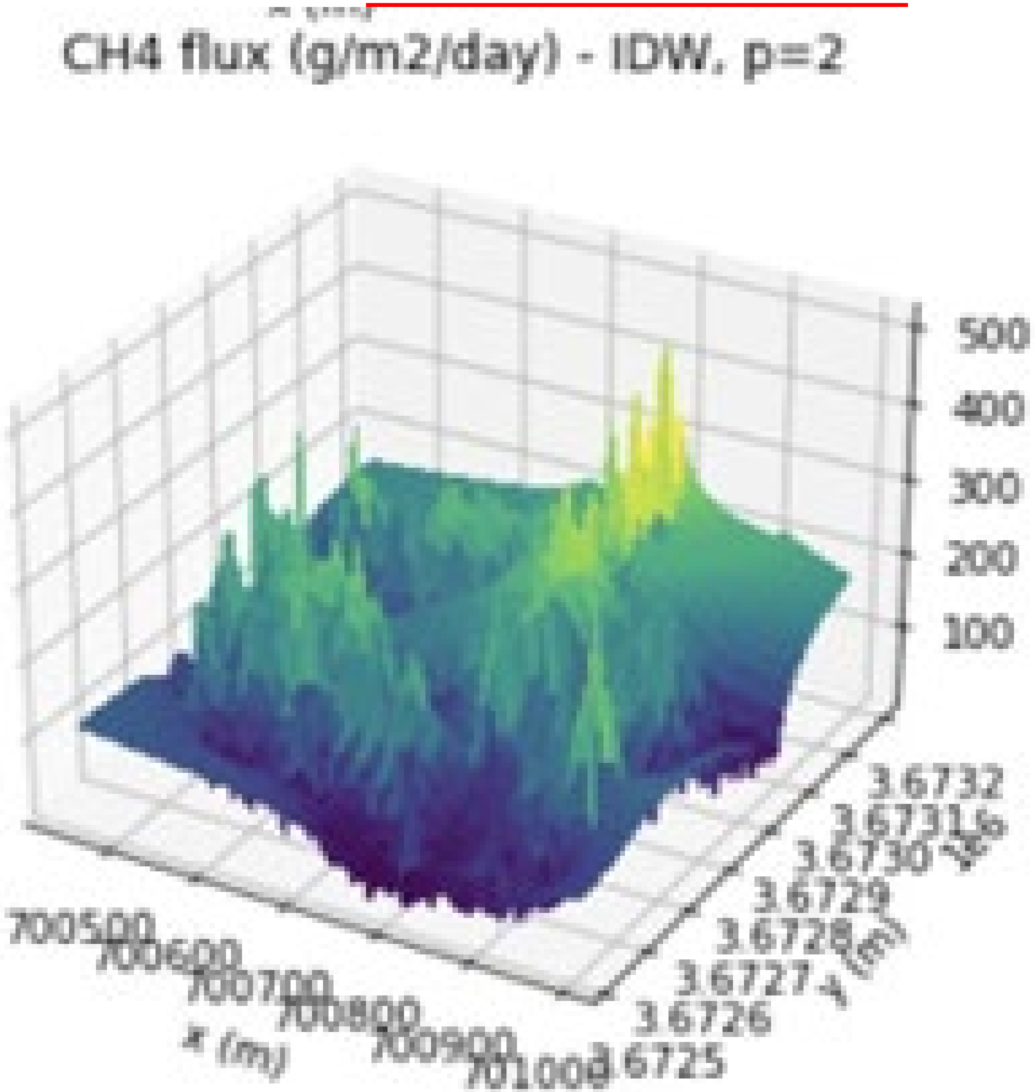


Use Simple ppm to $g/m^2/d$ Correlation to Predict Area Flux

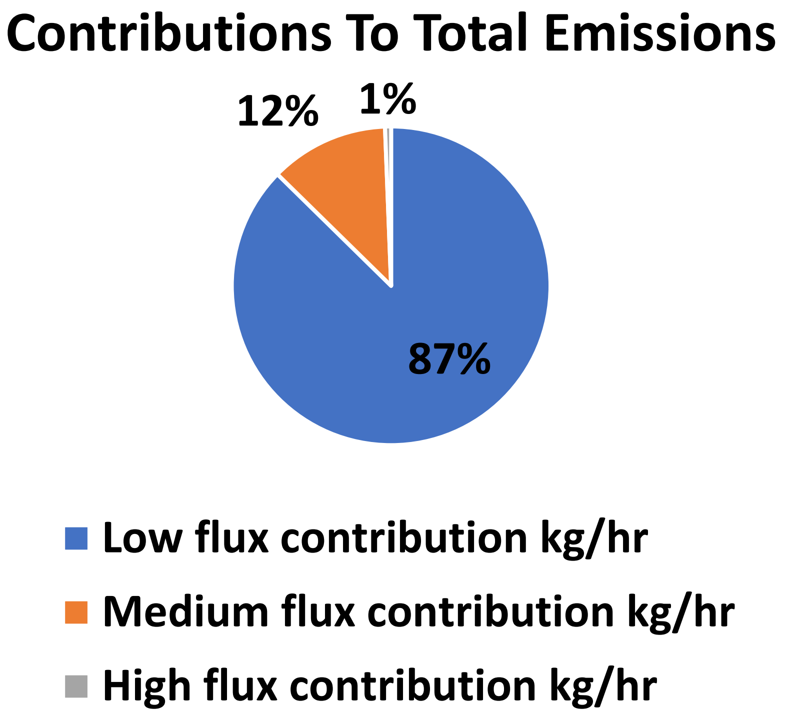


SEM2Flux Approach 2: Geospatial

Actionable Output of Approach

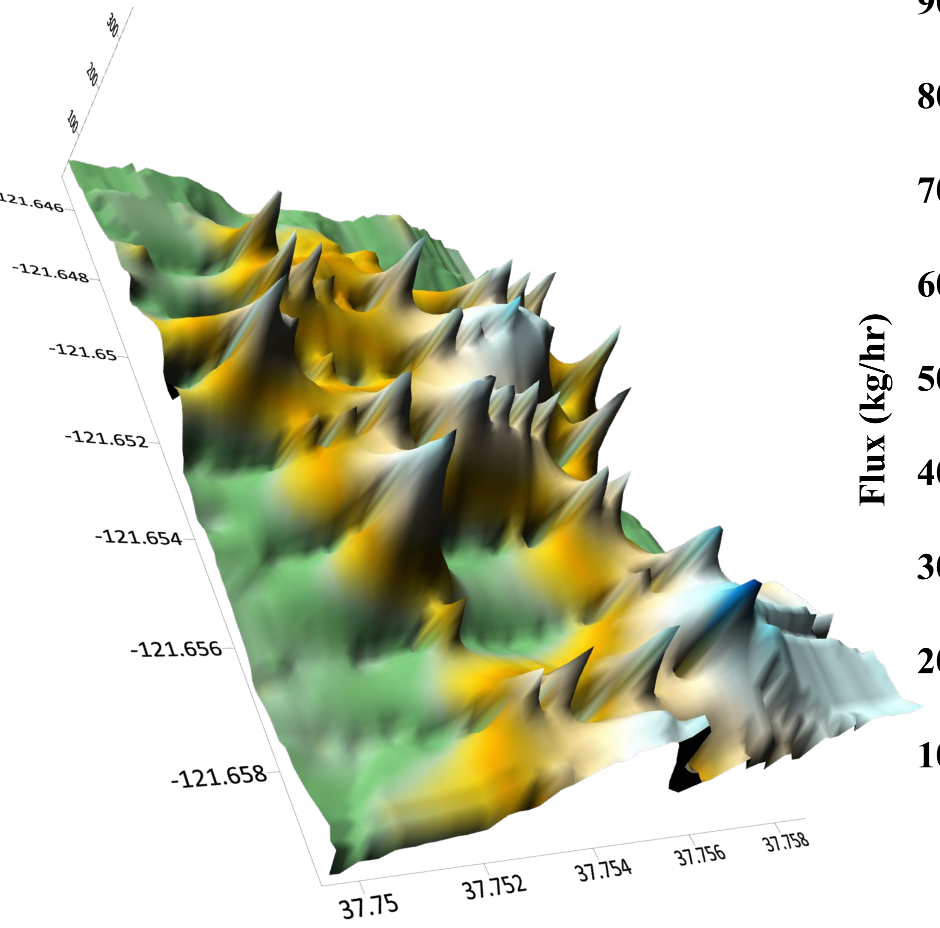


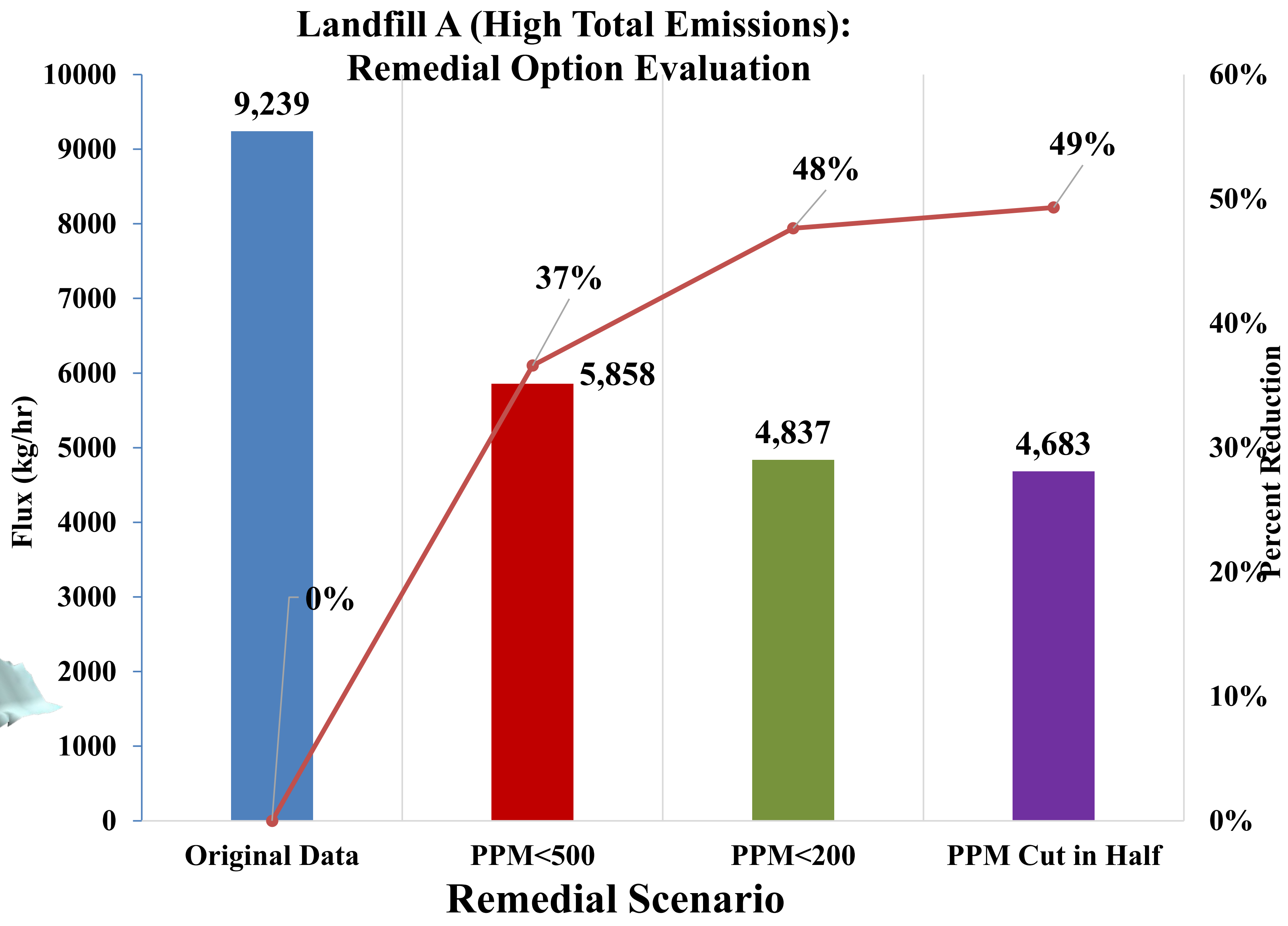
Emission rate kg/hr	Low flux contribution kg/hr	Medium flux contribution kg/hr	High flux contribution kg/hr
406	354.8	48.9	2.5



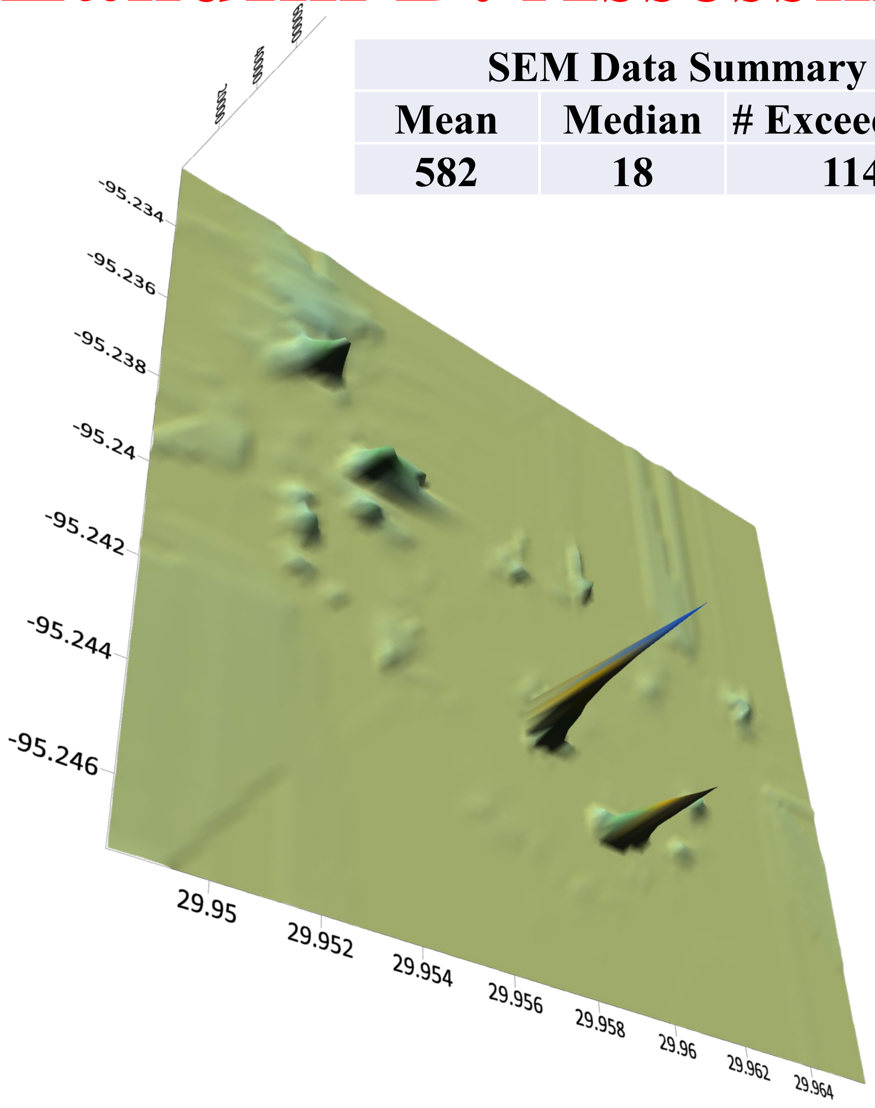
Landfill A: Assessment of Possible Remedial Approach

SEM Data Summary		
Mean	Median	# Exceedances
1473	60	103

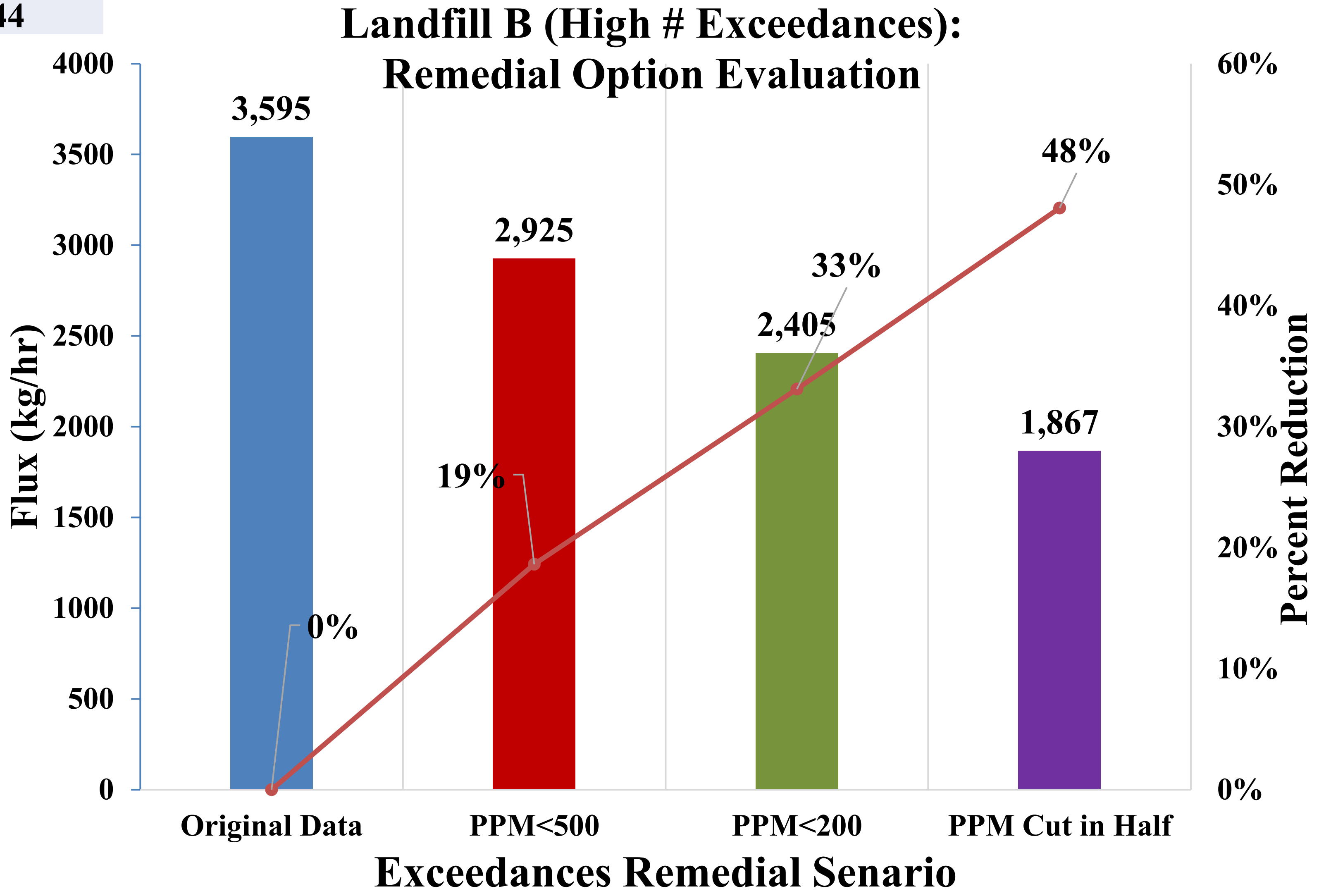




Landfill B: Assessment of Possible Remedial Approach



SEM Data Summary		
Mean	Median	# Exceedances
582	18	1144



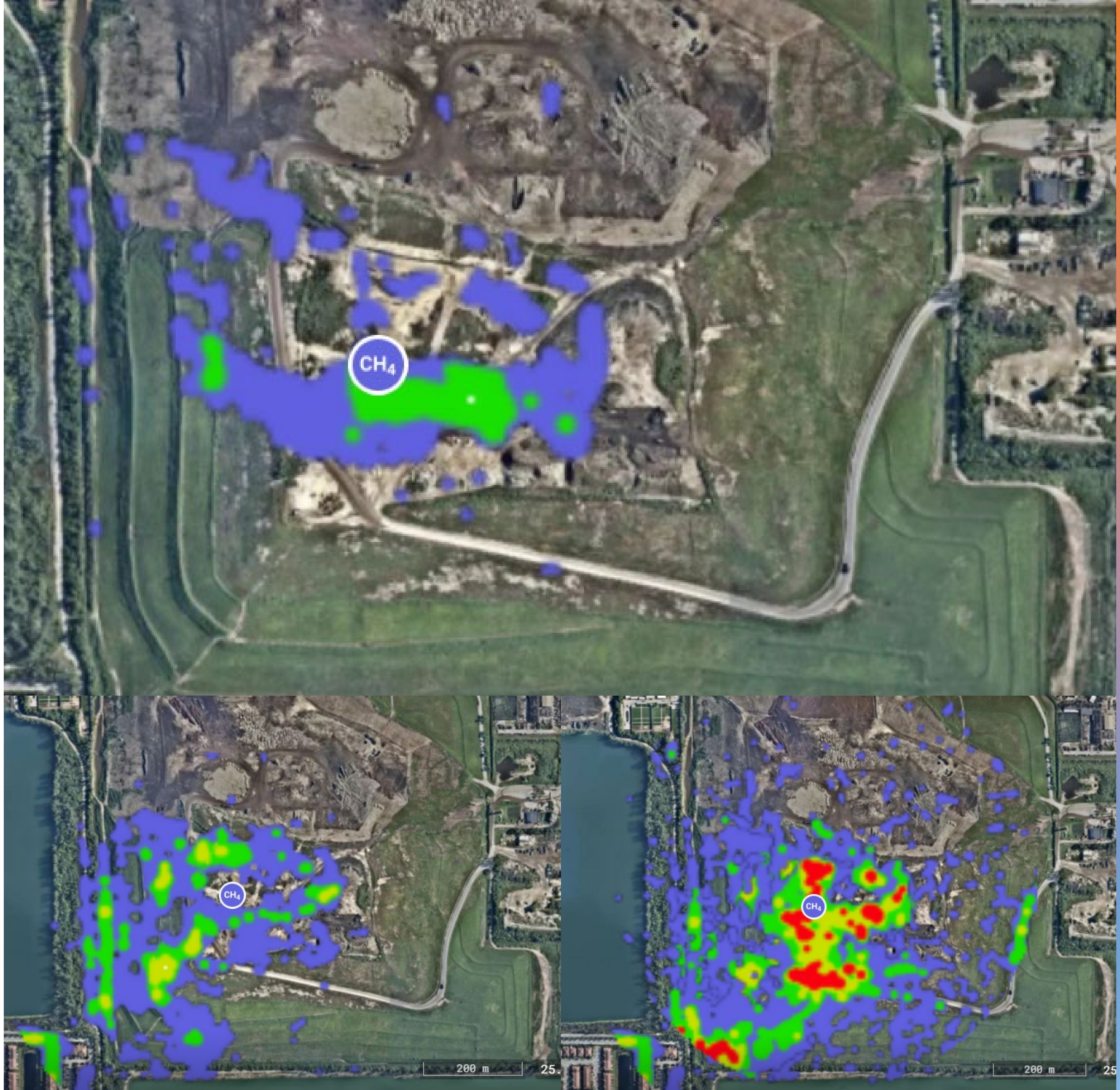
Using a Digital Twin Approach for Designing and Evaluating Landfill Gas Emissions Modeling and Monitoring

Assessing the Uncertainties in Integrated Mass Enhancement (IME) in Landfill Methane Emissions Applications

Hinkley Center
for Solid and Hazardous
Waste Management

FAMU-FSU
College of Engineering

UCF
College of Engineering
and Computer Science
UNIVERSITY OF CENTRAL FLORIDA



Landfill Digital Twin: Virtual Controlled Release Experimental Site

Create a prototype digital twin of a selected Florida landfill and Demonstrate its utilities in designing and evaluating landfill methane emissions modeling and monitoring approaches

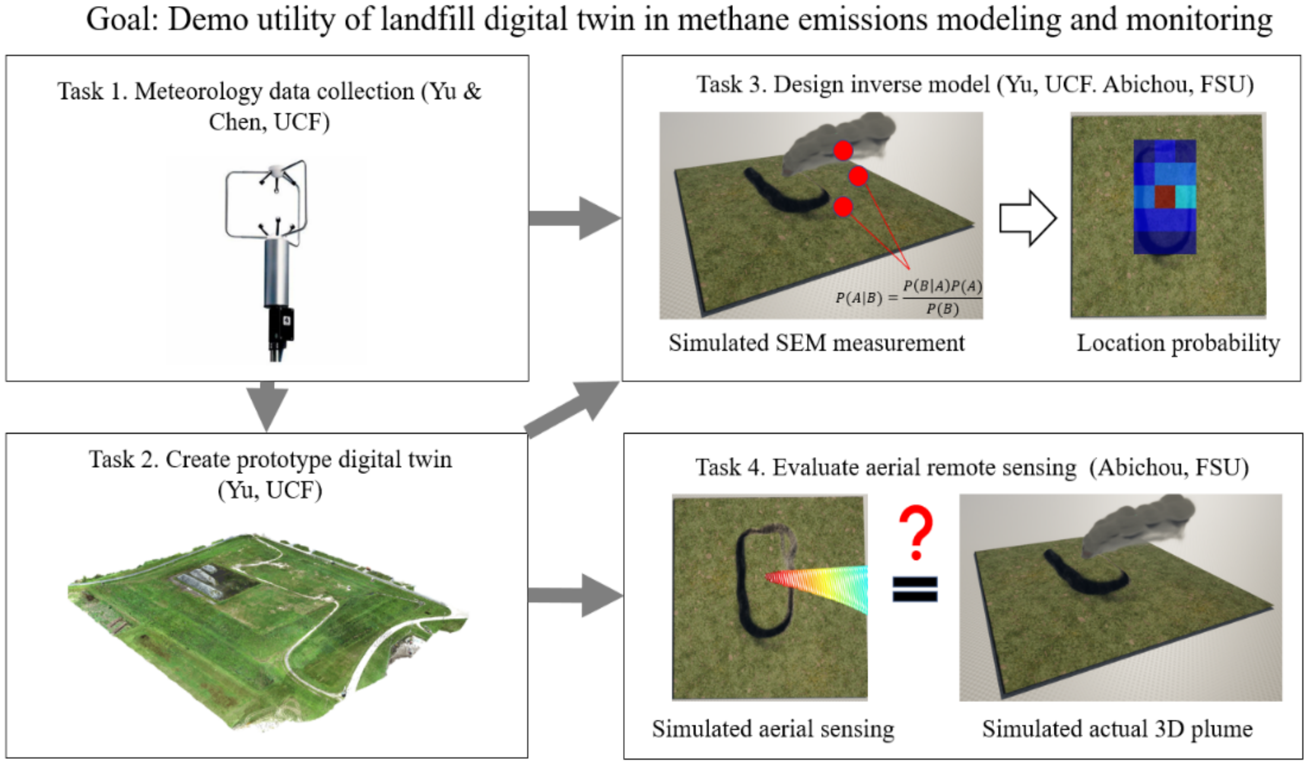
Digital twin is the digital "clone" of a real-world system

- Virtually represent real-time operating status
- Simulate physical, operational, and environmental characteristics

Digital twin enables **repeated experiments** not feasible in real world, such as iteratively designing, developing, and validating methane monitoring and modeling approaches

Digital twin can also be used to **simulate other aspects of landfill** such as scenario planning and operation forecasting

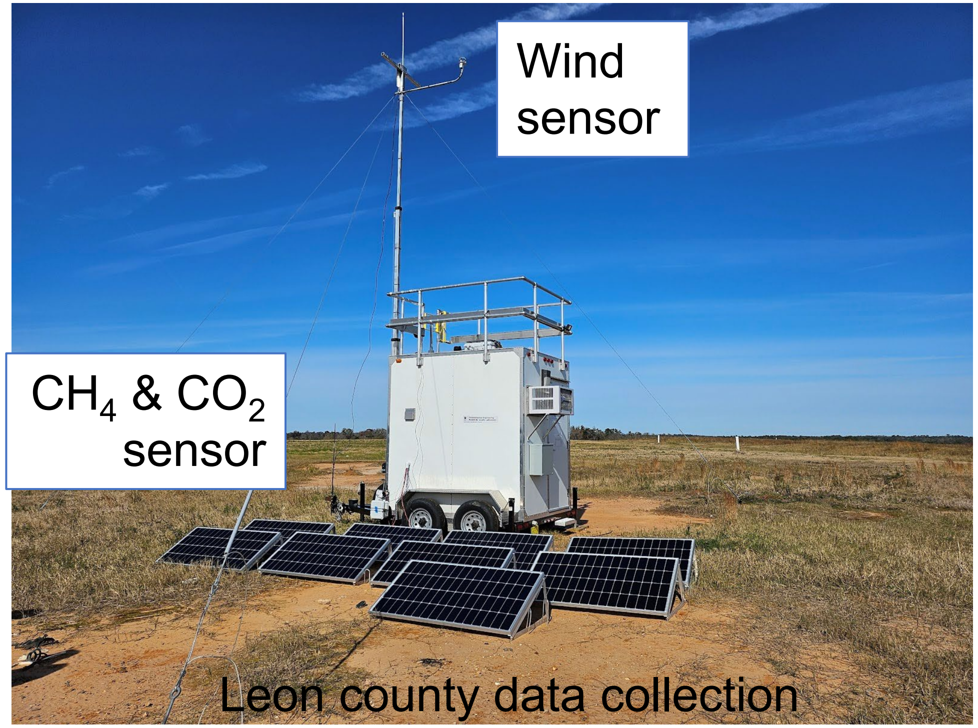
Real-world sensor data can also be integrated

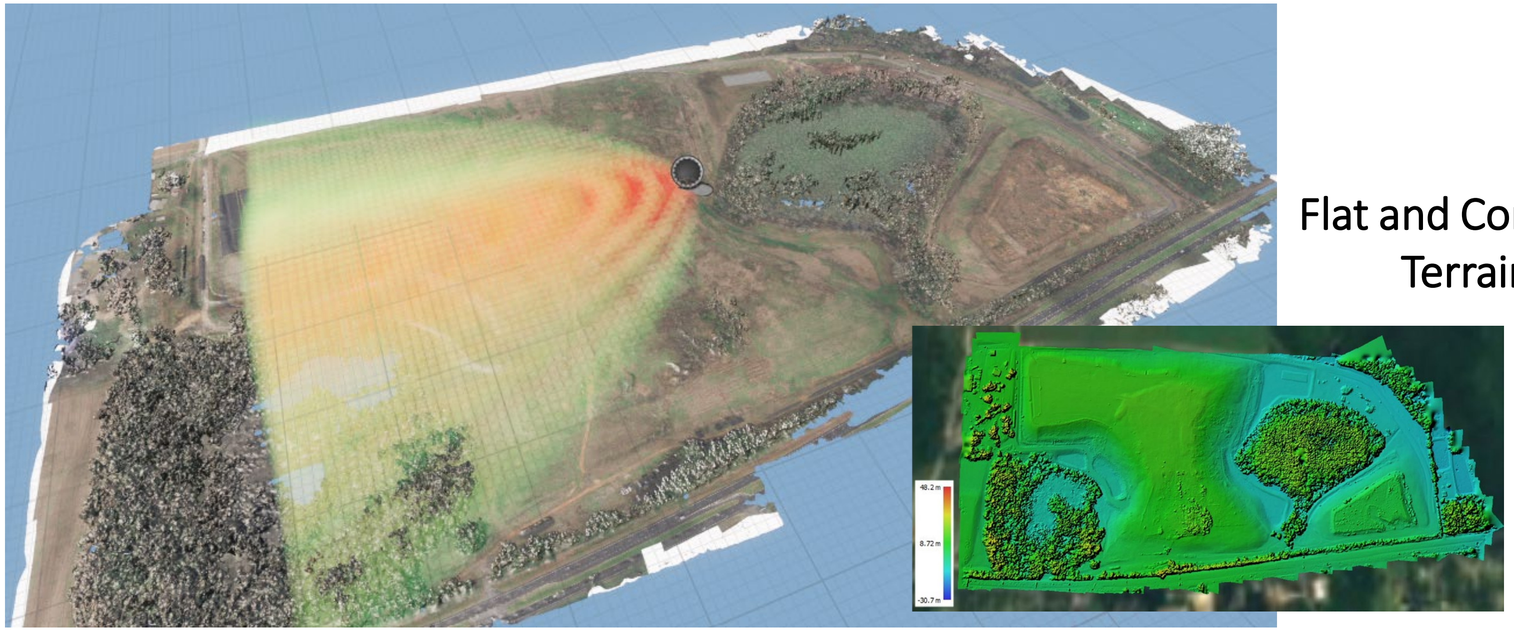


Design and/or evaluate CH_4 monitoring/modeling methods (SEM, Continuous Monitoring, Drones, Downwind, Aerial, …. techniques)

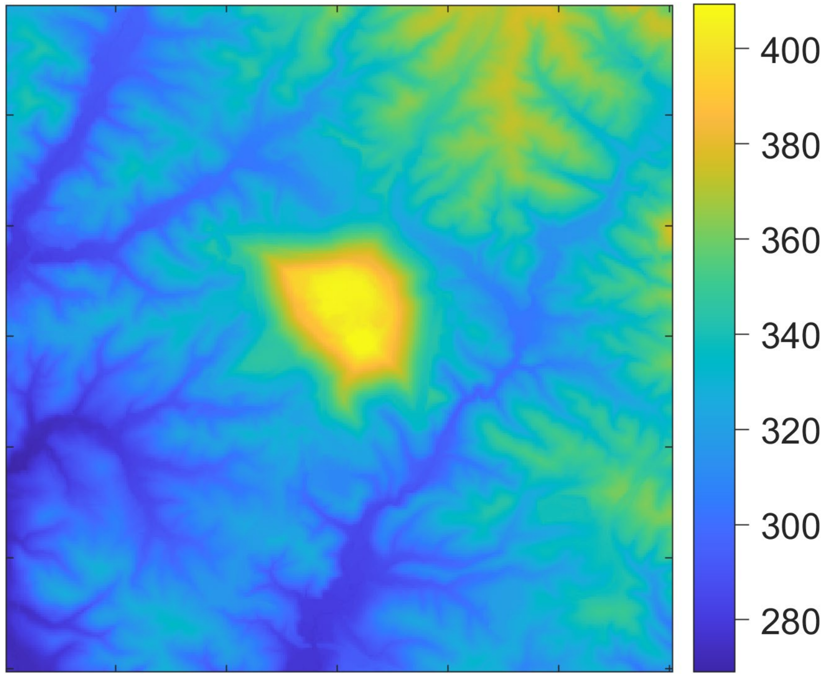
Created Prototype Digital Twins

- Goal: Generating high resolution 3D CH_4 data & visualization in space and time
  - Collected high resolution terrain data for Leon County landfill
  - Obtained high resolution terrain data from a Georgia landfill
  - Created landfill digital representation in Unreal Engine
  - Simulated 3D CH_4 field using AERMOD model
- Collected wind data at 10 m for 3-4 months



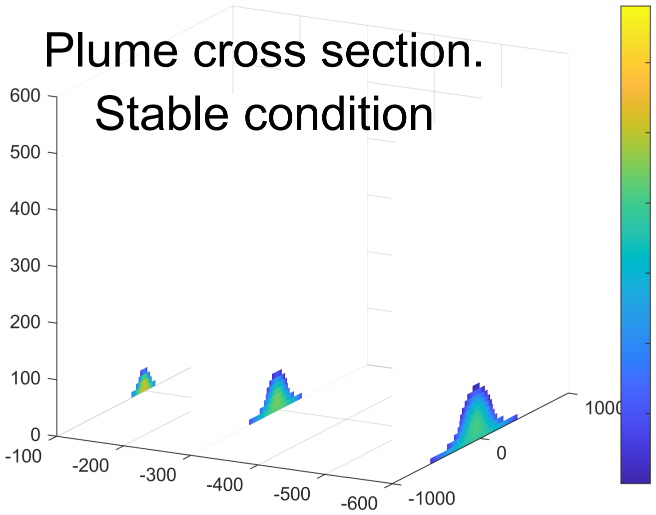


Flat and Complex Terrain

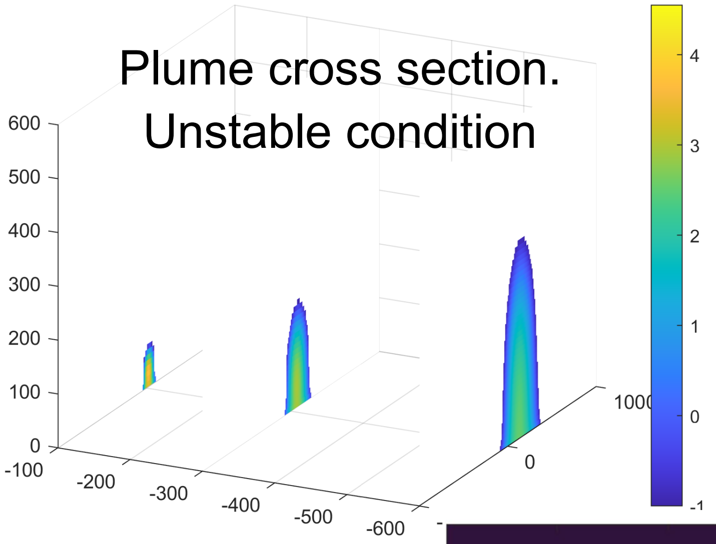


AERMOD Modeling and Column Concentration Integration

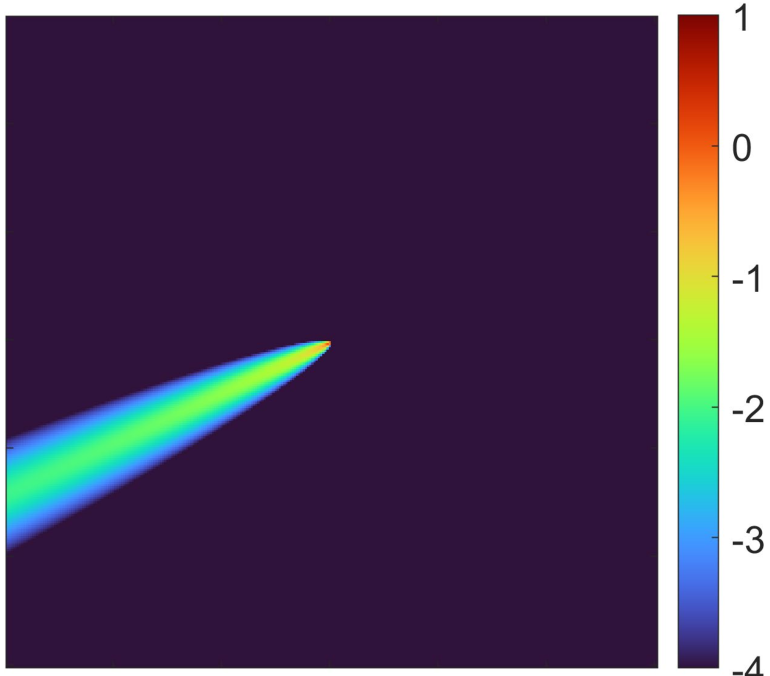
- Performed many AERMOD for 2168 hours, about 90 days: **Generated 2168 scenes**



10 x 10 x 10 m



10 x 10 x 10 m



Vertically integrated (0-1500 m)

AERMOD Results,

No Background.

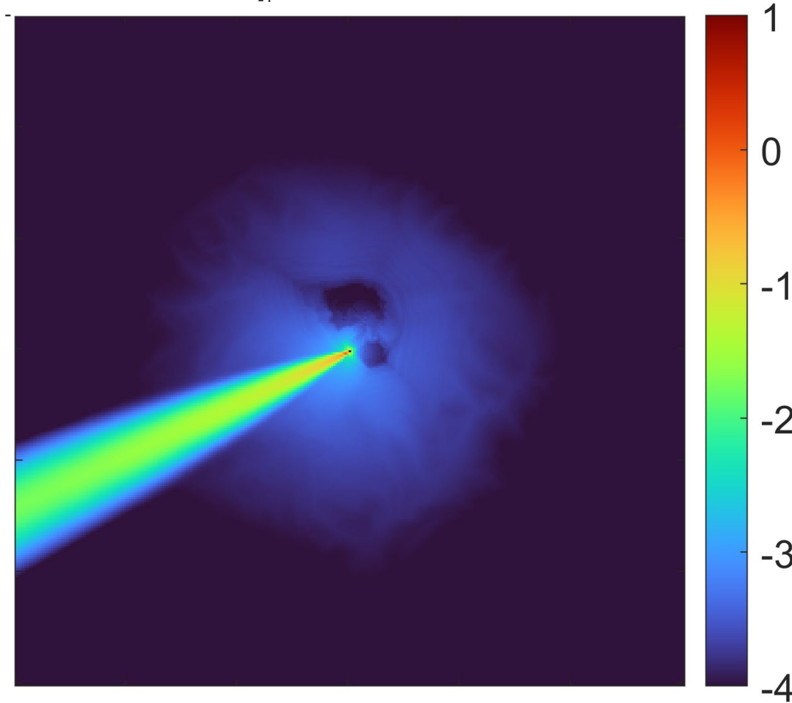
log10 (kg per pixel).

True rate is 100 kg/h

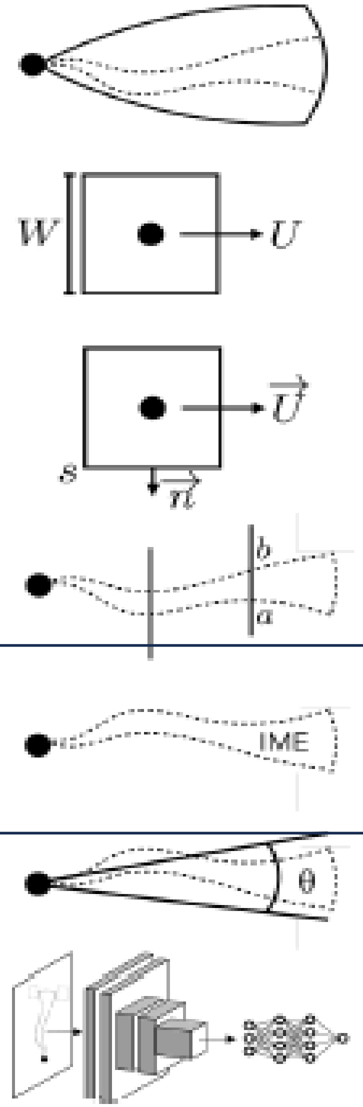
2168 Hourly scenes

Flat terrain

Complex terrain



ppm.m → Flux: Mass/Time



Gaussian Plume	$Q = U\Delta\Omega(x,y)\left(\sqrt{2\pi}\sigma_y(x)e^{\frac{y^2}{2\sigma_y(x)^2}}\right)$
Local mass balance	$Q = UW\Delta\Omega$
Gauss theorem	$Q = \oint_s \Omega(s)\vec{U}\cdot\vec{n}\,ds$
Cross-sectional flux (CSF)	$Q = U\int_a^b \Delta\Omega(x,y)dy$
Integrated mass enhancement (IME)	$Q = \frac{U_{\text{eff}}\,\text{IME}}{L}$
Angular width	$Q = f(\text{IME},\theta)$
Machine learning	$Q = \text{CNN(Plume image)}$

IME approach Varon et al. (2018) and others

Sources of Uncertainties in IME Emissions Rate

Flux: Mass/Time (kg/h)

$$U_{eff} = 1.1 \log U_{10} + 0.6$$

Uncertainties in U_{eff}

$$Q = \frac{U_{eff}}{L} \text{IME}$$

Uncertainties in L: Length of plume m

Uncertainties in IME (kg of methane)

HRRR (~3 km resolution)
GEOS-FP (~25 km resolution)
On Site wind data

Our analysis focused on:

- **Wind speed**
- **Noise levels**
- **Terrain topography**
- **Sources of U_{10} wind data.**

Author	Ueff
(Cusworth et al., 2020)	$1.1 \log U_{10} + 0.6$
(Roger et al., 2024)	$0.34 U_{10} + 0.44$
(He et al., 2024)	$0.37 U_{10} + 0.64$
(Ayasse et al., 2019)	U_{10}
(Varon et al., 2019)	$\log U_{10} + 0.5$
(Guanter et al., 2021)	$0.34 U_{10} + 0.44$
(Ayasse et al., 2023)	$1.1 \log U_{10} + 0.6$
(Sánchez-García et al., 2021)	$0.12 U_{10} + 0.38$
(Thorpe et al., 2023)	U_{10}
(Irakulis-Loitxate et al., 2021)	$0.34 U_{10} + 0.44$
(Maasakkers et al., 2022)	$0.34 U_{10} + 0.66$ for $0.34 U_{10} + 0.42$
(Foote et al., 2021)	U_{10}
(Chulakadabba et al., 2023)	$\log U_{10} + 0.6$
(Pei et al., 2023)	$0.34 U_{10} + 0.44$
(Varon et al., 2020)	$1.14 U_{10}$, 1.24 U10, $1.16 U_{10}$
(Ehret et al., 2022)	$0.9 \log U_{10} + 0.6$
(Gorroño et al., 2023)	$0.23 U_{10} + 0.74$
(Marjani et al., 2024)	$0.34 U_{10} + 0.44$
(Schuit et al., 2023)	$0.59 U_{10}$
(Bruno et al., 2024)	$0.23 U_{10} + 0.7$
(Pang et al., 2023)	$0.55 \log U_{10} + 0.62$

Emission Rate Q, using the IME Method

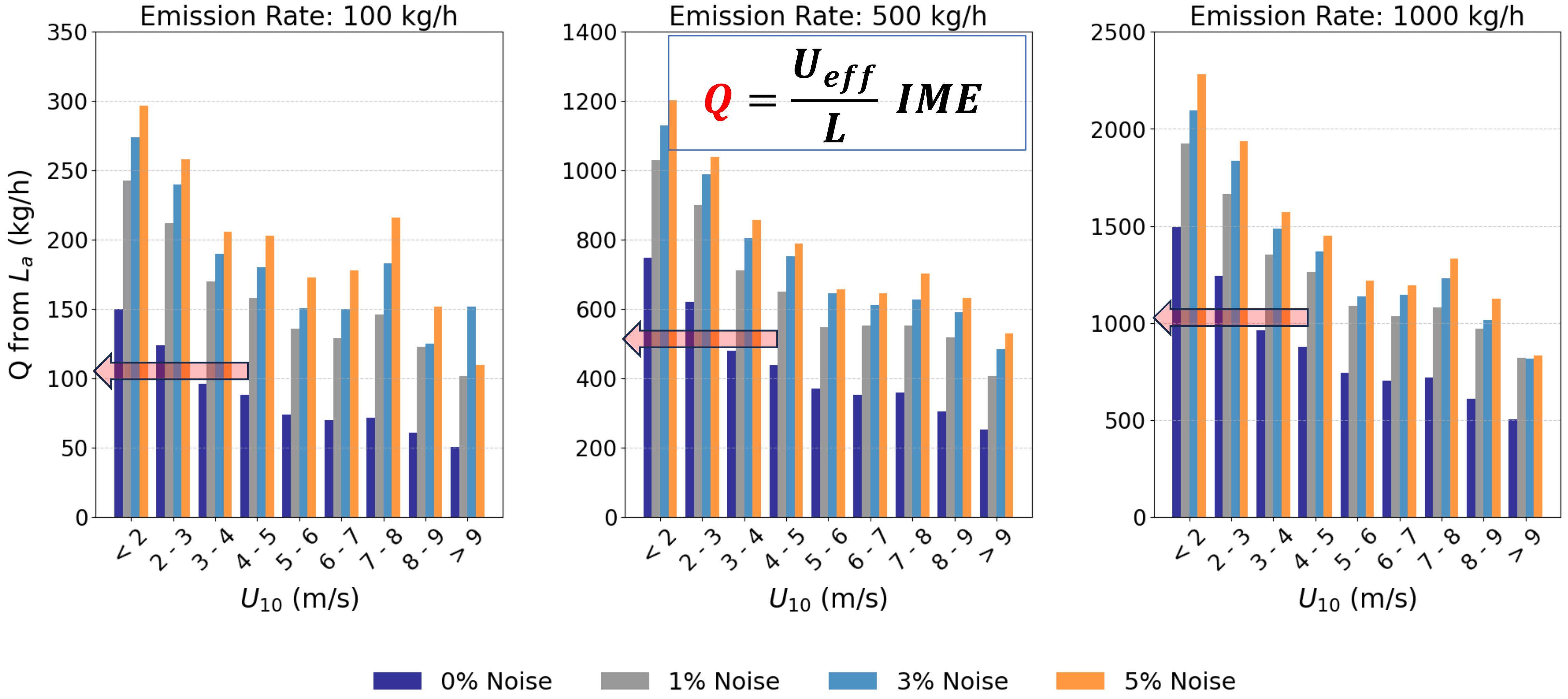
Flat Terrain

1. Over Estimation at low wind speed. Worse with noise

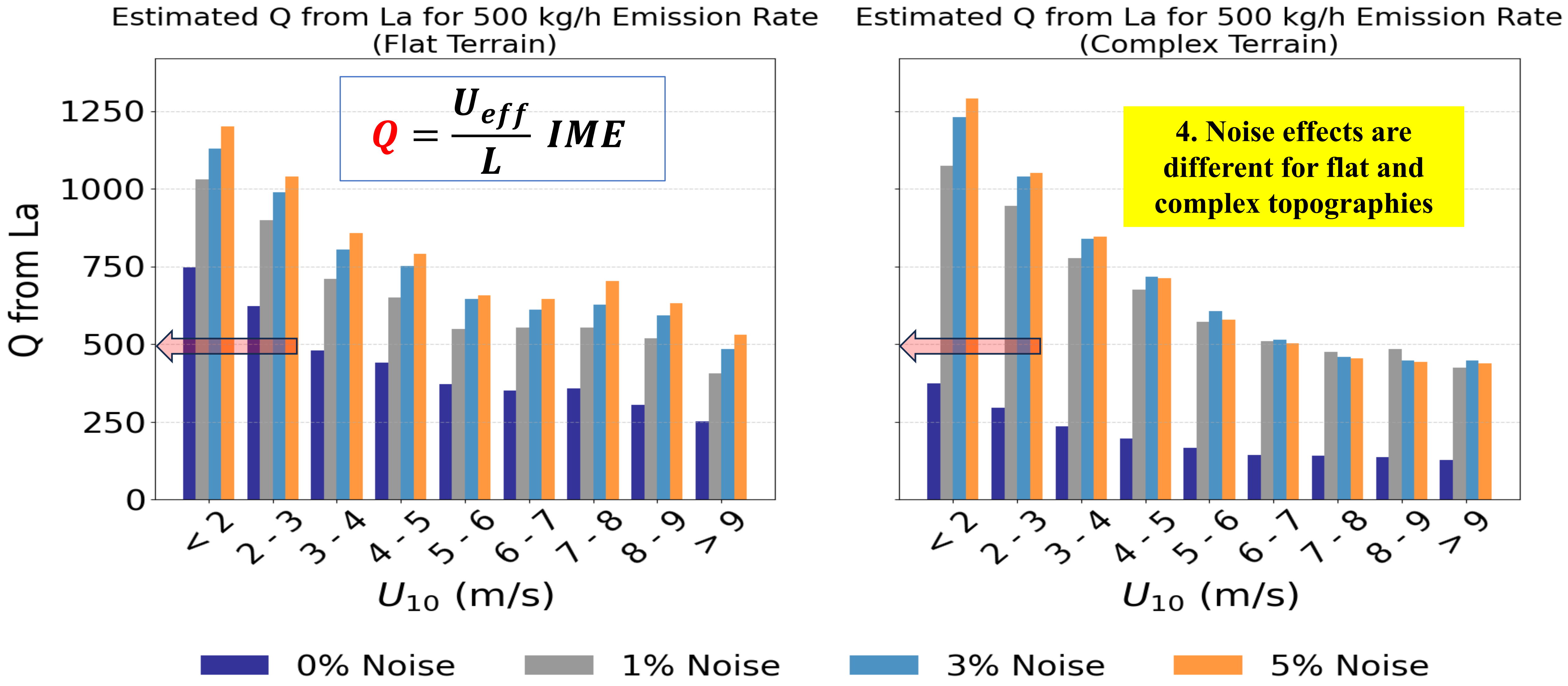
2. Under Estimation at high wind speed. Worse with no noise

3. Noise leads to higher rates at all wind speeds

$$Q = \frac{U_{eff}}{L} IME$$



Emission Rate Q, using the IME Method
500 kg/h Emission Rate across
Flat and Complex Terrain

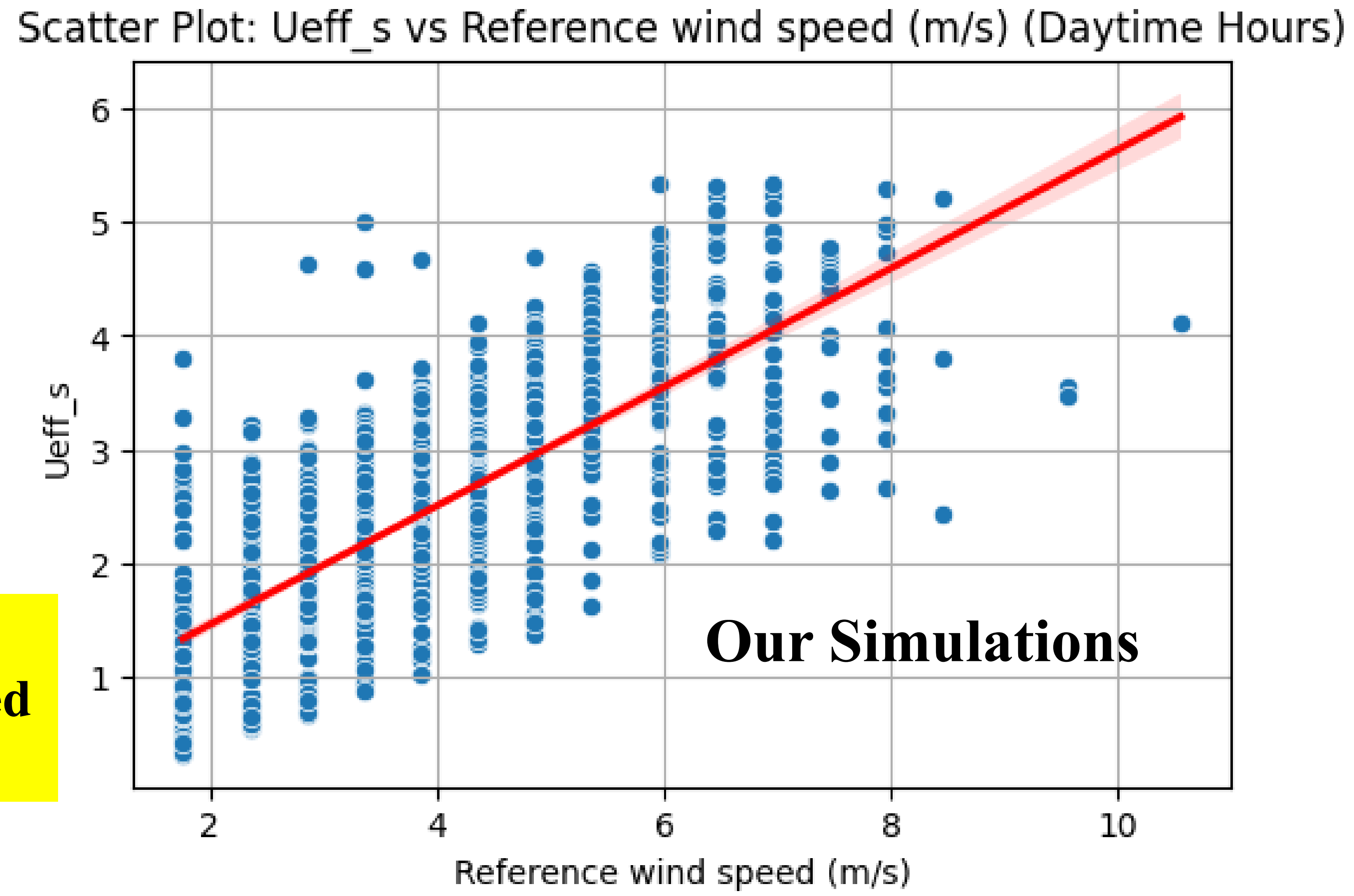


Sources of Uncertainties

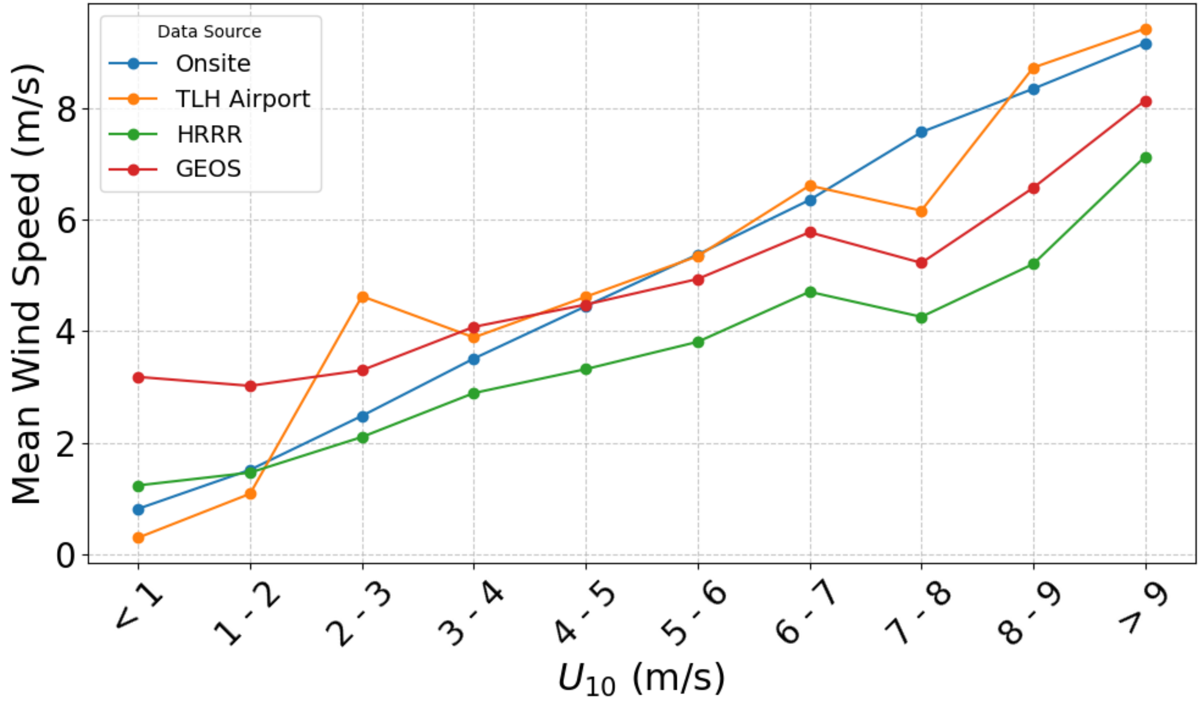
Varon's Simulation:
Reference Wind Speed:
Controls simulations

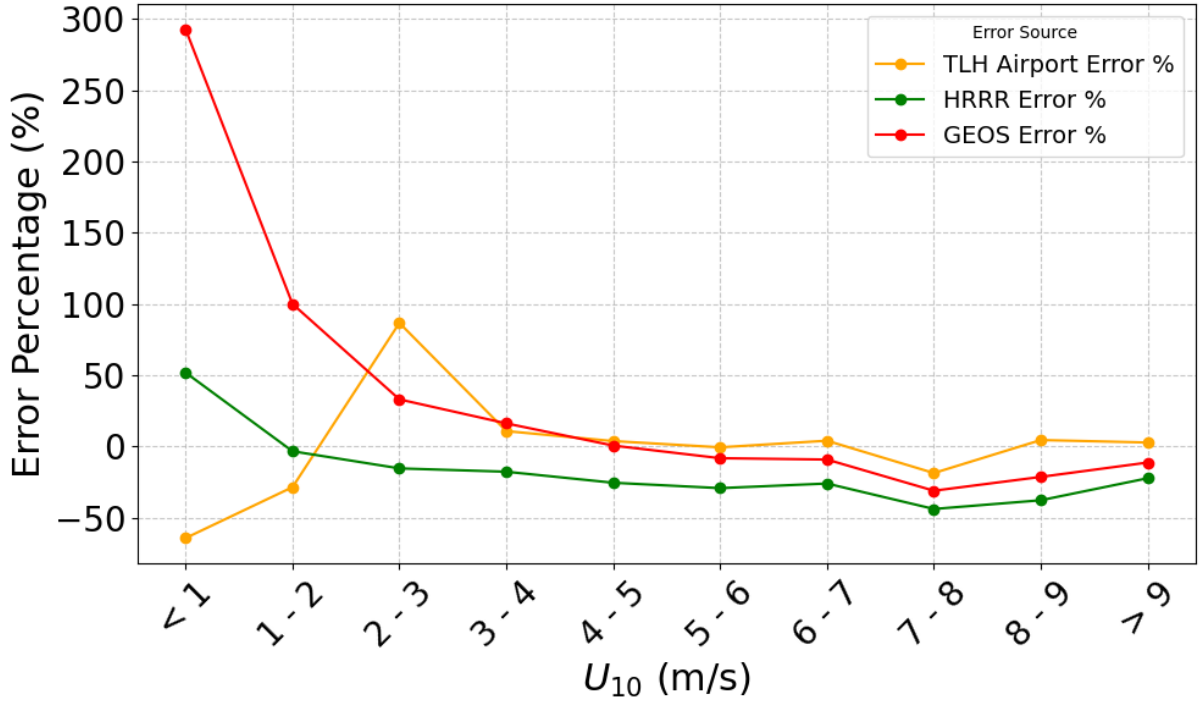
$$U_{\text{eff}} = 1.1 \log U_{10} + 0.6$$

U_{eff} is affected by other parameters besides wind speed
Need to more research!!!!!!



Other Sources of Uncertainties





Cross-comparison of mean wind speeds from on-site measurements, nearby TLH airport, HRRR and GEOS models.

$$U_{\text{eff}} = 1.1\log U_{10} + 0.6$$

Large difference between on site and database global wind data models especially at low wind speed

Key Takeaway on IME Approach

- Current IME algorithm may have significant uncertainties
  - U_{eff} wind formula may not account for all atmospheric conditions and the disproportionate change of mass enhancement and plume scale
  - Terrain feature could impact IME accuracy
  - The use of wind data from weather model may introduce more uncertainties
  - ~ 10 x over-estimation possible
- <u>Location specific calibration w/ local wind data may be necessary</u>

✓ **We need to develop site-specific or conditions-specific U_{eff} Equations each satellite observation?**

✓ **We need more controlled releases under diverse atmospheric condition for IME calibration ?**

Deliverables

Delangel Jorge M.
Student
(Graduated 2023)

Sakina Amankwah
Student
Graduated (12/2024)
Looking for a Job!!!

Questions?

Tarek Abichou
Professor
Civil & Environmental Engineering
FAMU-FSU College of Engineering
Phone: (850)410-6661
E-mail: abichou@eng.famu.fsu.edu

Contact Information