Landfill Gas and ET Covers

Tarek Abichou, Ph.D., PE

College of Engineering

Department of Civil and Environmental Engineering

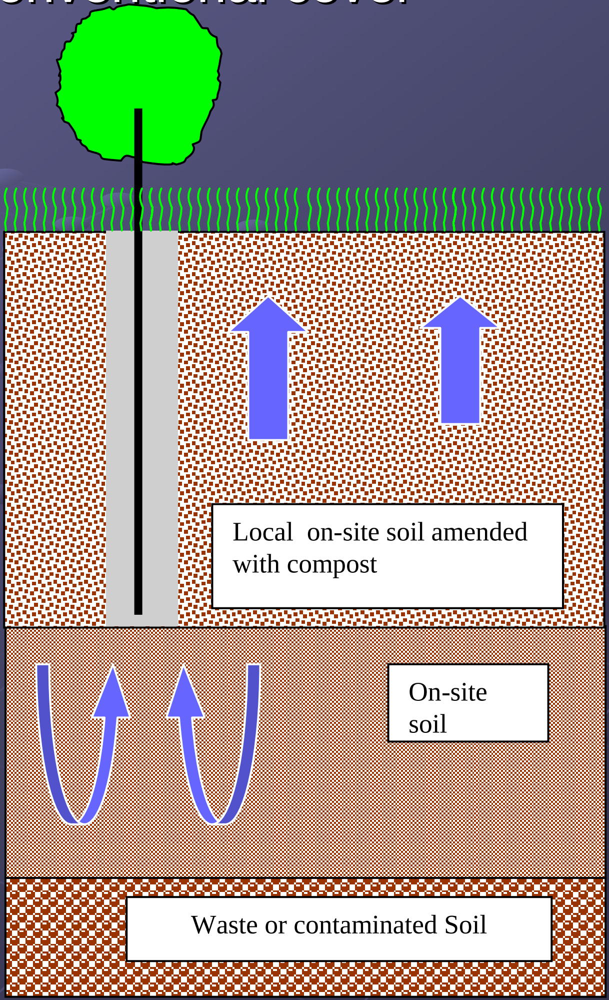
Florida State University

Phone: (850)410-6661

Email: abichou@eng.fsu.edu

Perspective: Alternative Covers

- RCRA Subtitle D: an alternative cover must provide performance that is equivalent to (or better) than that of the intended conventional cover
- control of erosion and *percolation*, along with **"acceptable" gas control.**



I have Designed landfill covers through my work with ACAP to deal with *Water Balance* equivalency:

People always asked: How about Gas?

Microbial Methane Oxidation

- Methane oxidation is an important sink for Methane produced in anaerobic environment such as rice fields and landfills
- The net reaction for microbial methane oxidation is

$$CH_4 + 2O_2 \longrightarrow CO_2 + 2H_2O$$

- Pathway of oxidation has been found to be via Type I and-or Type II Methanotrophs
- Methanotrophs can use methane as the only carbon and energy source
- The Enzyme methane mono-oxygenase (MMO) catalyzes the conversion of methane into methanol
- Landfill Applications
  - Can we optimize oxidation rate
  - Manipulate existing covers to increase methane oxidation
  - Incorporate bio-oxidation into landfill cover design and to gas management plans
- Considerable work has been done on biofilters to oxidize landfill gas (lab columns, large scale filters or scrubbers)
- Some work has been done methane oxidation through landfill covers

Factors affecting oxidation

- Water content profile
- Temperature profile
- Organic matter content
- Porosity
- Climatic and ambient conditions
  - Barometric pressure
  - Vegetation
- Oxygen penetration
- Methane availability

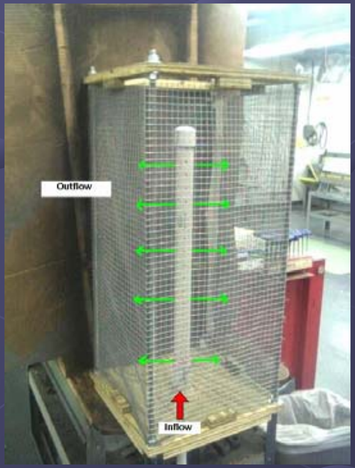
Methane Oxidation in Biofilters

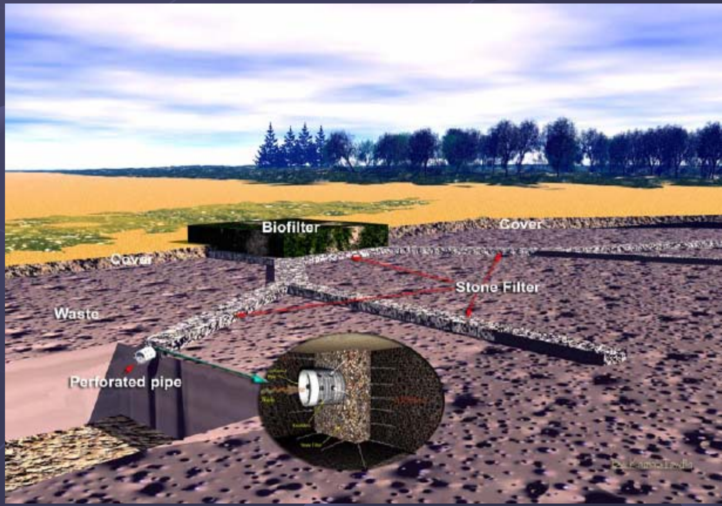
(Oxidation = IN – OUT)

flow meters measure flow rate, GC measure concentration

Active biofilters

(bottom flux is controlled, different media is tested)





Passive biofilters (bottom flux is not controlled)

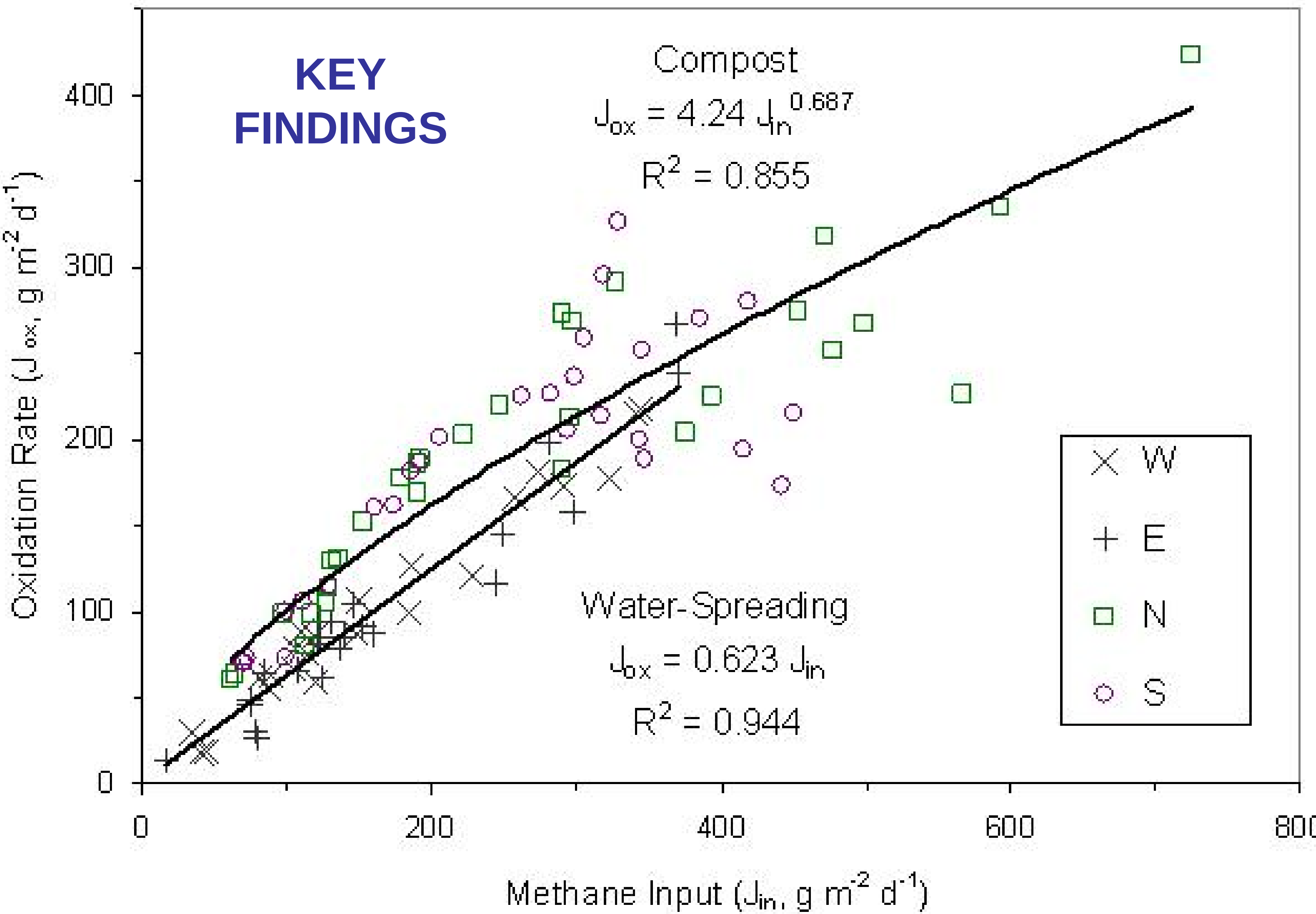
Methane Oxidation: Biofilters

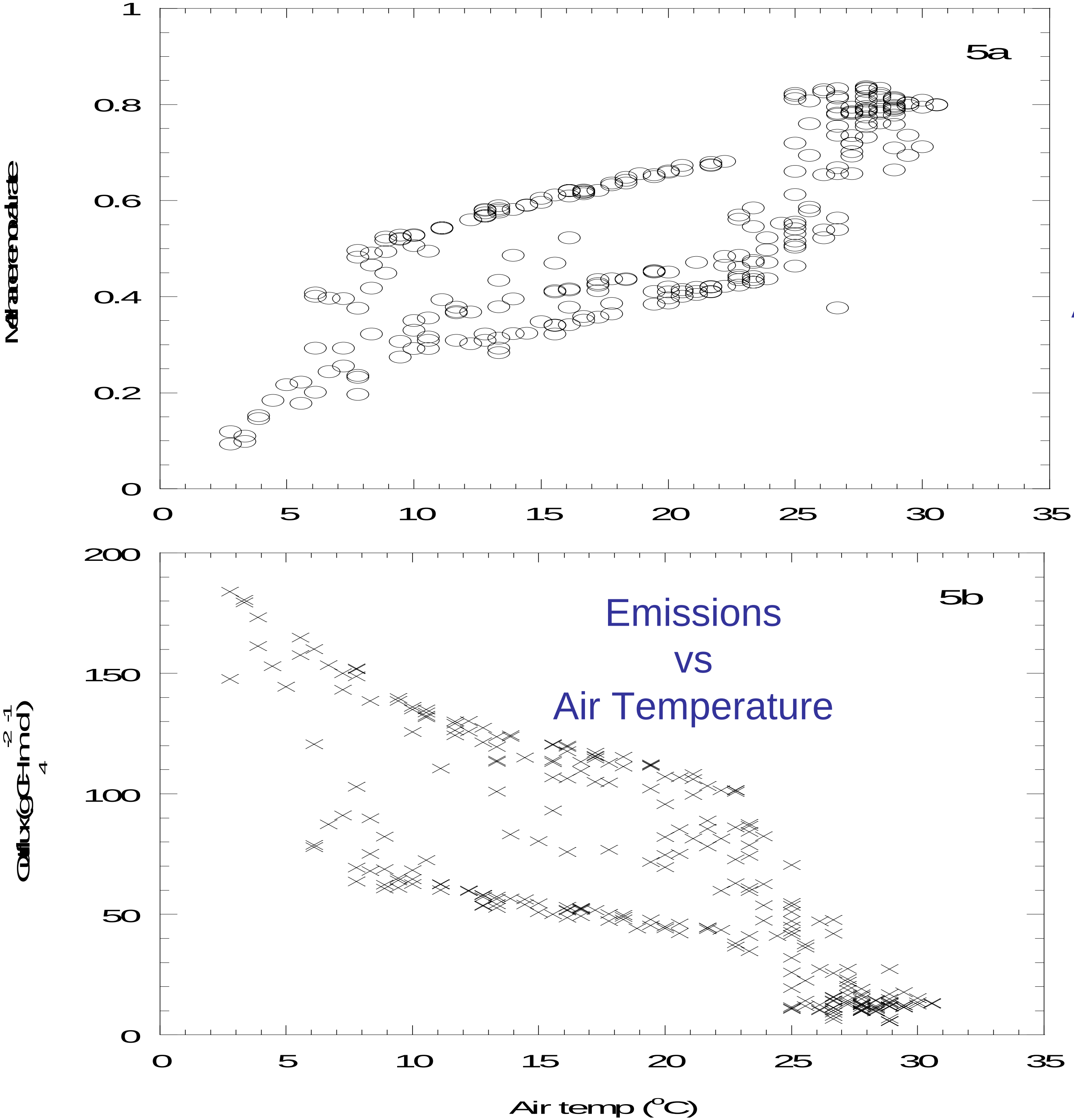
material/Media	Maximum methane oxidation rate	Fraction of methane oxidized	Reference
	g m^{-2} d^{-1}	%	
Coarse sand	166	61	Kightley et al., 1995
Agricultural soil	171	82	De Visscher et al., 1999
Landfill cover soil, sandy loam	125	47	Hilger et al., 2000
Loamy sand	435	83	Park et al., 2002
Loamy sand	210	81	Scheutz and Kjeldsen, 2003
Leaf compost	500	95	Wilshusen et al., 2004
Compost and sand	54	98	Berger et al., 2005
Coarse sand	267	72	Powelson et al. 2006 FSU STUDY
Compost	125	95	Yuan et al. (2006) FSU STUDY
Compost tire chips mixture	334	20	Abichou et al. (2006) FSU STUDY
Compost and polystyrene pieces	423	58	Powelson et al. 2006 FSU STUDY

Depth of Oxidation Zone

Soil type	Maximum oxidation zone†	Test type‡	References
	----cm----		
Sandy-clay loam	5-10	Incubation	Czepiel et al., 1996
Sand,silt,clay mixture	15-40	Column	Visvanathan et al., 1999
Sandy clay	40-60	Incubation/field	Nozhevnikova et al.,1993
Sandy loam	40-60	Incubation	Borjesson and Svensson.,1997
Sandy clay	3-12	Column	Whalen et al.,1990
Soil/Vermiculite	15-60	Column	Barratt, 1995
Sand and clay	20-30	Column	Kightley et al., 1995.
Compost	40-90	Field scale	Humer and Lechner, 2001

KEY FINDINGS



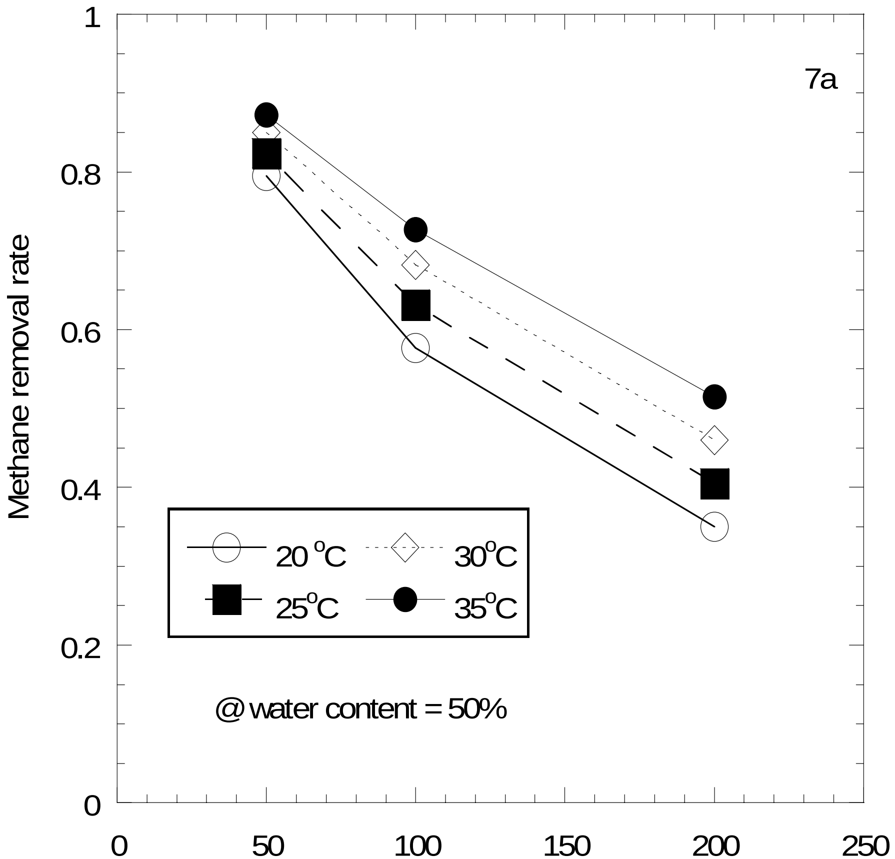


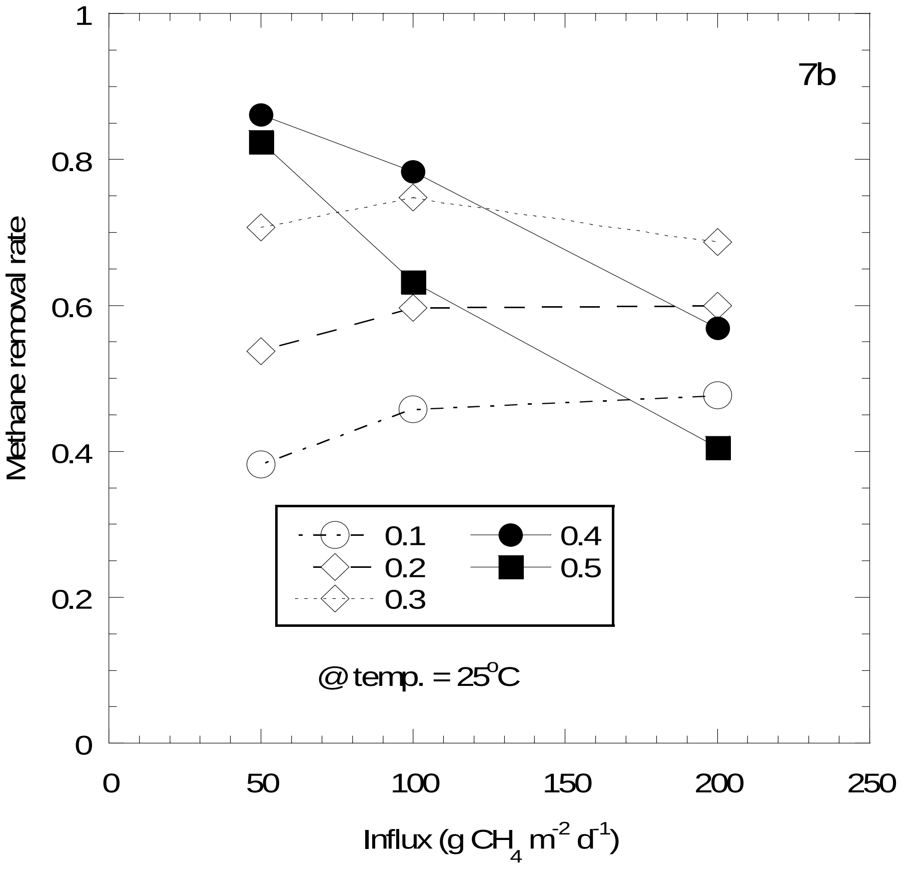
Oxidation
vs
Air Temperature

KEY FINDINGS

Water Content & Influx Influence on Oxidation*

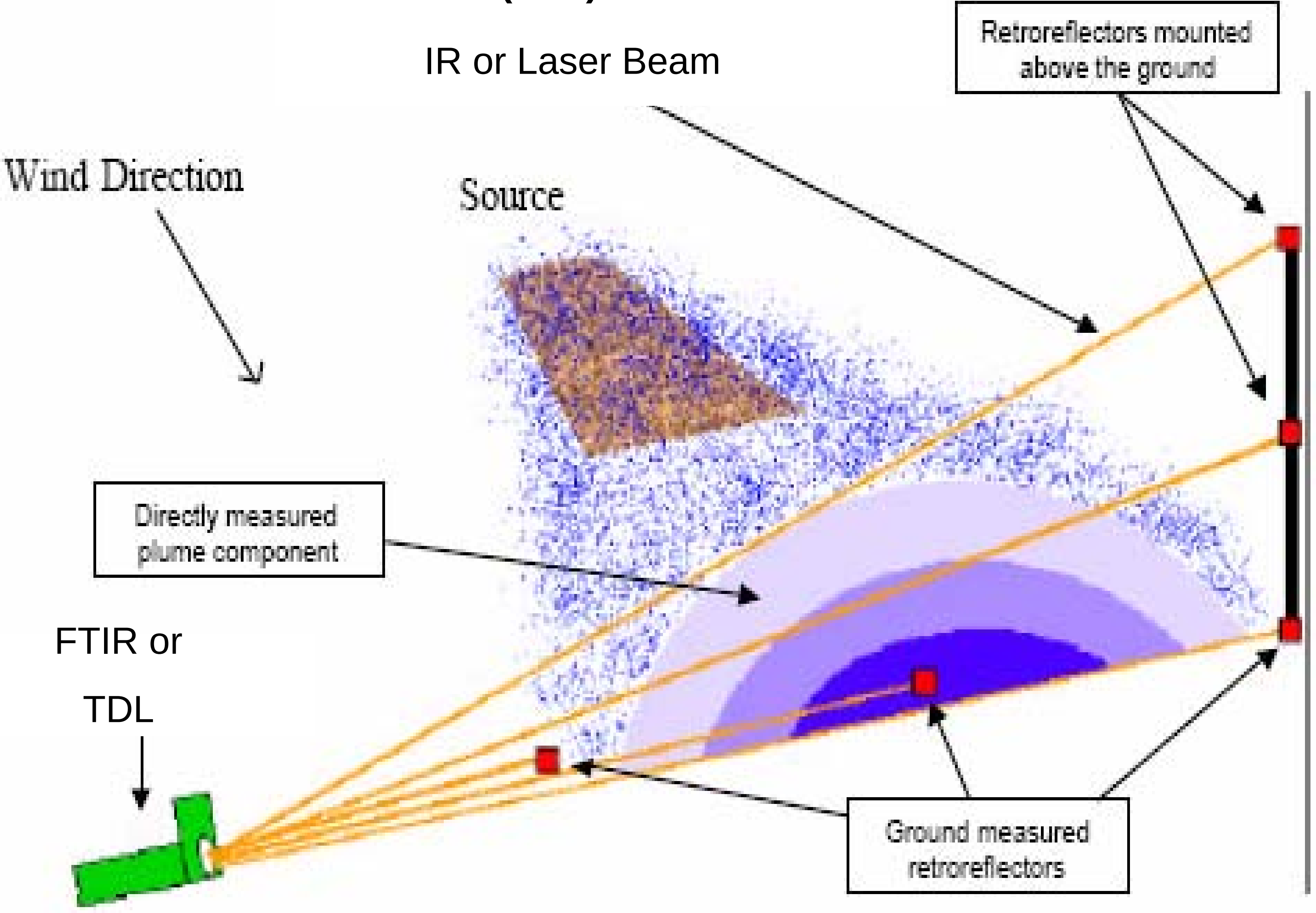
* these are modeling results





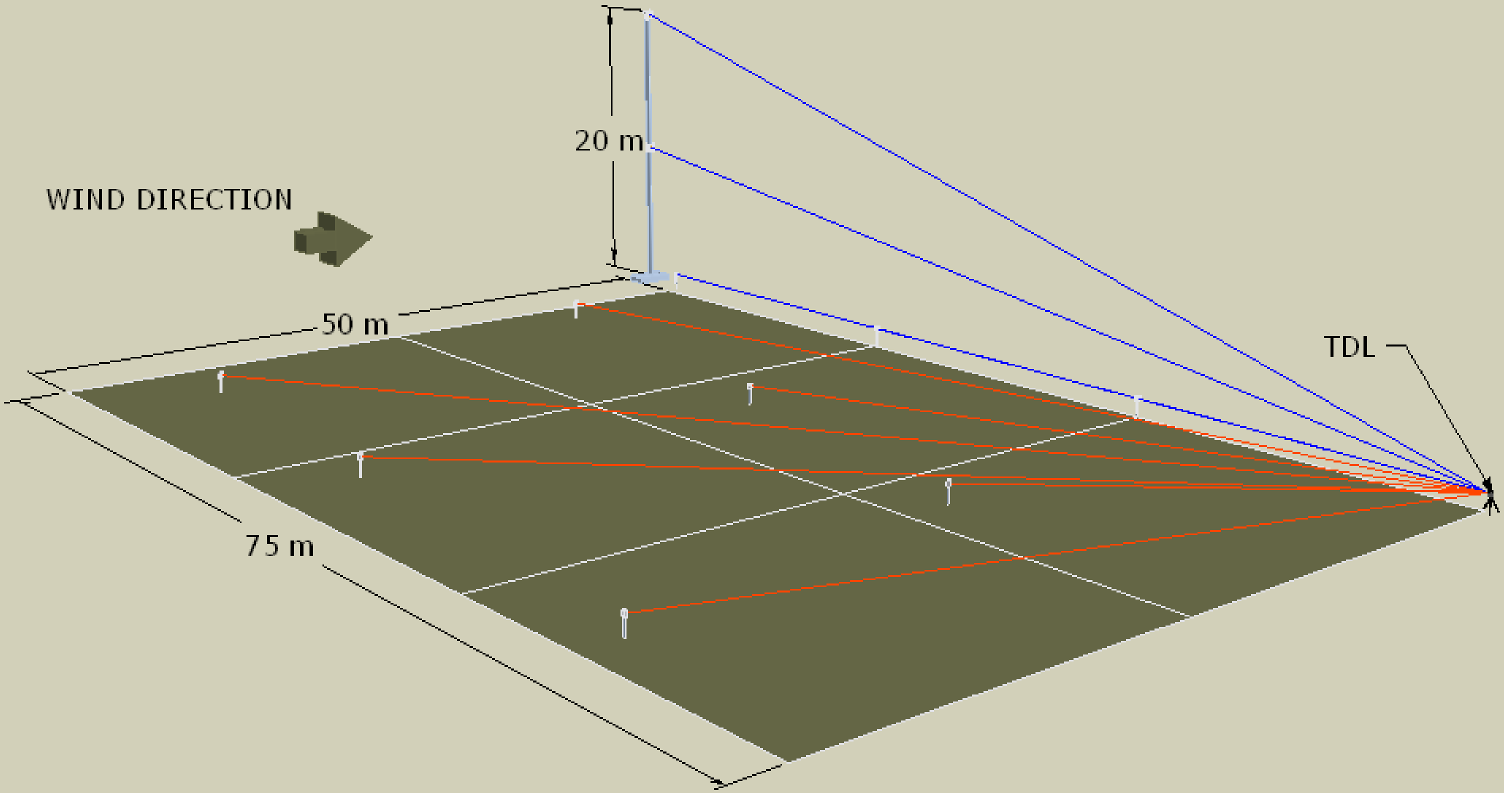
How about oxidation in landfill covers?
Let’s look at emissions first

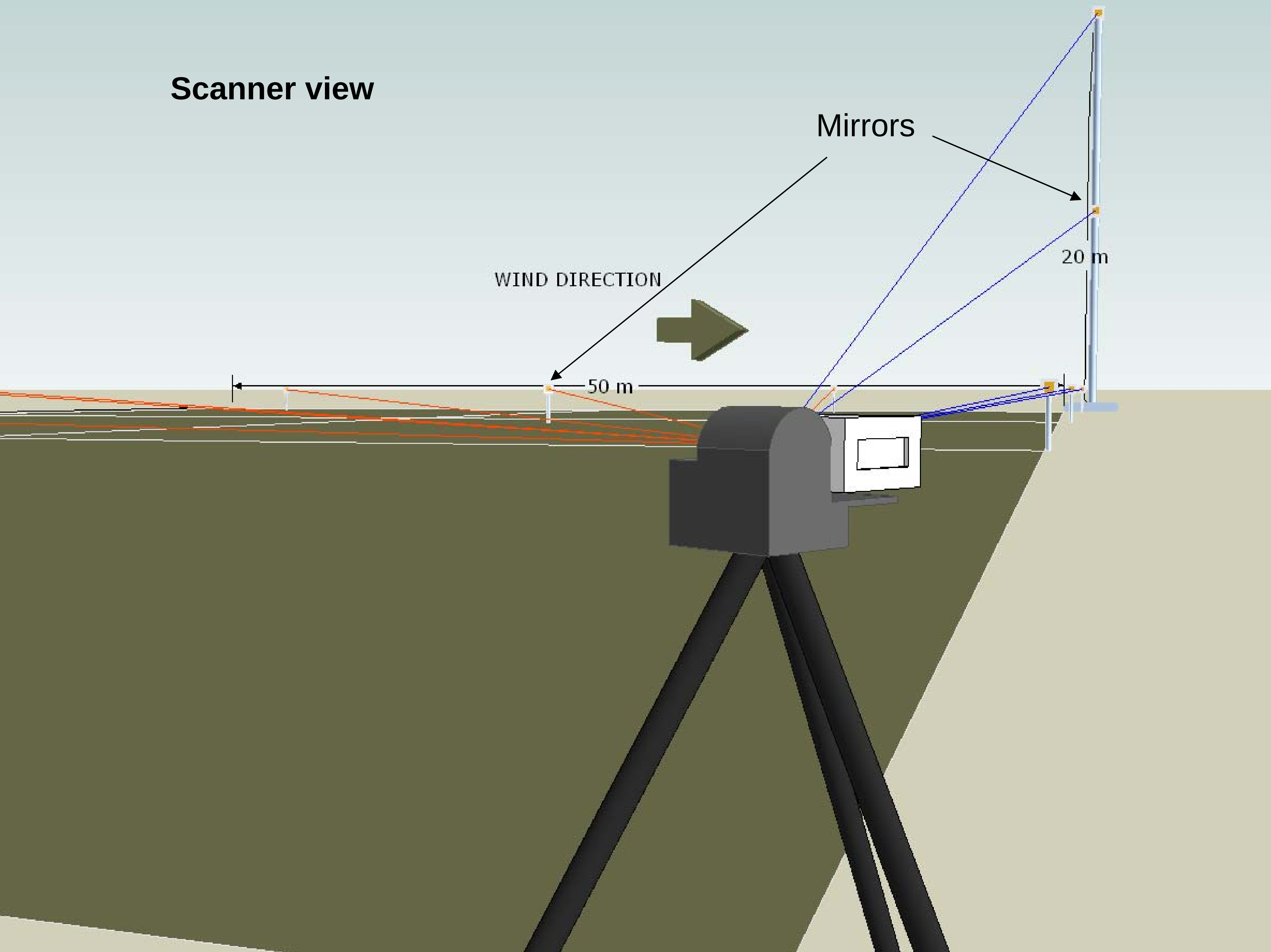
Remote sensing methods: Fourier Transform Infrared (FTIR) and Tunable Diode Laser (TDL)



Landfills are too large and tend to be hilly, wind patterns are affected by topography

Some are trying to combine horizontal scans with vertical scans in order to extend this method to emissions from landfills



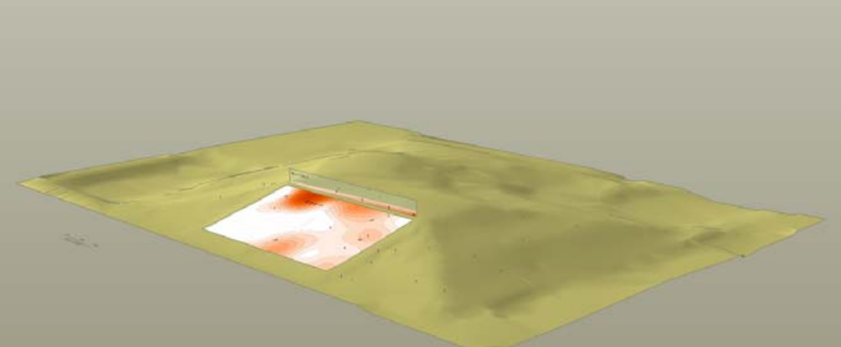


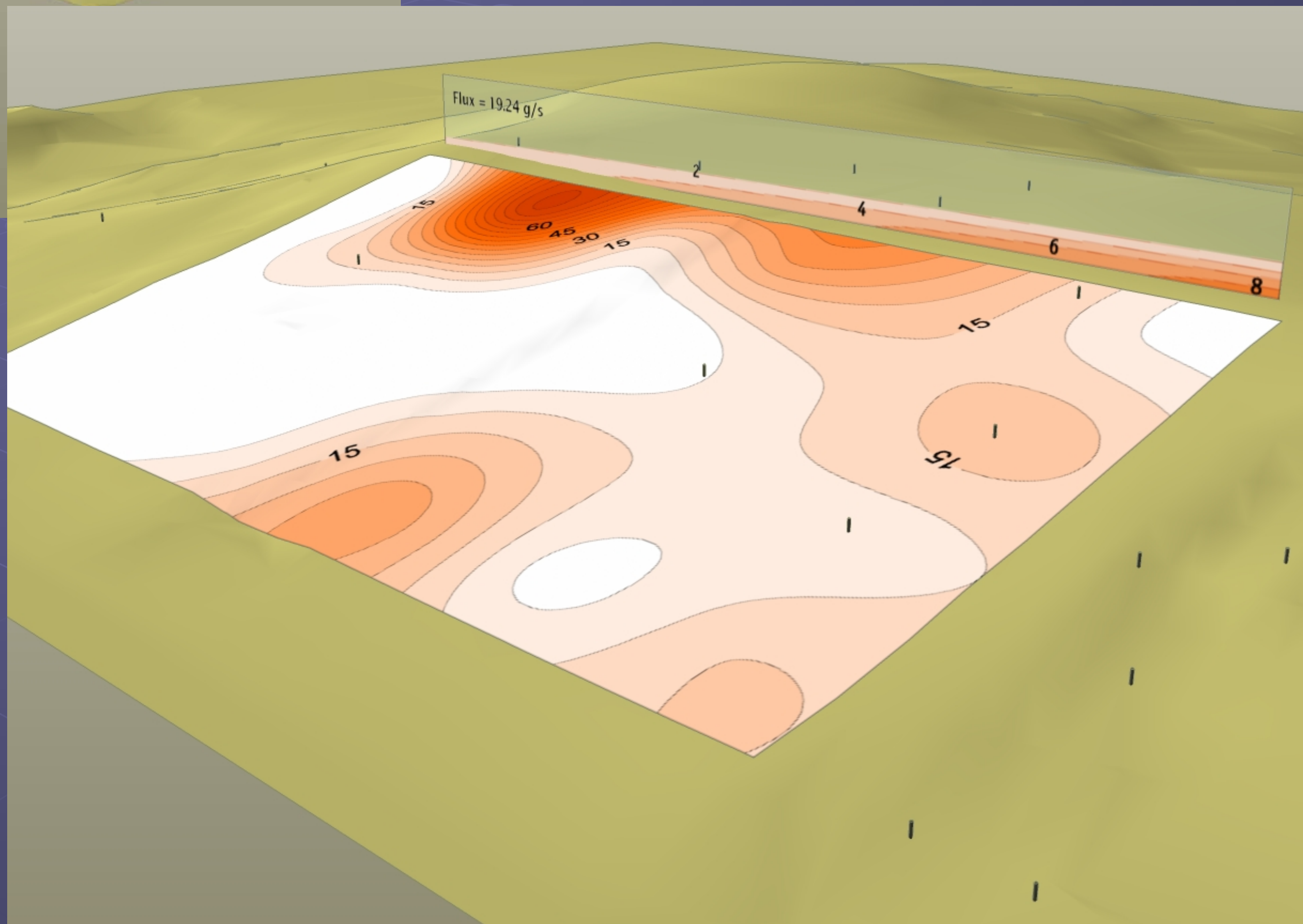
Scanner view
Mirrors
20 m
WIND DIRECTION
50 m

Example Results of TDL study

-These are concentration profiles

-How do you go from ppm to Flux (mass/area/time)

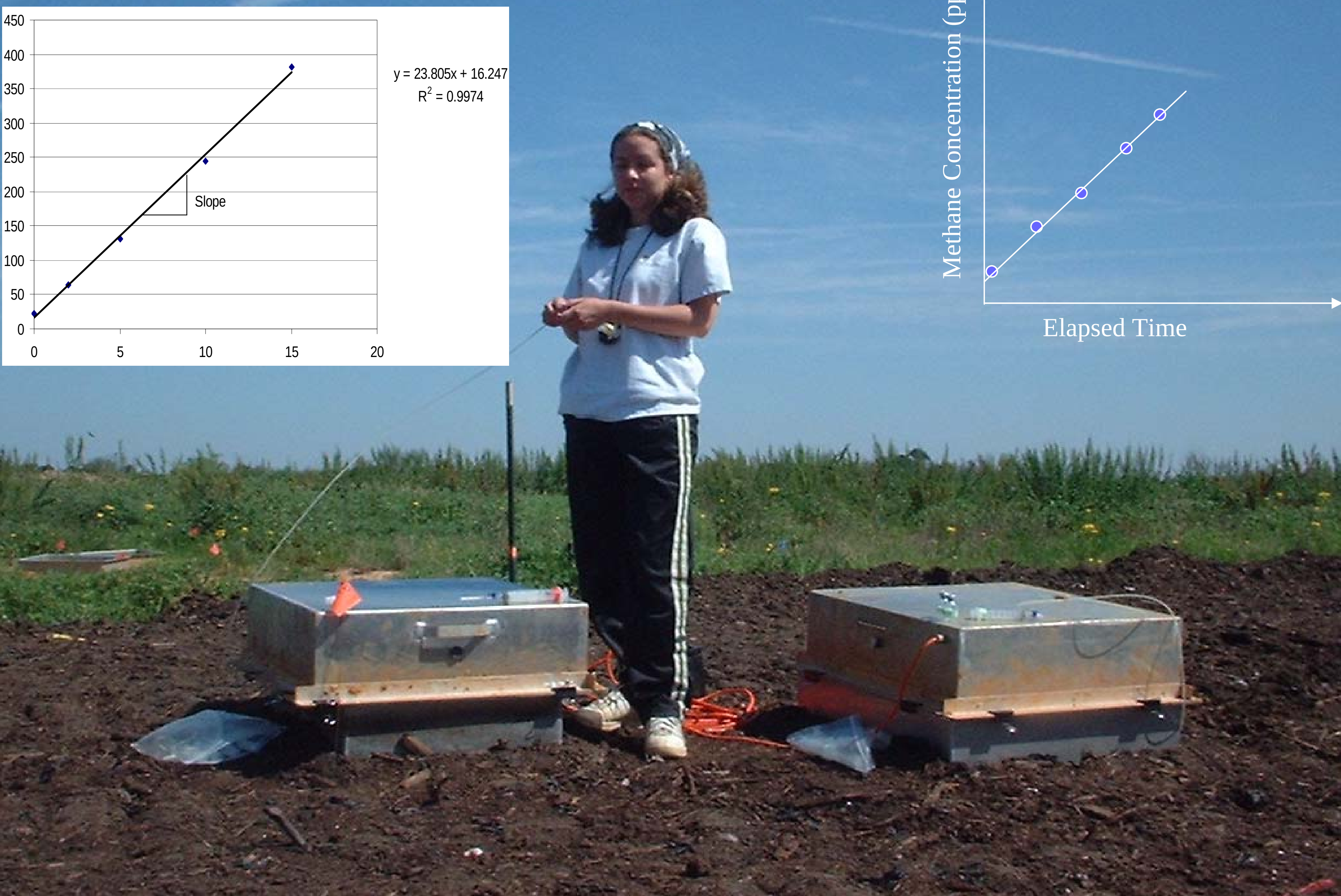


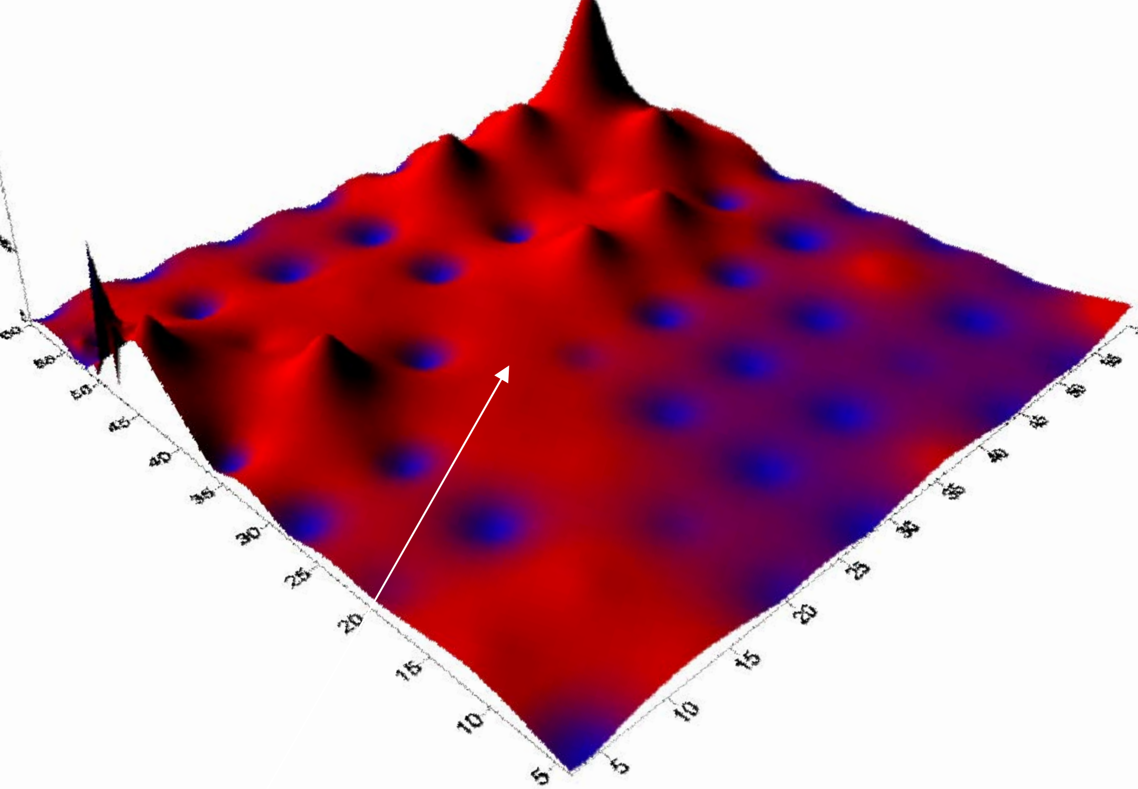


Chamber flux measurements of methane emission

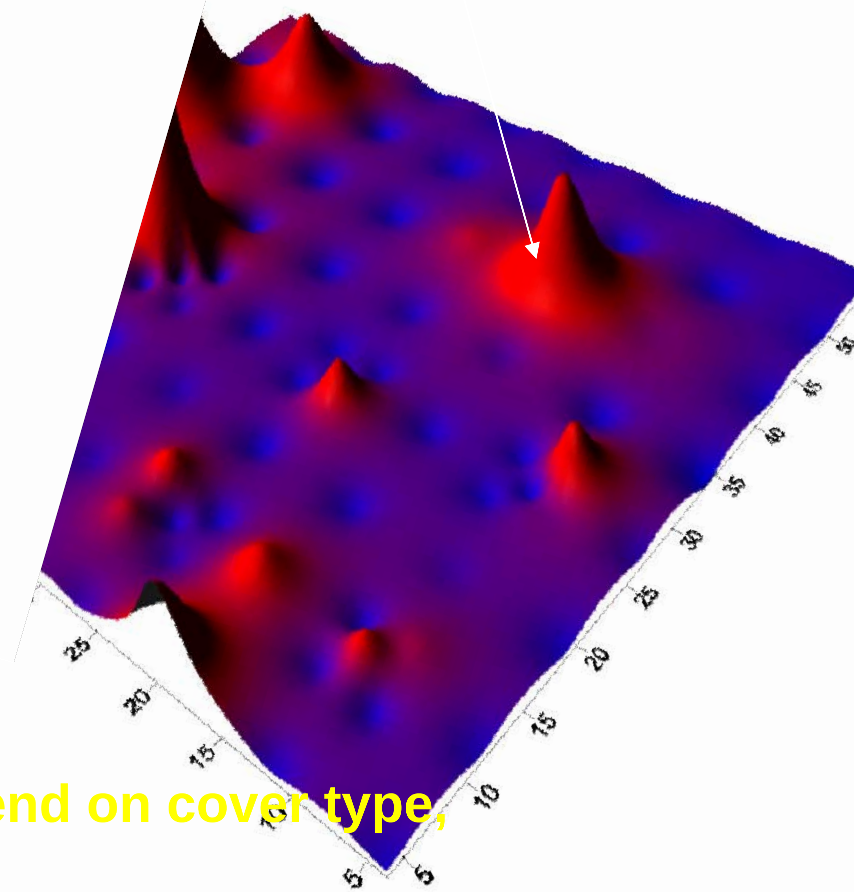
Chamber flux measurements of methane emission

Chamber flux measurements of methane emission





Methane Emission from an intermediate cover ~ 65-75 cm well vegetated
Can also simulate old closed landfill
(Note the hot spots).



Methane Emission from an intermediate cover ~ 15 cm thick with no vegetation
(Note more uniform emission).

Methane emissions are not uniform, depend on cover type, vary with time, and climatic conditions, !

[Leon County Florida data, 2003, 2004]

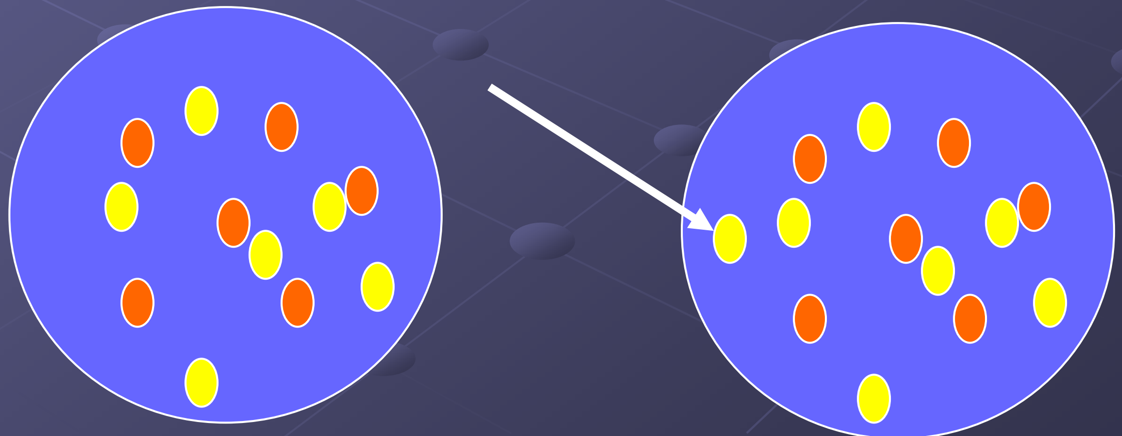
Methane oxidation in landfill covers

- Has been well documented
- Difficult to measure
- Influx from the underlying waste can not be measured
- Use of Stable Isotope technique to measure oxidation

There are 2 C isotopes
The addition of an extra neutron has a subtle but significant effect on chemistry

$^{12}C = 99\%$ abundant

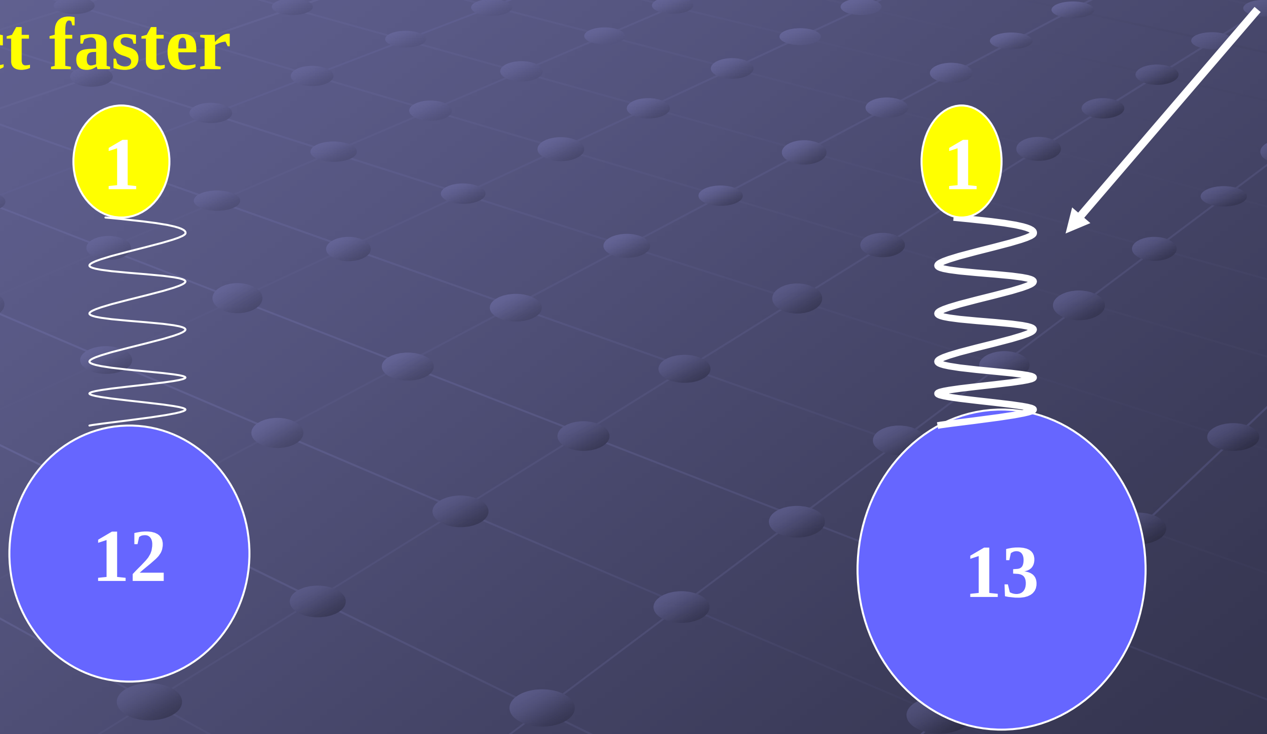
$^{13}C = 1\%$



$^{12}CH_4$ reacts faster the $^{13}CH_4$ leaving residual methane ^{13}C enriched, or heavy

These molecules react faster

This bond is harder to break



The "δ" Scale

$$\delta‰ = (R_{sample}/R_{std} - 1) \times 1000$$

where R = $^{13}C/^{12}C$ ratio

- -60‰ = anoxic zone methane (LIGHT-- ^{13}C depleted)
- -40‰ = oxidized methane
- -26‰ = organic matter
- 0‰ = marine limestone (HEAVY-- ^{13}C enriched)

The more negative the value, the less 13C

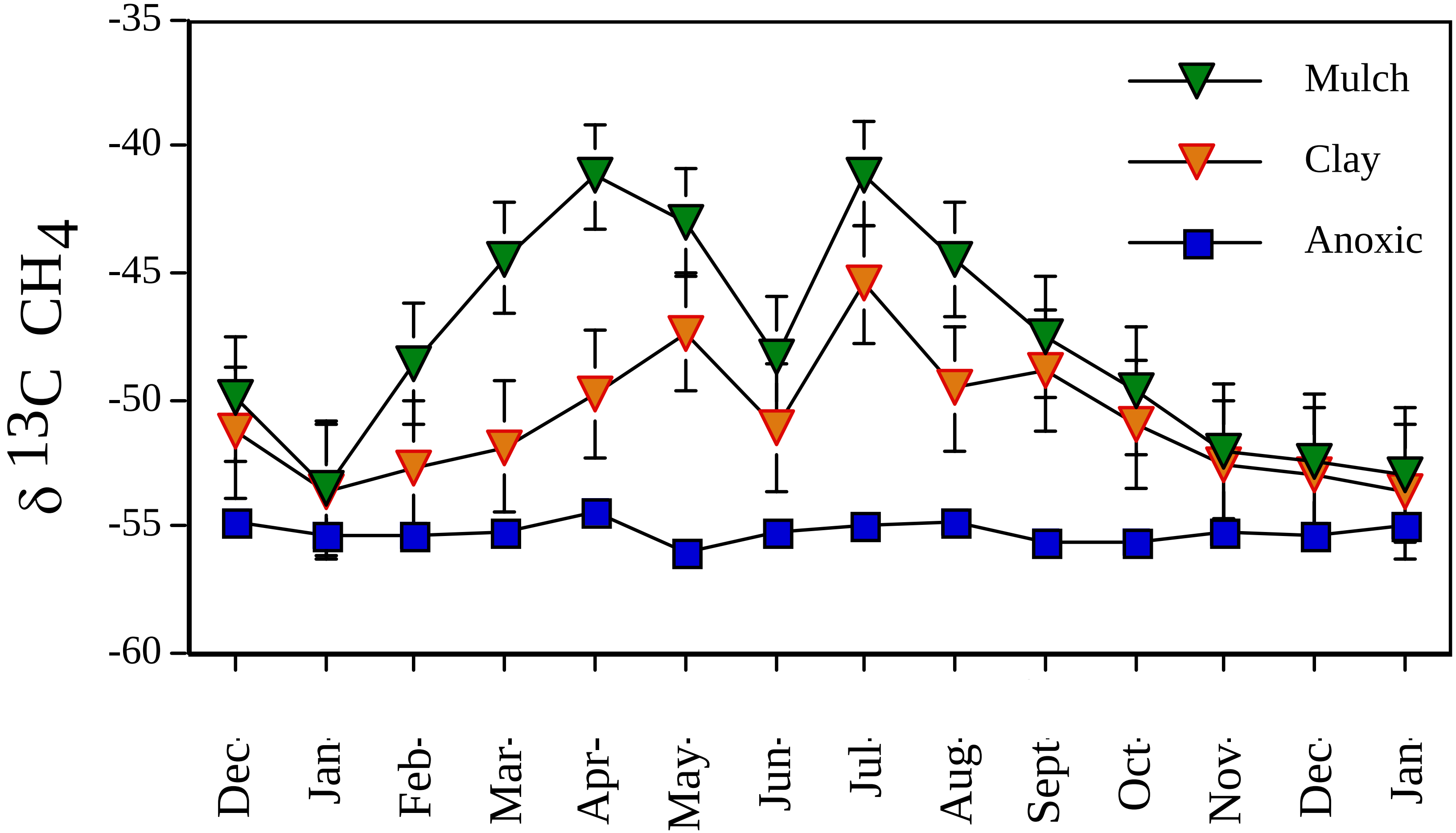
To Calculate % Oxidation

We assume flux driven by flow, and that a pressure gradient exists from anoxic zone to the surface.

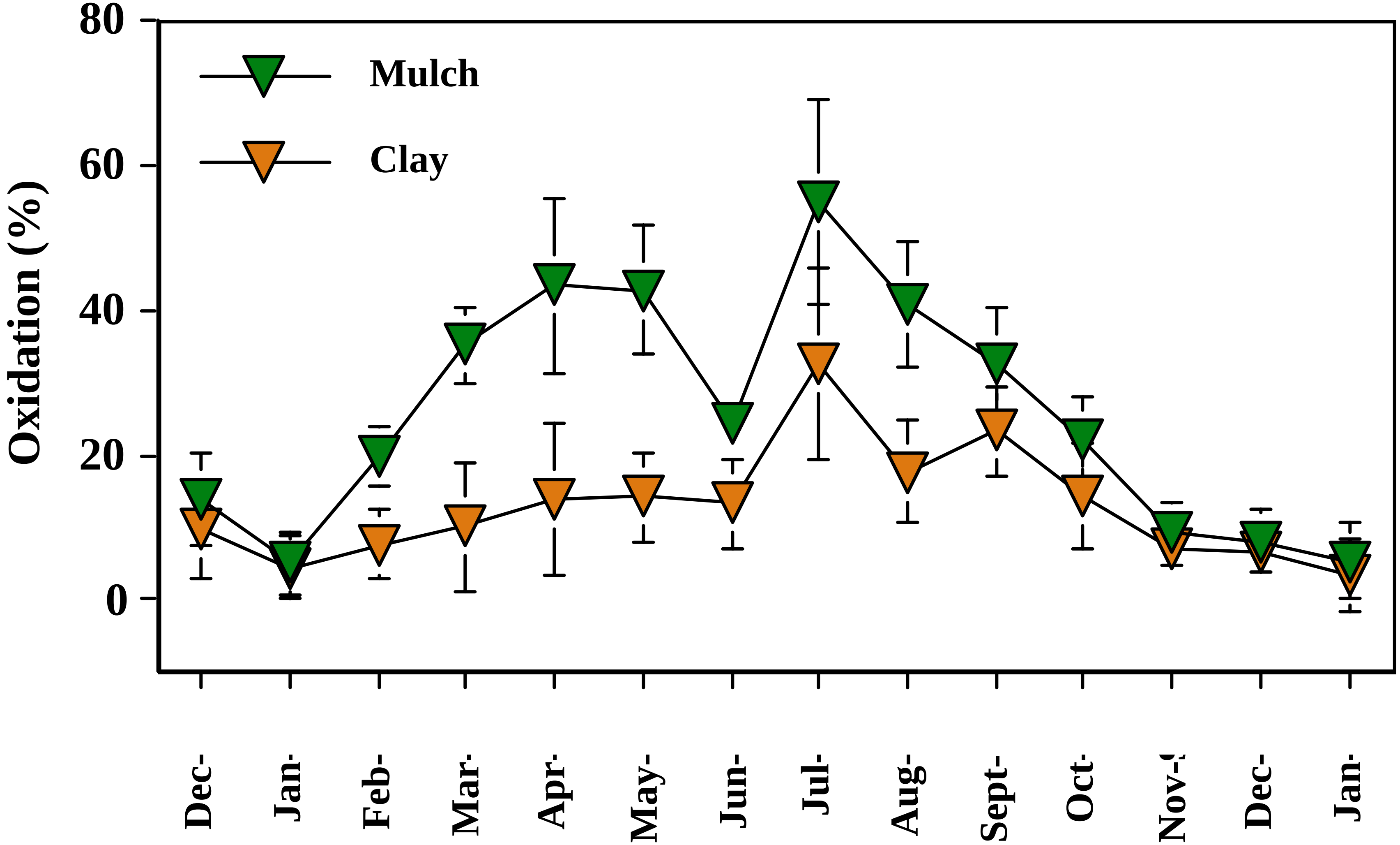
$$f_o\% = [(\delta E - \delta A)/(\alpha - 1)]*1000*100$$

- where f_o is the % of CH_4 oxidized in transit through the cover soil
- $\delta E = \delta^{13}C$ value of emitted CH_4
- $\delta A = \delta^{13}C$ value of anoxic zone CH_4
- α is the isotopic fractionation factor for bacterial oxidation, measured in a closed system incubation.

Seasonal Variation of $\delta^{13}C$ at Two Contrasting Soil Covers: Stable Isotopes can differentiate between methane with different signature

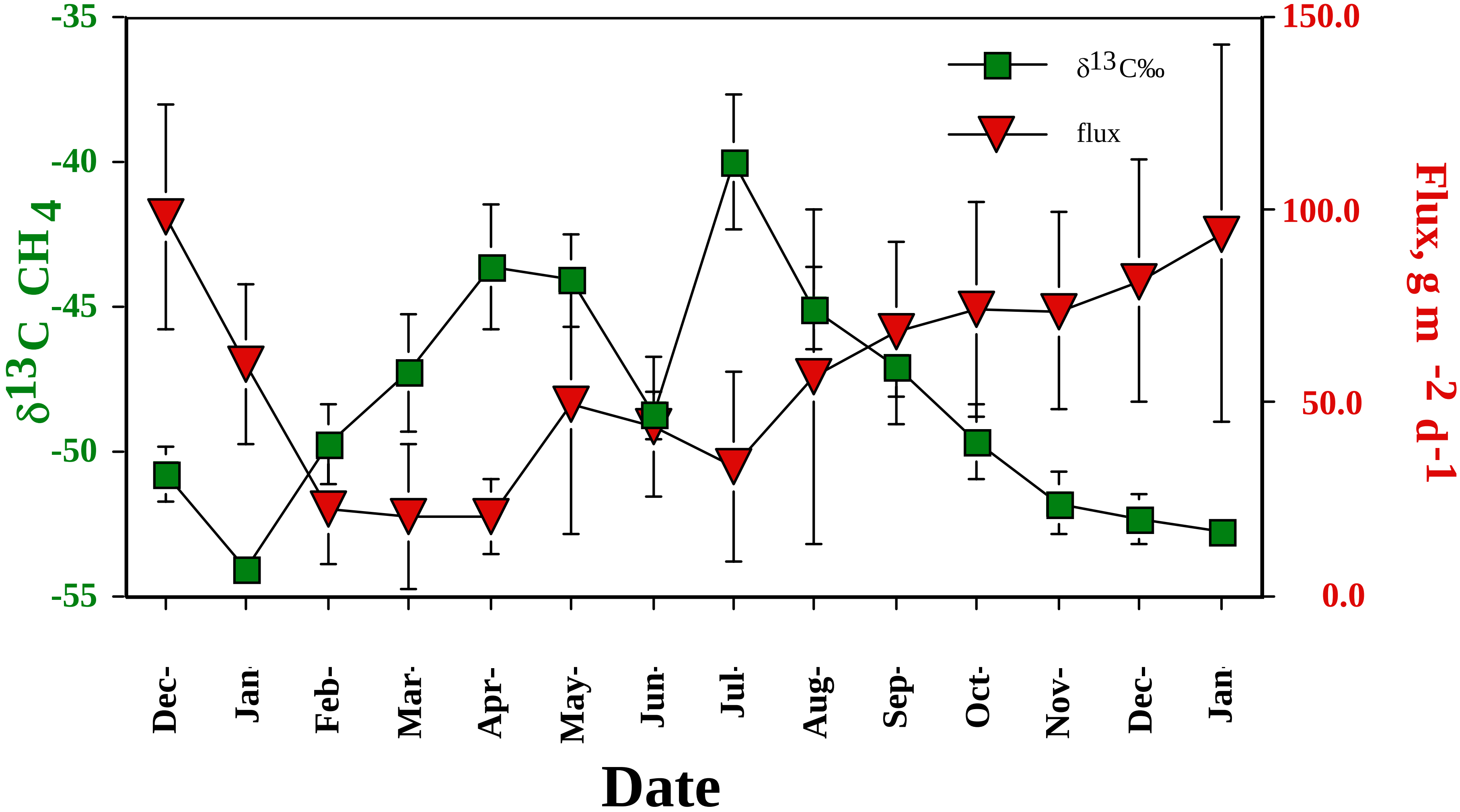


And therefore can be a measurement of degree of oxidation, typically referred to as % Oxidation

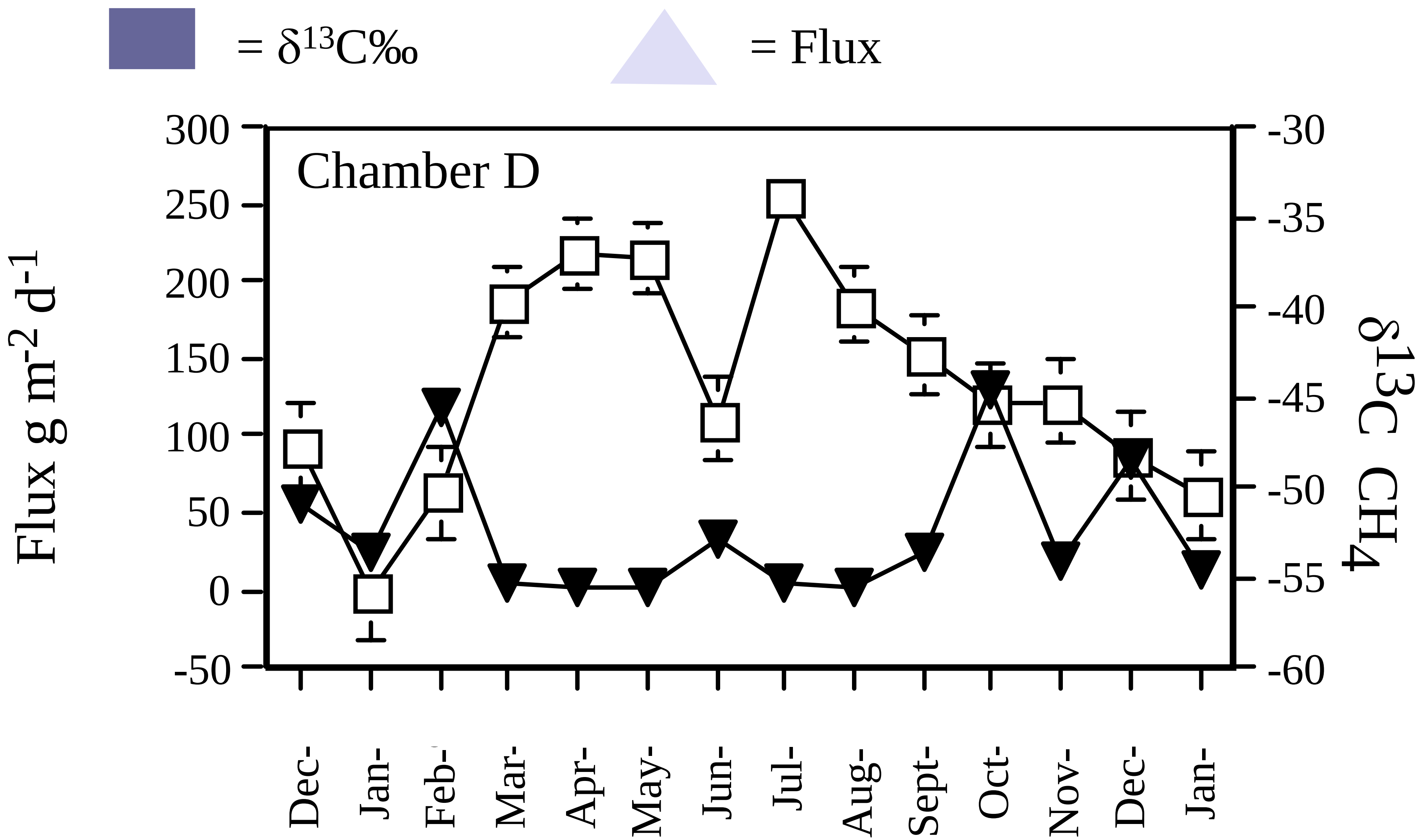


Can methane oxidation control emissions (flux) from the surface of landfills:

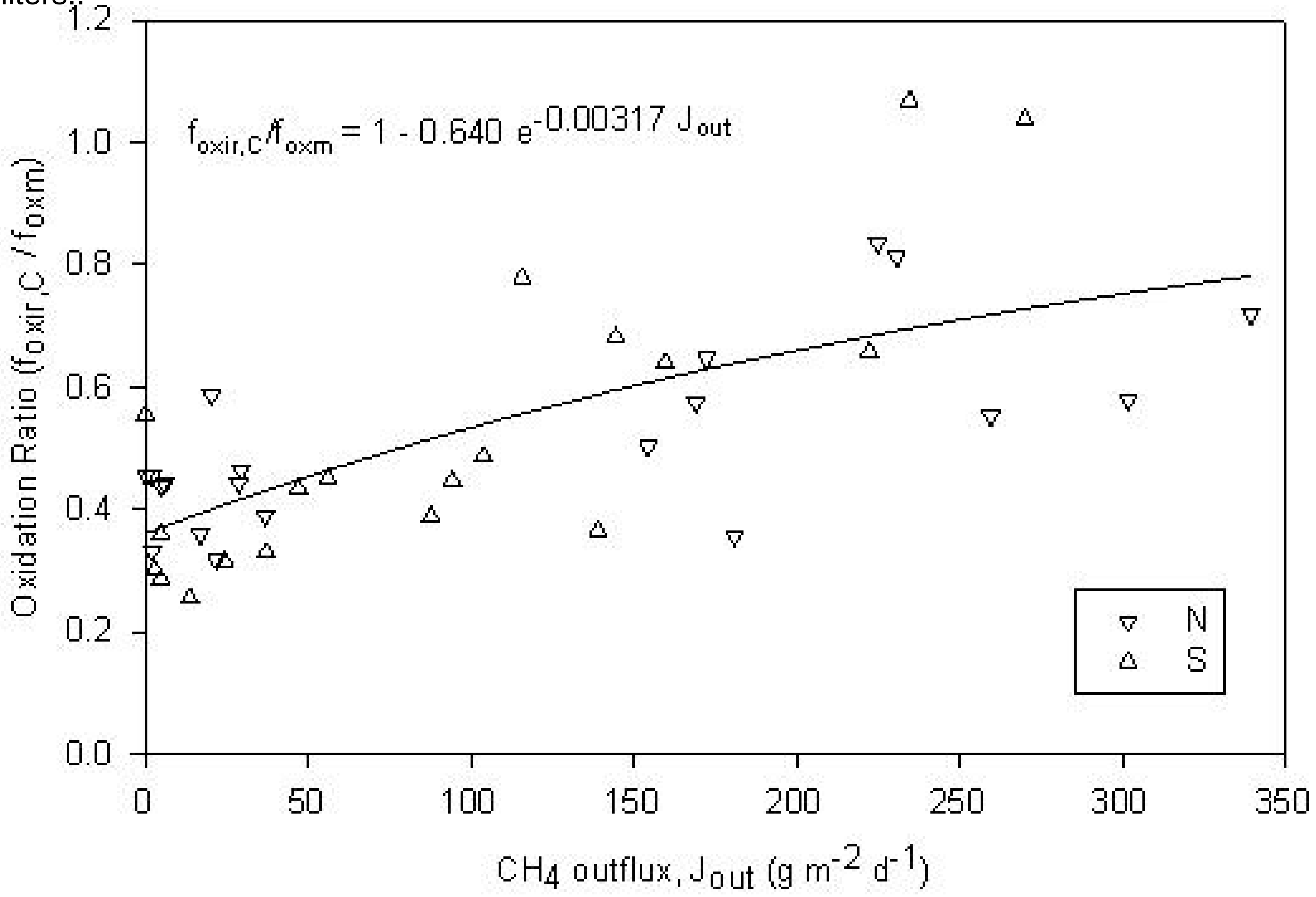
these results are for several data points measured at FL landfill cover



At a single chamber (to avoid spatial variability): Oxidation Controls Flux



The fraction of CH4 oxidized calculated from isotopes (foxir,C) as a proportion of the fraction oxidized calculated from flux measurements (foxm) versus methane outflux (Jout) for the two compost biofilters..



Modeling Landfill Gas Transport Through Landfill Covers:

Moving beyond the water balance

Tarek Abichou, Jeff Chanton, and Lei Yuan

Florida Sate University

Florida USA

Combined Dynamic Model

- Water Flow
- Heat Flow
- Gas Flow
- Oxidation

Model Dynamic Links

INPUT

- Rainfall
- PET
- Temperature
- Vegetation

Dynamical INPUT

- Water content
- Temperature
- B. Pressure
- Gas pressure in landfill

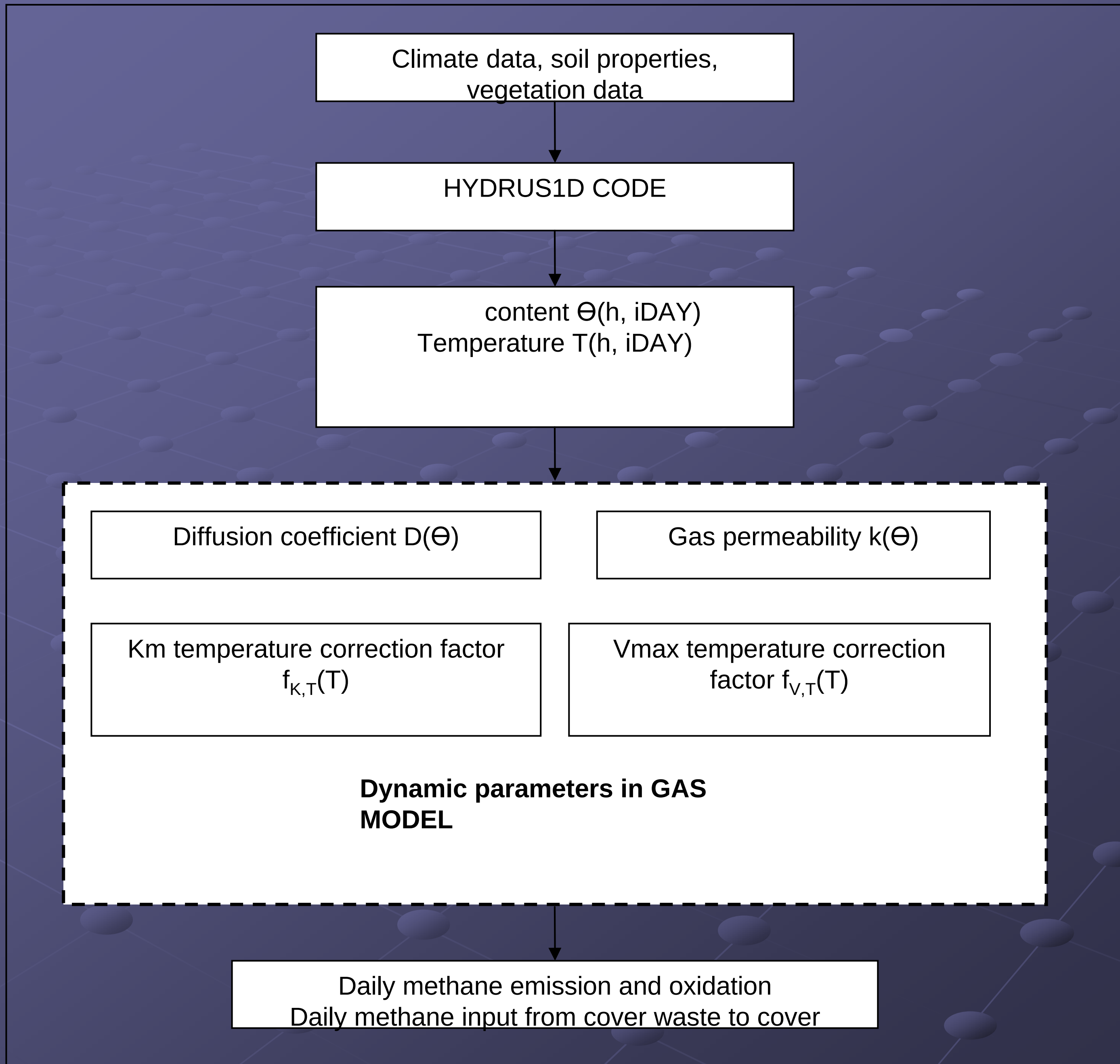
OUTPUT

- Emission
- Inflow
- Oxidation

Unsaturated Water Flow Coupled with Heat Flow Model

Gas Transport & Reaction Model

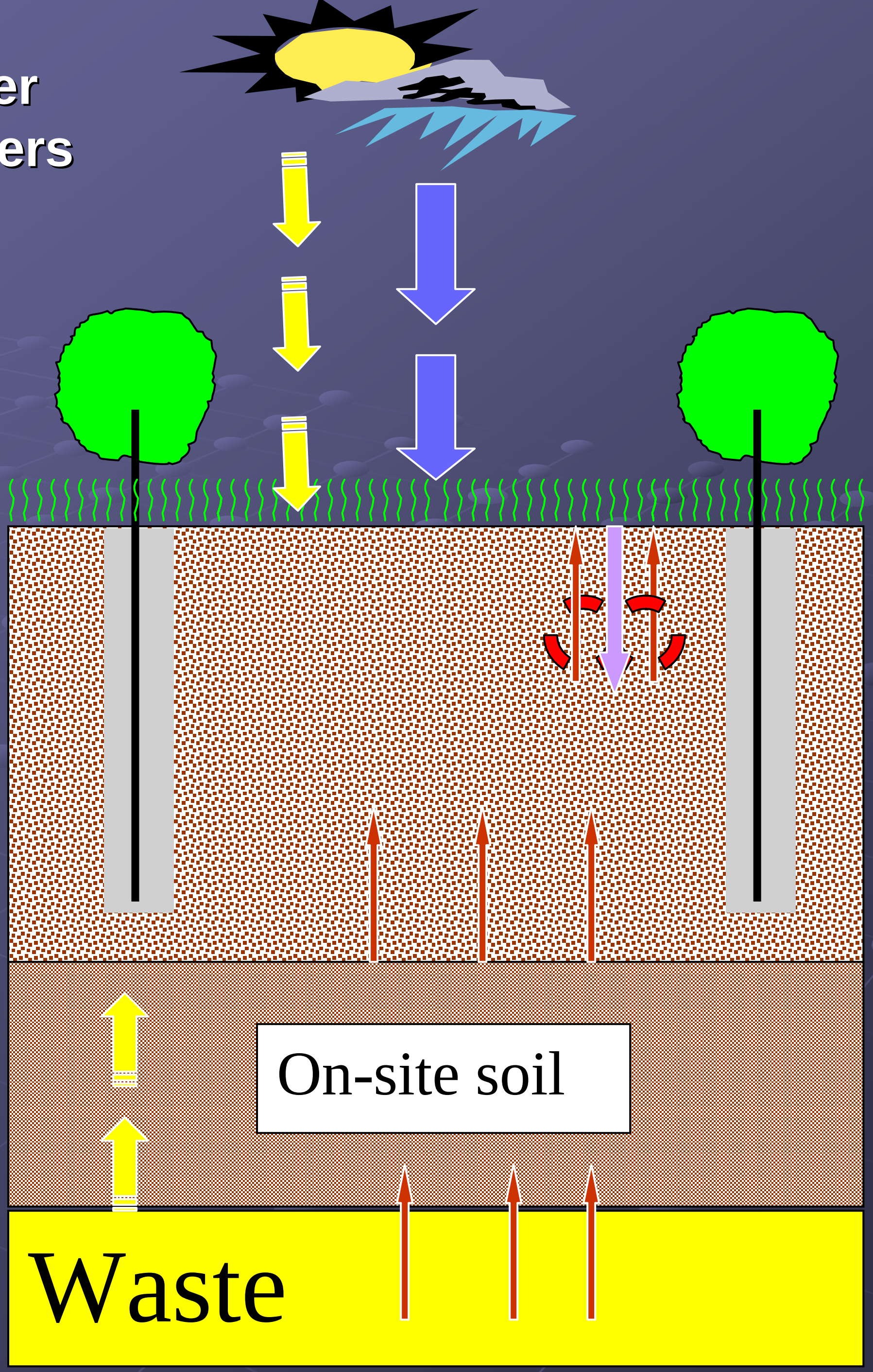
Model Flow Chart



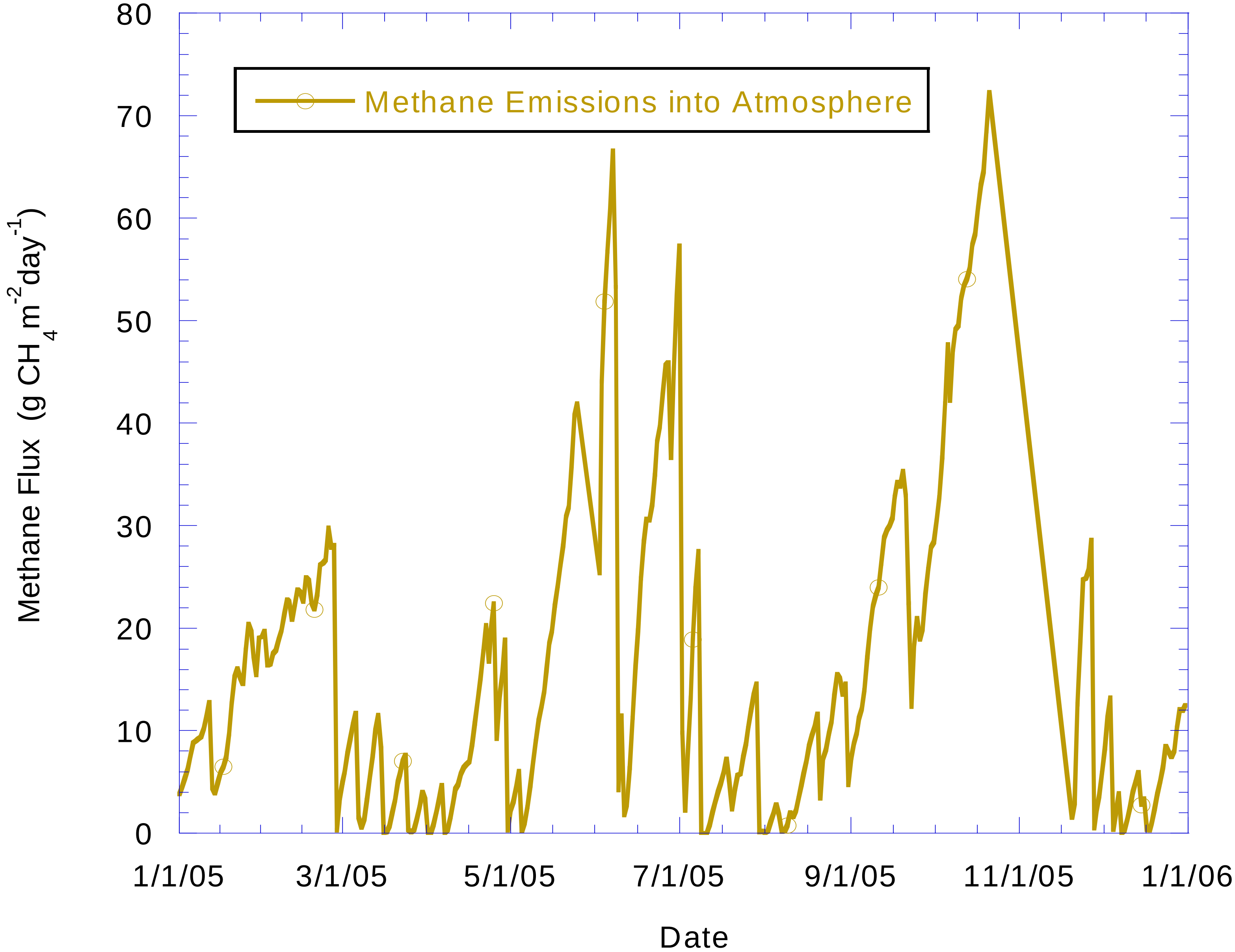
Combining: Gas, Heat, and Water Transport Through Landfill Covers

Processes:

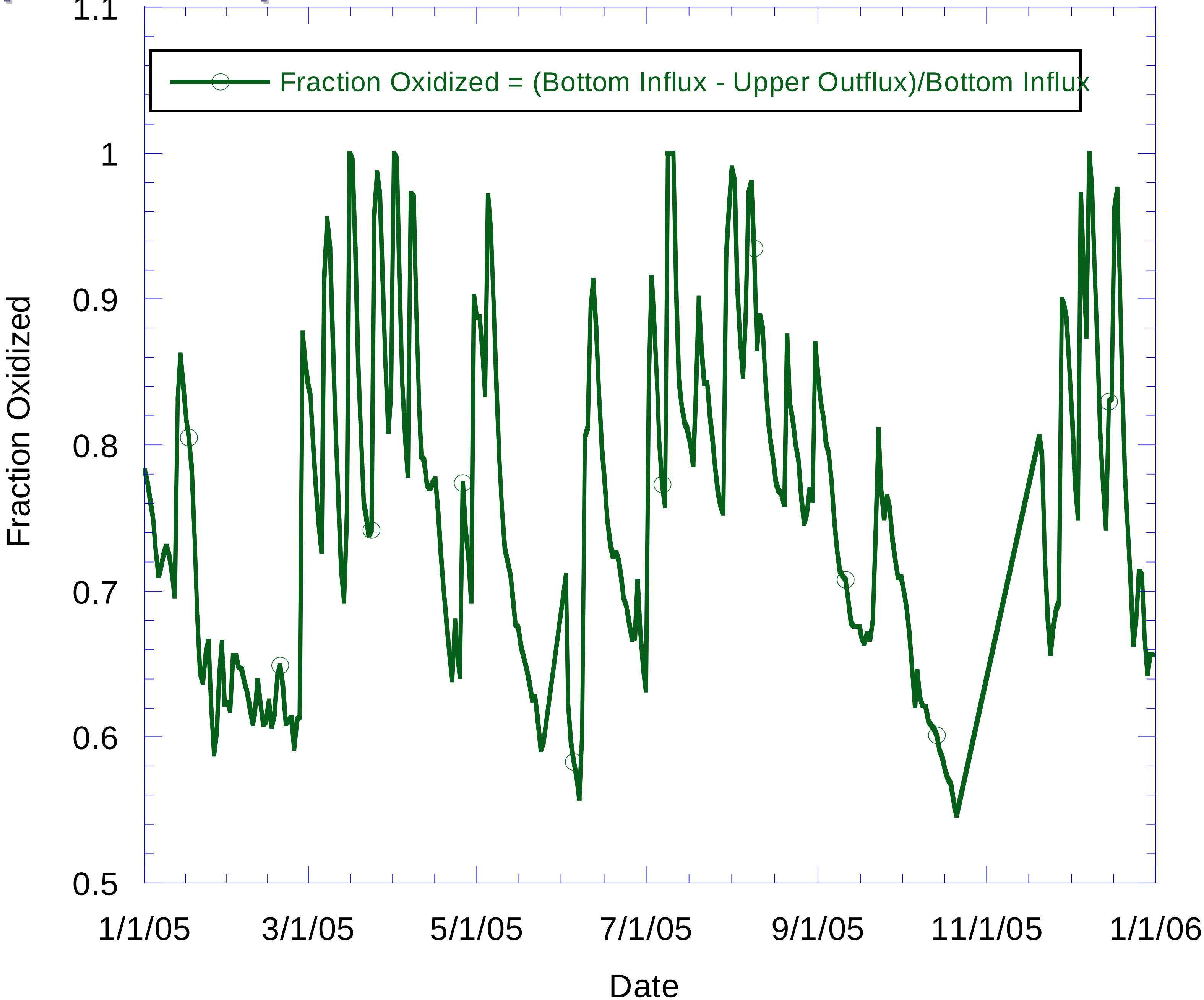
- -Precipitation
- -runoff
- -infiltration
- -Solar Radiation
- -Evaporation
- -Root uptake (Transpiration)
- -Surface temperature
- -Heat from the waste
- -Landfill gas diffusion
- -Landfill gas advection
- -Air diffusion from surface
- -Air advection from surface
- -Methane Oxidation
- -Bacterial growth



Typical Output: Methane Emission at a FL Landfill



Typical Output: Methane Oxidation at FL Landfill



The following slides are a some what detailed description of the model:

I will briefly skim through them

Richards' Equation for Unsaturated Water Flow, with a sink term to account for root up-take:

- Several codes are available to solve this equation for water content at any depth (x) and at any time (t)

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x}\left[K(\theta)(\frac{\partial h(\theta)}{\partial x}) \right] - S$$

$K(\theta)$	Unsaturated hydraulic conductivity function
θ	Volumetric water content
x	Spatial coordinate: depth
t	Time
S	Sink term for root water uptake
$h(\theta)$	Water pressure head (soil suction)

Convection-Dispersion Equation for Heat Flow

Several codes are available to solve this equation for soil temperature at any depth (x) and at any time (t)

$$\frac{\partial C_p(\theta)T}{\partial t} = \frac{\partial}{\partial x}\left[\lambda(\theta)\frac{\partial T}{\partial x}\right] - C_w\frac{\partial qT}{\partial x} - C_w ST$$

$\lambda(\theta)$ Coefficient of apparent thermal conductivity of soil

$C_p(\theta)$ Volumetric heat capacities of soil

C_w Volumetric heat capacities of the liquid phase

Heat and water flow are coupled

Existing LFG flow Transport Models

Previous models have been developed to simulate gas flow and methane oxidation in column studies and field setting

Process based models:
Hilger et al. (1999)
Stein et al. (2001)
De Visscher and Van Cleemput, (2003)
Empirical models
Czepiel et al. (1996)
Park et al. (2004)
Special case model:
Bogner et al. (1997): particle collision model

Limitations:

- Static (constant) in water content and temperature
- Boundary conditions: Specified Flux for bottom boundary.
  - Suitable for columns tests but not for covers in the field
- Do not perform long term simulations for different climates
- Too much focus on biological oxidation (oxidation controls emissions)…. Soil physics plays a very important role in emissions

Principles of Gas Flow

Gas Transport and Reaction Model

Governed by Continuity Equation

$$a \frac{dC_i}{dt} = -\nabla \cdot J_i + R_i$$

- t **Time**
- a **Air filled porosity: depends on water content**
- C **Concentration of gas component i depends on temperature**
- J **Flux**
- R **Reaction rate**

Will look at these next

Flux = Advective Flux+ Diffusive Flux

$$a \frac{dC_i}{dt} = -\nabla \cdot J_i + R_i$$

Advection Flux (Darcy's Law)

$$J_a = -\frac{K}{\mu}\frac{\partial P}{\partial x} C_i$$

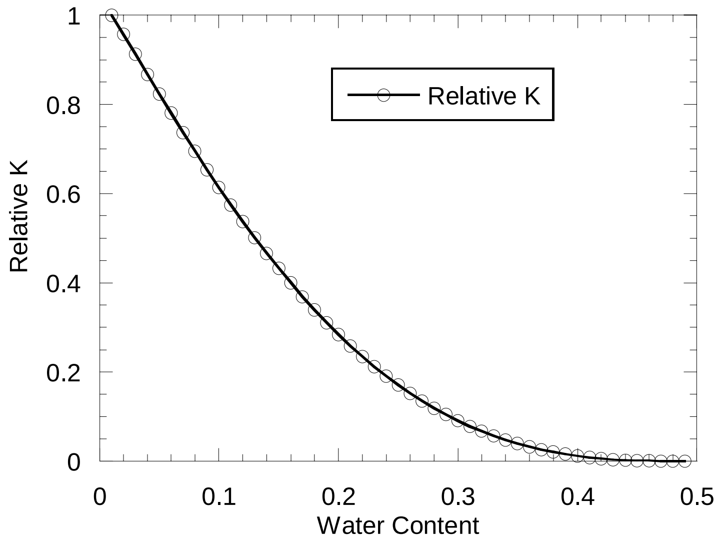
- μ Gas viscosity: depends on gas temperature
- K Intrinsic permeability: depends of water content
- P Pressure

Diffusion Flux (Fick's Law)

$$J_d = -D_i \nabla C_i$$

- D diffusion coefficient: depends on water content

Static ⇒ Dynamic Parameters



Typical gas permeability function

$$k_{relative} = \frac{k(\theta)}{k_0} = (1 - \frac{\theta - \theta_r}{\theta_s - \theta_r})^2 (1 - (\frac{\theta - \theta_r}{\theta_s - \theta_r})^{(2+\lambda)/\lambda})$$

θ_r Residual water content

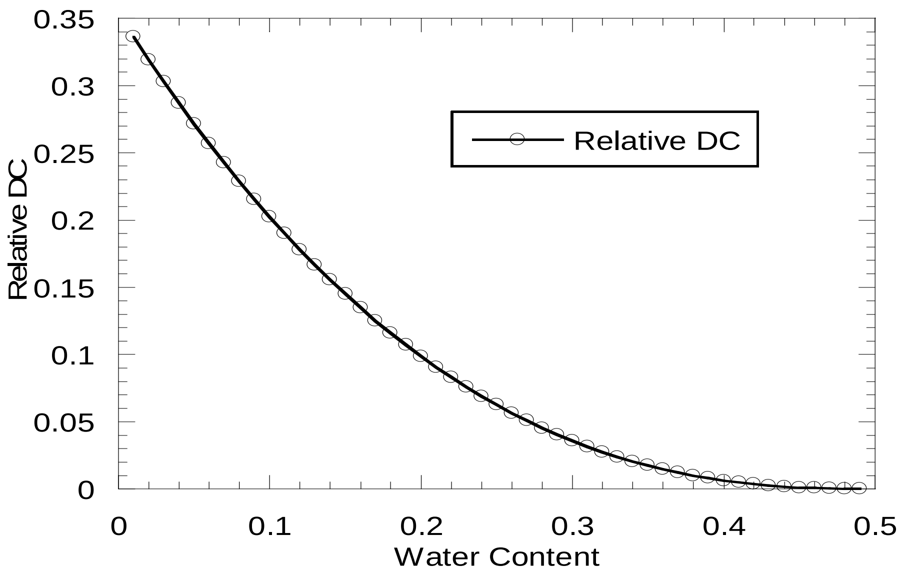
θ_s Saturated water content

λ Based on VG parameters

θ Water content

ϕ Total Porosity

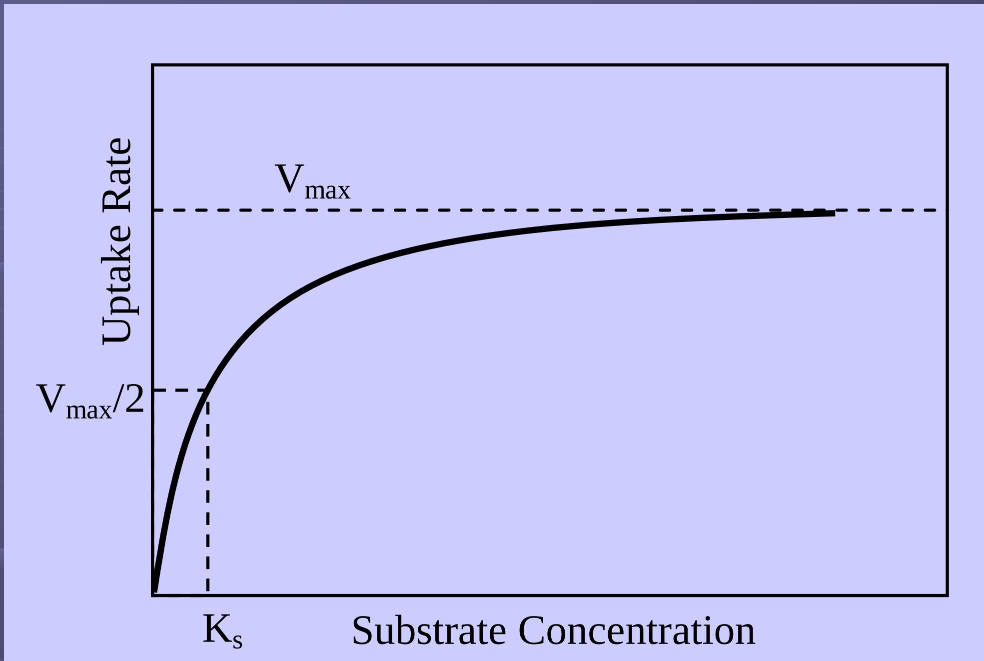
$$D_{relative} = \frac{D_{soil}(\theta)}{D_{air}} = \frac{(\phi - \theta)^{2.5}}{\phi}$$



Gas diffusion coefficient function

Reaction Rate

Modified Monod Model for dual (CH_4 & O_2)substrate



$$a\frac{dC_i}{dt} = -\nabla \cdot J_i + R_i$$

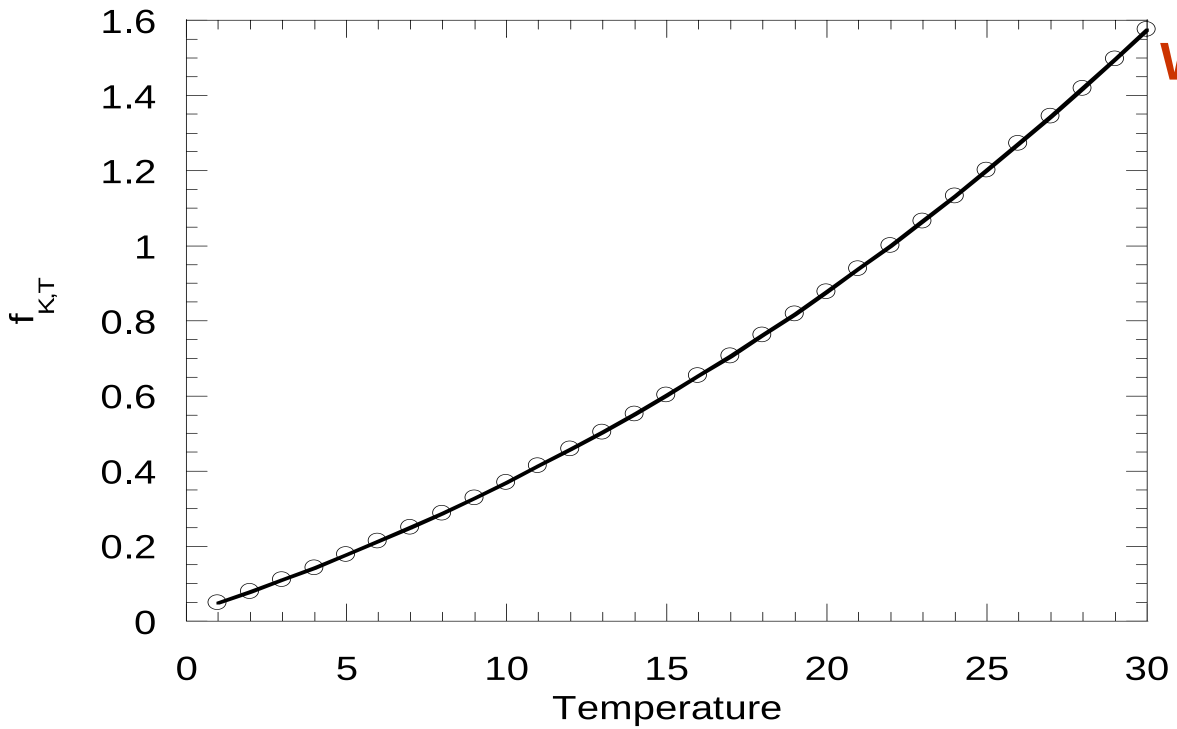
$$R_{CH_4} = V_{\max}\left[\frac{C_{CH_4}}{C_{CH_4} + K_{CH_4}}\right] \cdot \left[\frac{C_{O_2}}{C_{O_2} + K_{O_2}}\right]$$

K_{O_2} K_{CH_4} Half saturation constants of O_2 and CH_4: depend on temperature

$V_{\max}$ Oxidation capacity of CH_4: depends on temperature and bacterial population, i.e. Depth

Static ➡ Dynamic Parameters

$$f_{K,T} = \frac{0.00678 + 0.009814T}{\exp(1700(\frac{1}{T+273.15} - \frac{1}{298.15}))}$$



We are developing our own correction function:
Using Spring Hill Soil
Measuring K_{CH4}
@
different temperatures

Static ⇨ Dynamic Parameters

Vmax Growth Model: to reflect bacterial population

$$u = \frac{u'_{\max}\left(1 - \frac{V_{\max}}{V_{\max,\max}}\right) C_{CH_4}}{K_{m[CH_4]} + C_{CH_4}} \frac{C_{O_2}}{K_{m[O_2]}} - d$$

$$\frac{dV_{\max}}{dt} = uV_{\max}$$

μ Specific growth rate (growth rate at any depth at any time)

$\mu'_{\max}$ Maximum gross specific growth rate (lab measured)

$V_{\max,\max}$ Maximum value of Vmax that can be reached (lab measured)

d Specific biomass decay rate

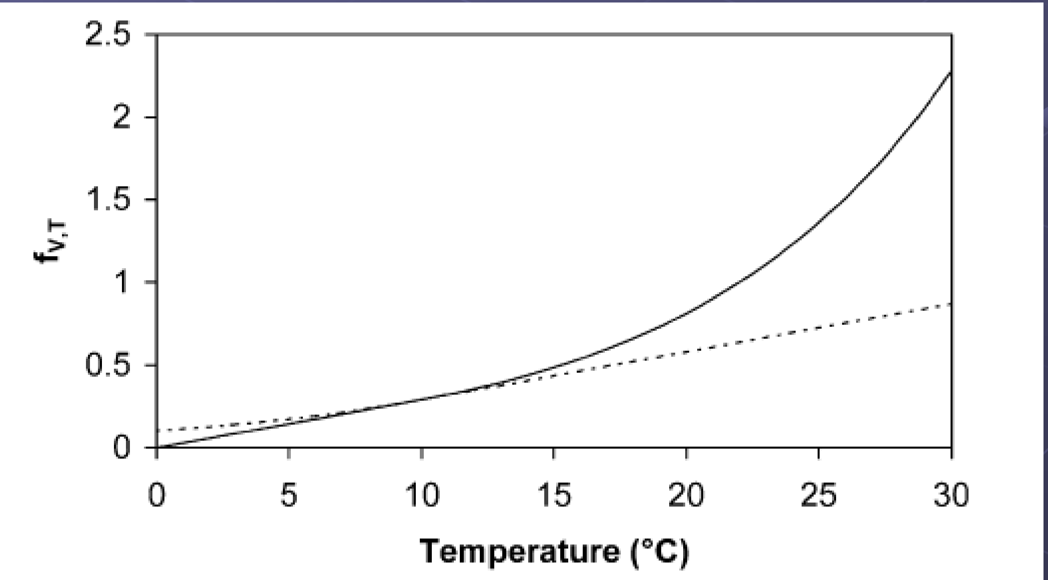
De Visscher and Van Cleemput 2003

Static ⇨ Dynamic Parameters

Temperature correction factor for reaction (applied to oxidation rate and growth rate)

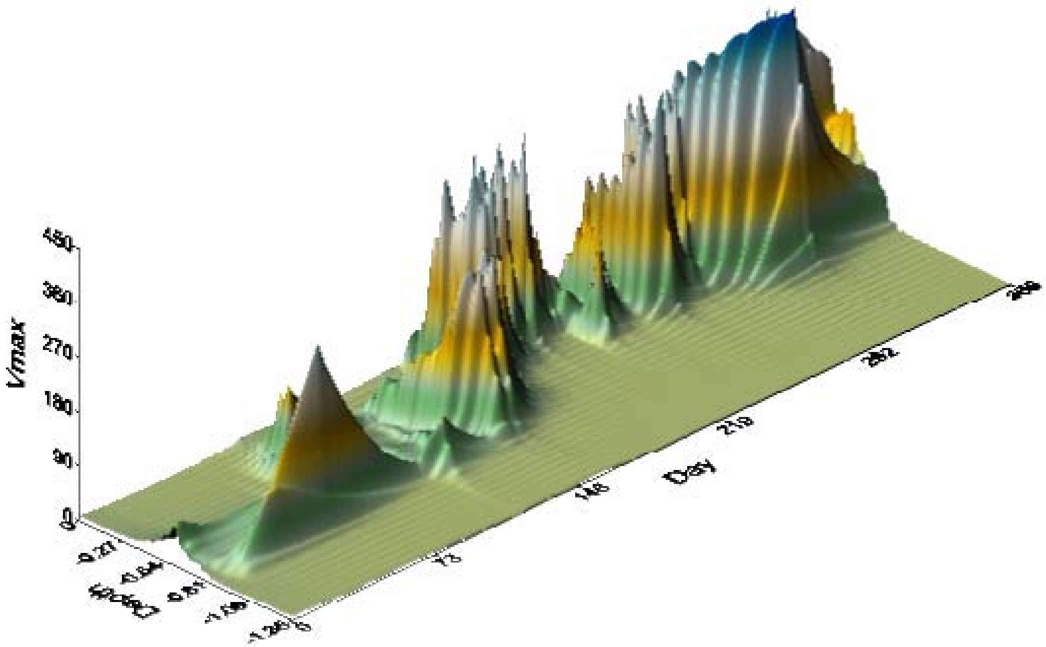
$$f_{V,T} = 2.8^{\frac{T-22}{10}}$$ T>10/ln2.8

$$f_{V,T} = \frac{\ln 2.8}{10} 2.8^{\frac{1}{\ln 2.8} - 2.2} \times T$$ T<10/ln2.8



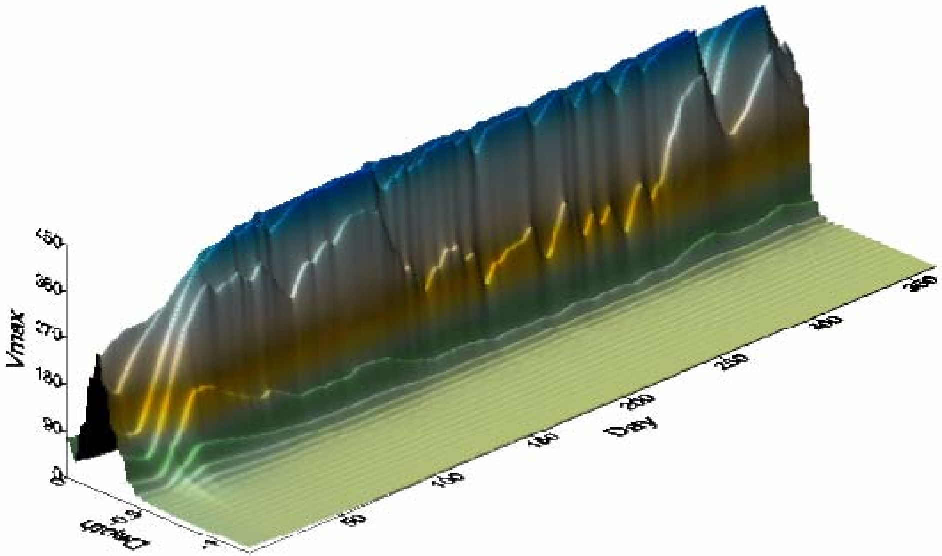
De Visscher and Van Cleemput 2003

Static ➪ Dynamic Parameters

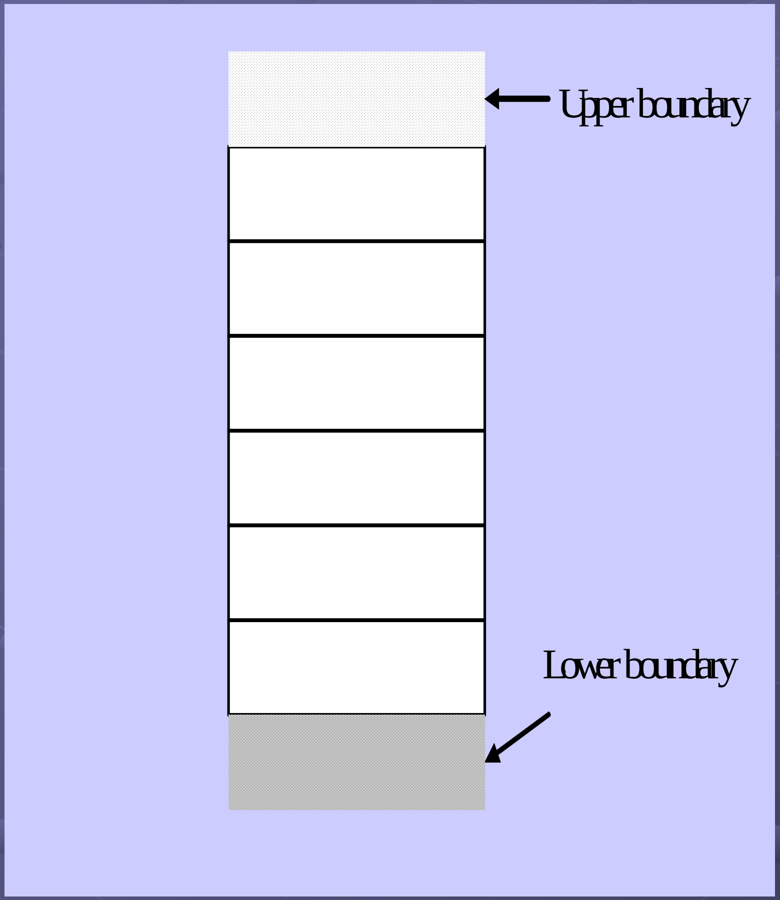


Vmax variation with climate and depth
Florida (Hot and Wet) simulations

Vmax variation with climate and depth
Southern CA (Hot and dry) simulations



Boundary Conditions



Option 1:

Upper boundary:

Atmospheric Concentration

Lower boundary:

Influx & Concentration

Option 2:

Upper boundary:

Atmospheric Concentration & Pressure

Lower boundary:

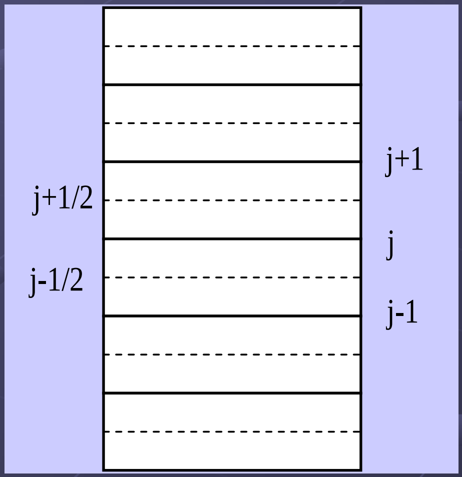
Pressure & Concentration

Finite Difference Scheme

Discretizing the Continuity Equation

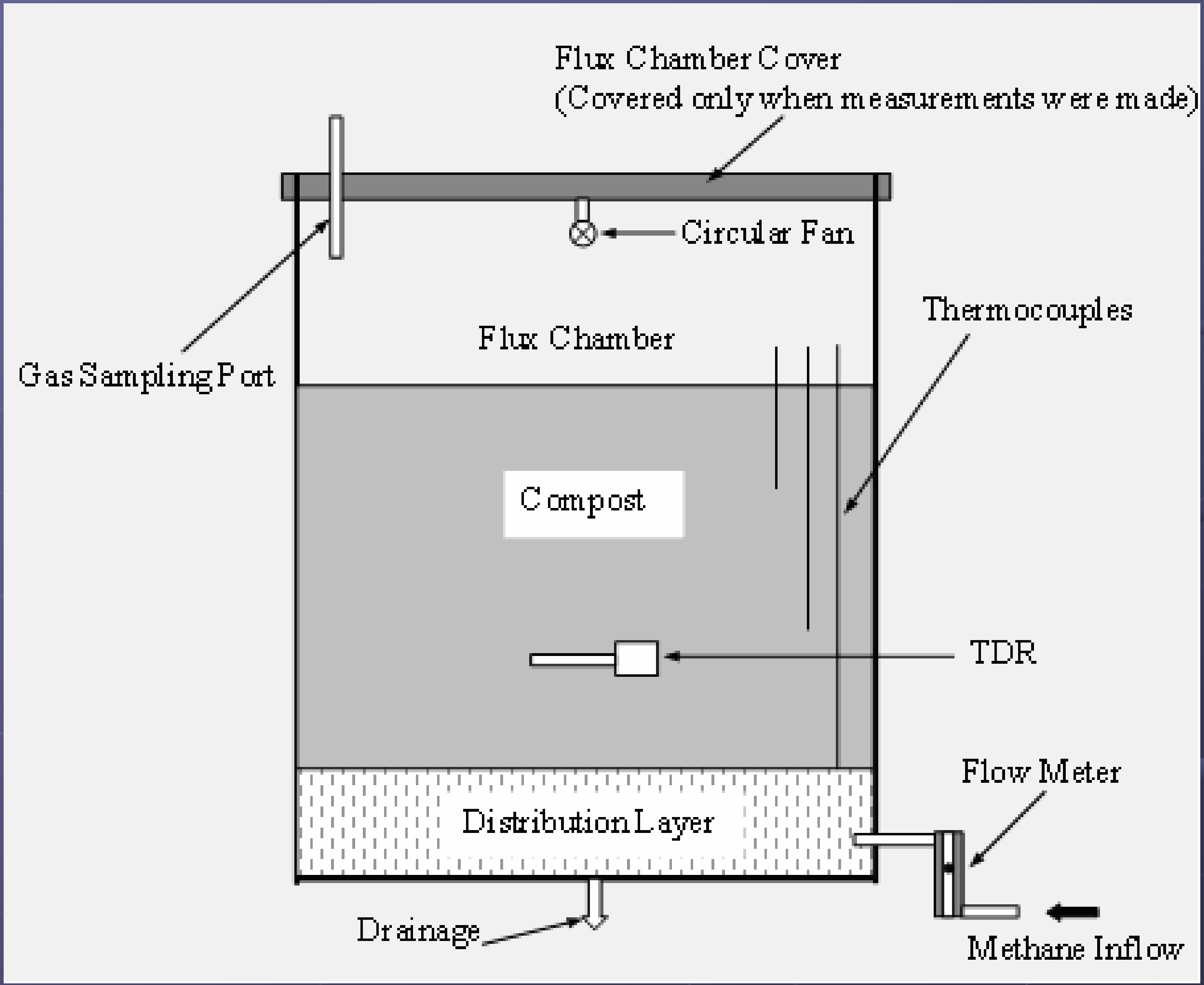
Central difference approximation

$$\frac{C_j^{k+1} - C_j^k}{\Delta t} = \frac{J_{j-1/2} - J_{j+1/2}}{\Delta x \cdot a_j} + \frac{R}{a_j}$$

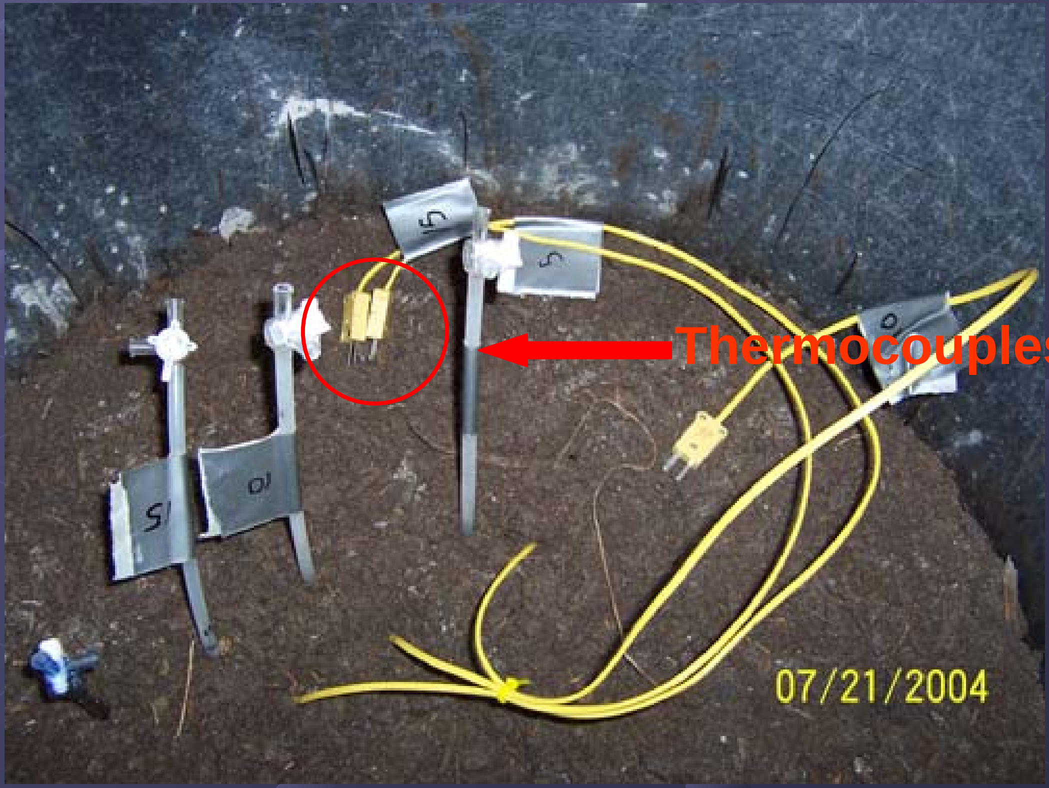


$$J_{i,j-1/2}^k = -\left[D_{i,j-1/2} \frac{(C_{i,j}^k - C_{i,j-1}^k)}{\Delta x} \right] - \left[\frac{k_{j-1/2}}{\mu_{j-1/2}} \frac{(P_j^k - P_{j-1}^k)}{\Delta x} \frac{(C_{i,j}^k + C_{i,j-1}^k)}{2} \right]$$

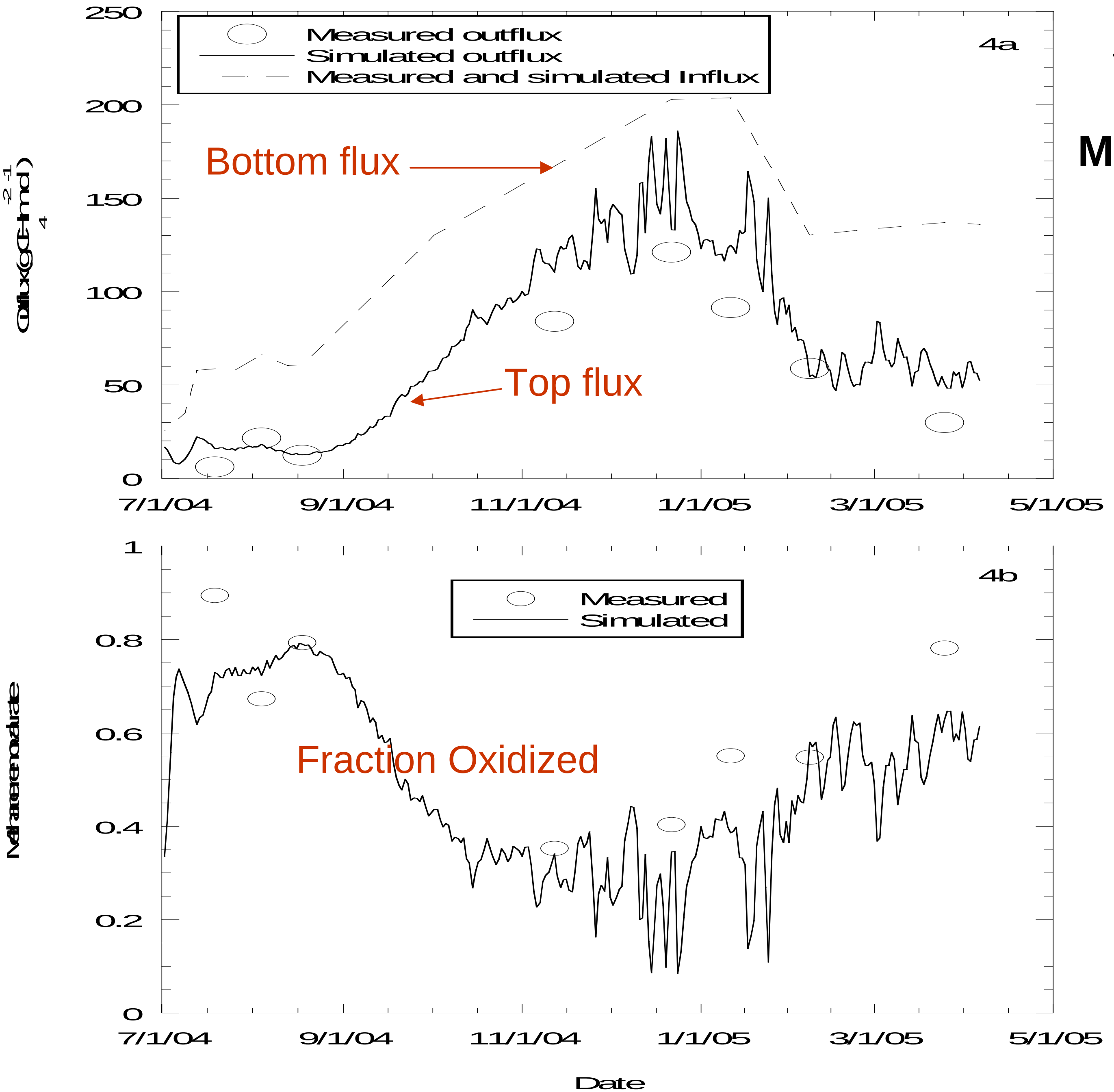
Calibration of model: Lab Biofilter/Column



Biofilter Setting

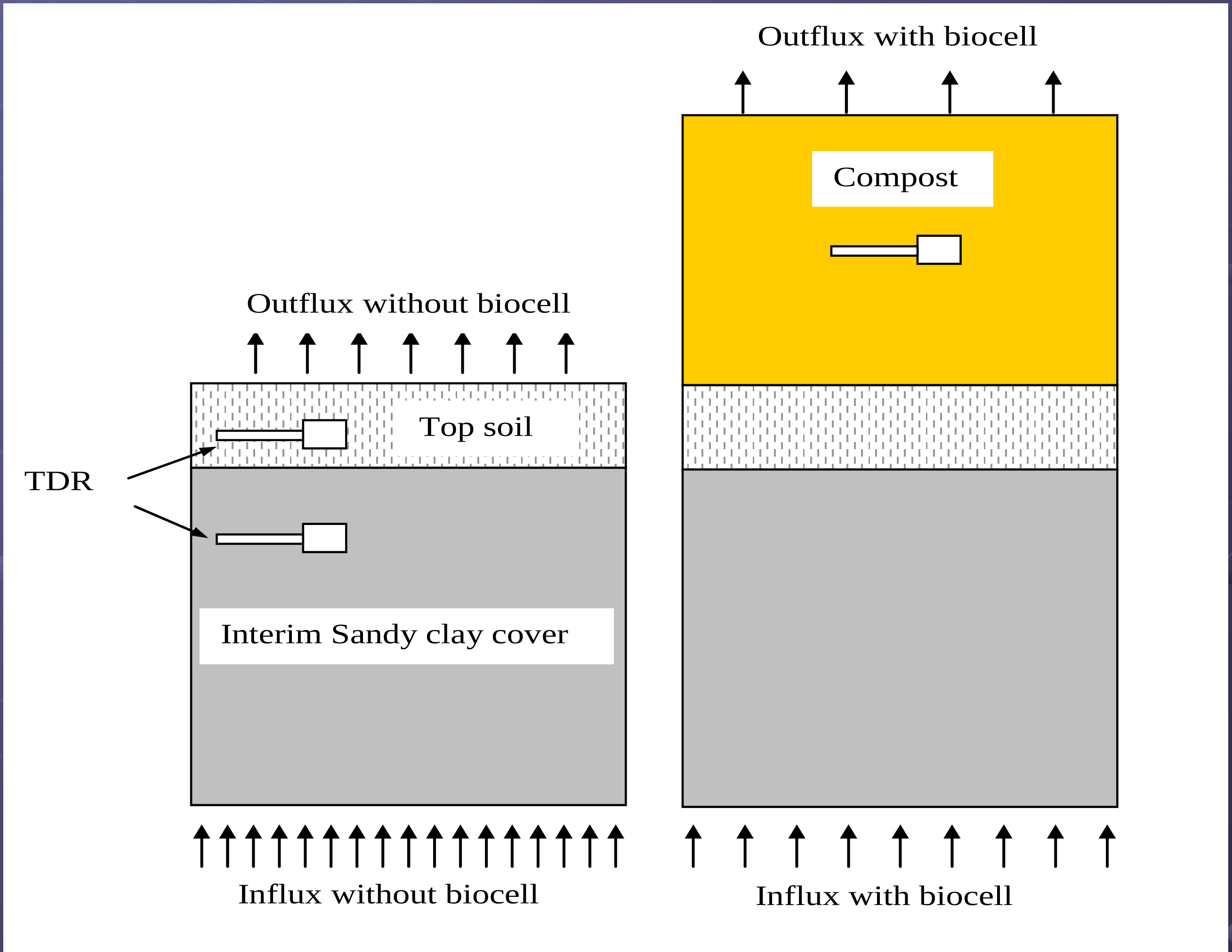


Biofilter Simulations vs. Measurement

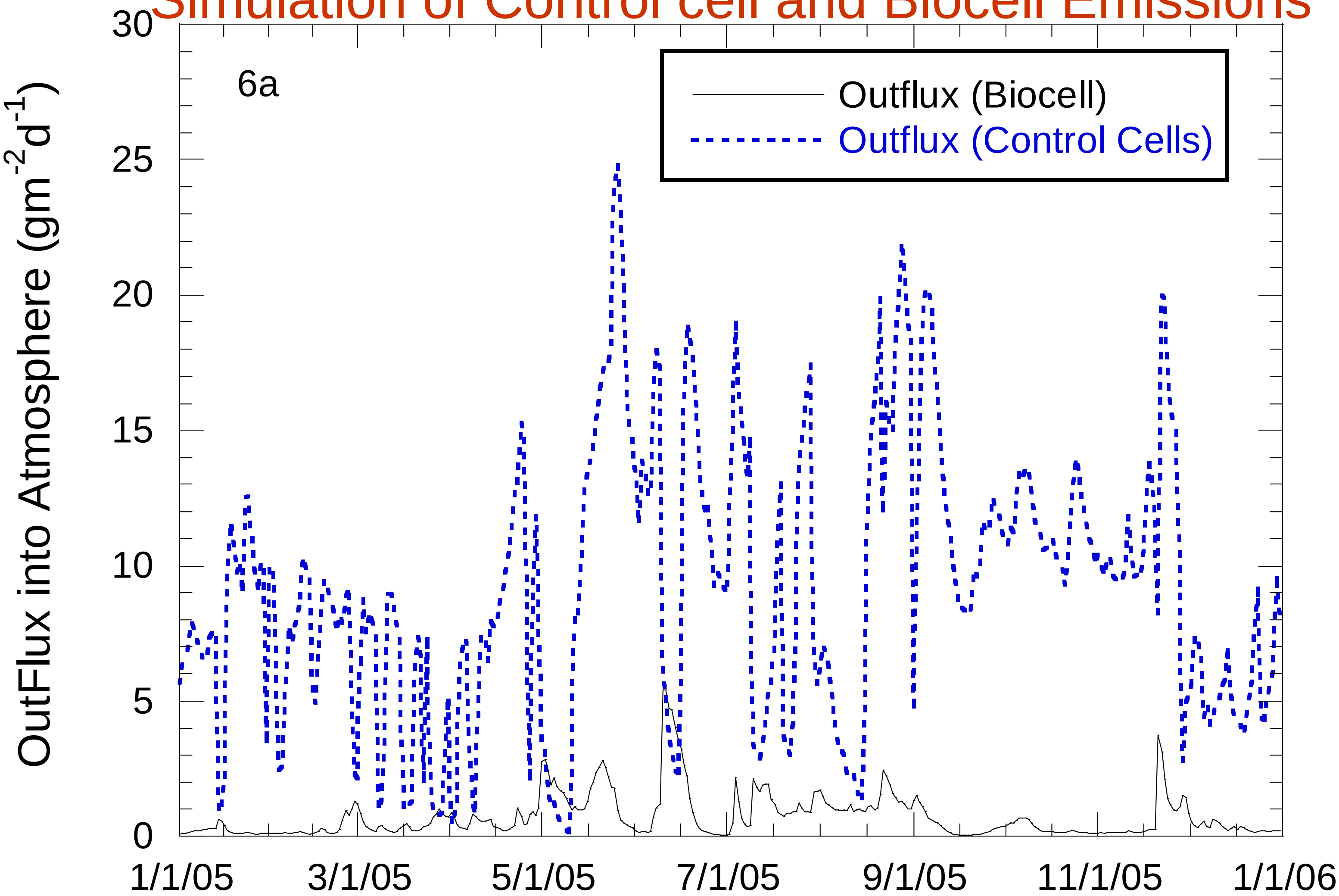


Calibration of model: Field Study

Modified the model developed for the biofilter to use field measured water content, temperature, in the cover, pressure in the waste, and barometric pressure

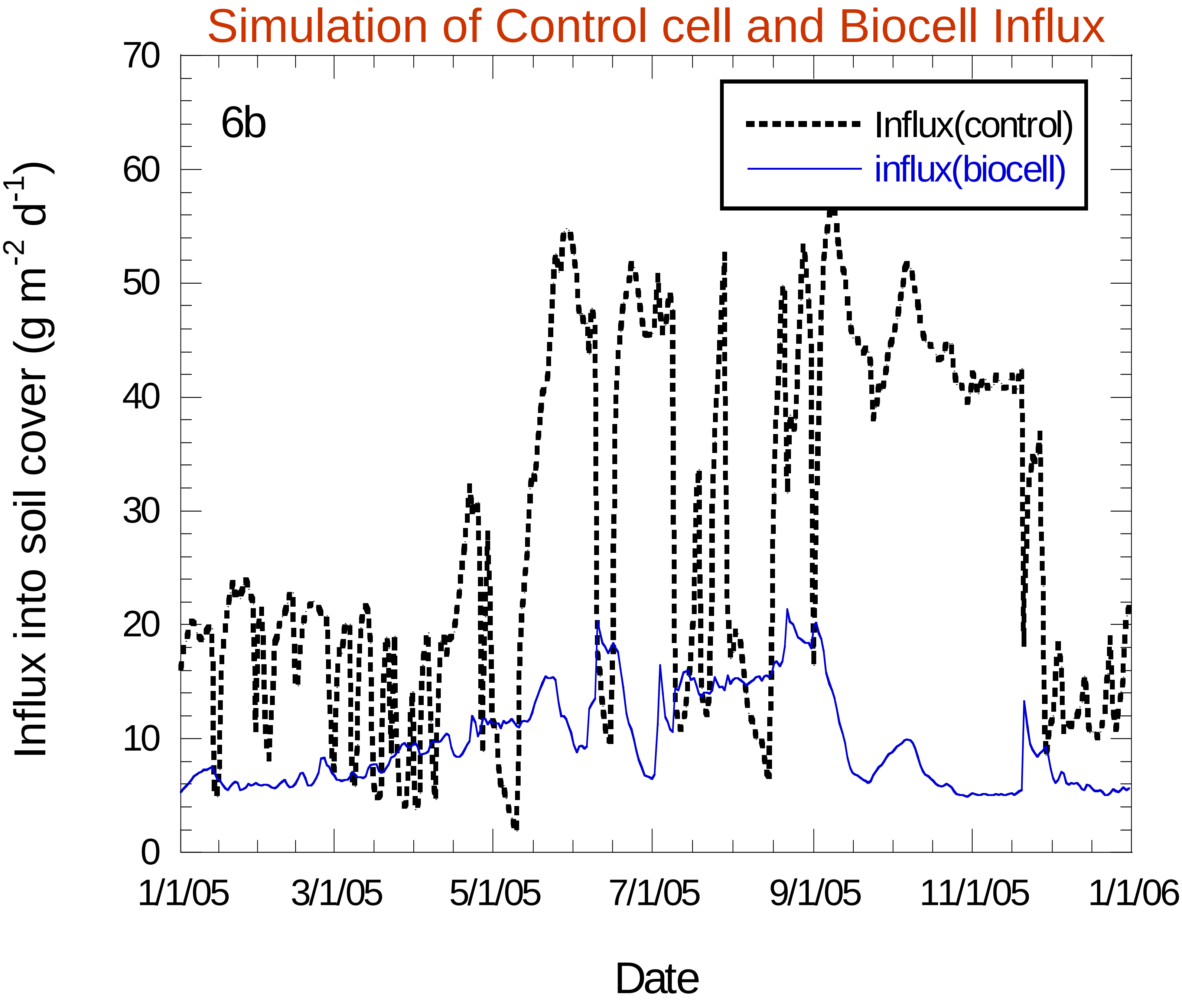


Simulation of Control cell and Biocell Emissions



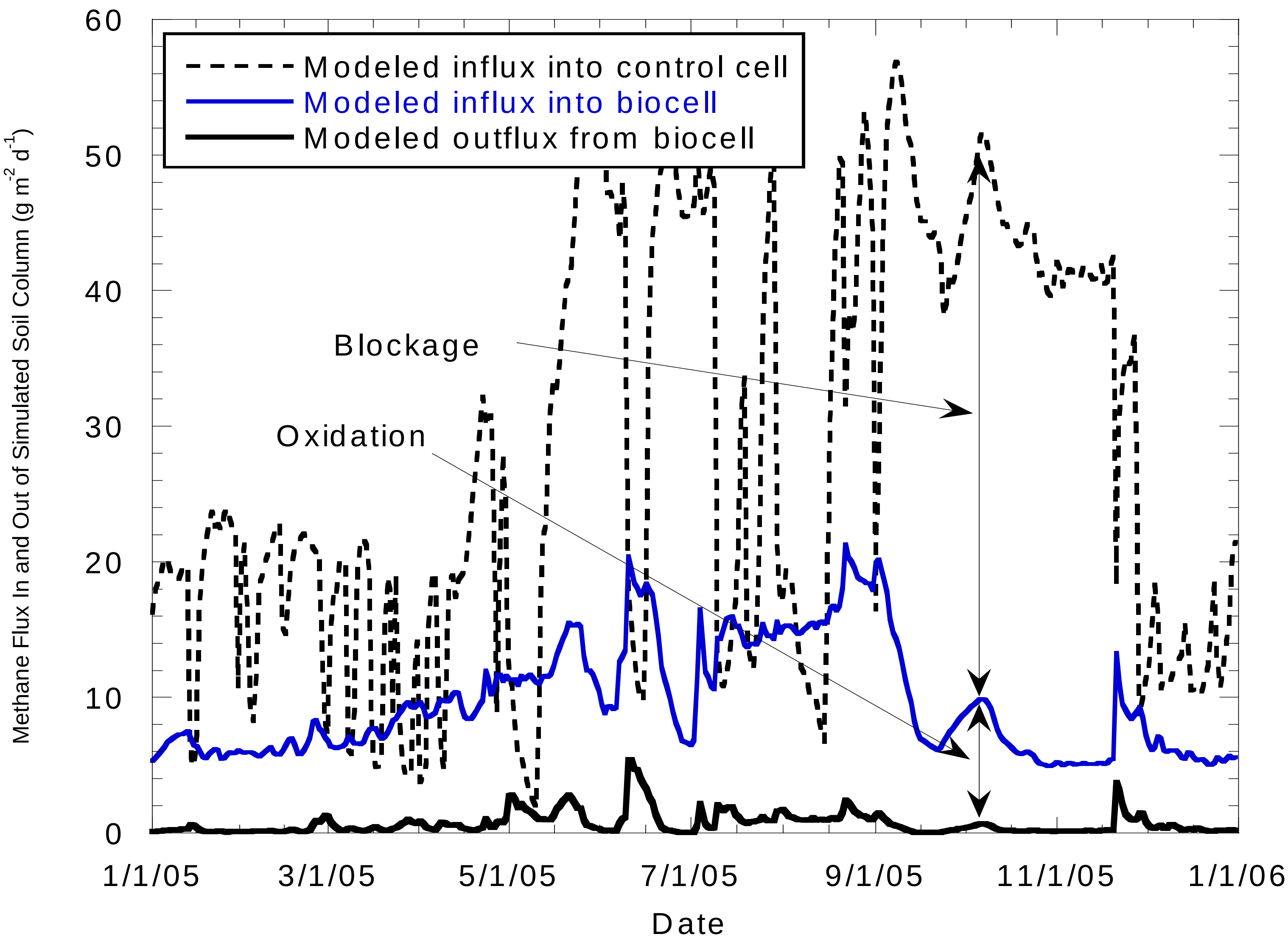
Yearly Average Biocell: 0.72 (0.32-4.8) g m^{-2} d^{-1}

Yearly Average Control 9.18 (7.4-10.96) g m^{-2} d^{-1}



Simulation of Control cell and Biocell Influx
6b
Influx(control)
influx(biocell)
Influx into soil cover (g m-2 d-1)
0
10
20
30
40
50
60
70
1/1/05
3/1/05
5/1/05
7/1/05
9/1/05
11/1/05
1/1/06
Date

Separation of Blockage and Oxidation



Applying Model to ET Covers:
Beyond the water balance

- Two Climates (Two ACAP Sites)
  - Semiarid-Cold (MT)
  - Semiarid-Warm (CA)
- Different Pressure Bottom Boundaries
  - High Pressure (1.1 atm)
  - Medium Pressure (1.04 atm)
  - Zero Pressure
  - Vacuum Pressure (-10 inches of water)
- Different Soil Oxidation Capacities
  - High Soil Oxidation Capacity (Vmaxmax=2000 nmol/kg s): Compost rich soil
  - Low Soil Oxidation Capacity (Vmaxmax=500 nmol/kg s): Typical soil

Step 1: Modeled the water balance

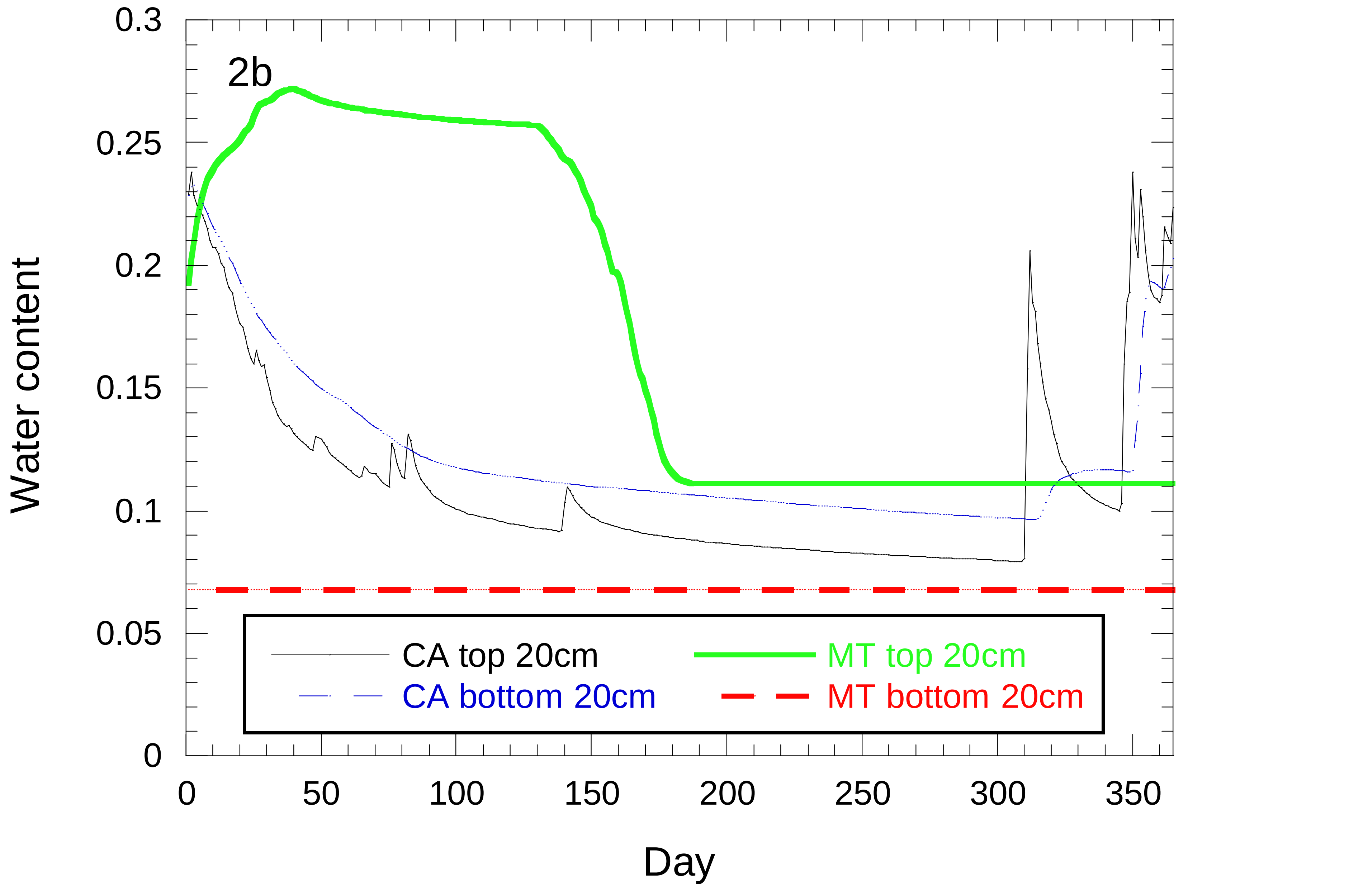
- Assumed that the equivalence criteria is: percolation around 5% of precipitation
- Used HYDRUS code to model 10 years of average yearly climatic conditions using measured soil properties at two ACAP sites

Site	Layer (top to bottom)	Thickness (cm)	α (1/cm)	n	θr	θs	Ks (cm/s)
CA	Surface layer	60	0.028	1.31	0	0.3	2.9×10^{-4}
	Storage layer	45	0.028	1.31	0	0.3	2.9×10^{-4}
	Interim layer	15	0.028	1.31	0	0.3	2.9×10^{-4}
MT	Surface layer	15	0.0676	1.42	0	0.37	3.4×10^{-4}
	Sandy silt	45	0.0195	1.28	0	0.30	4.0×10^{-4}
	Silty sand	60	0.0711	1.45	0	0.36	7.9×10^{-4}

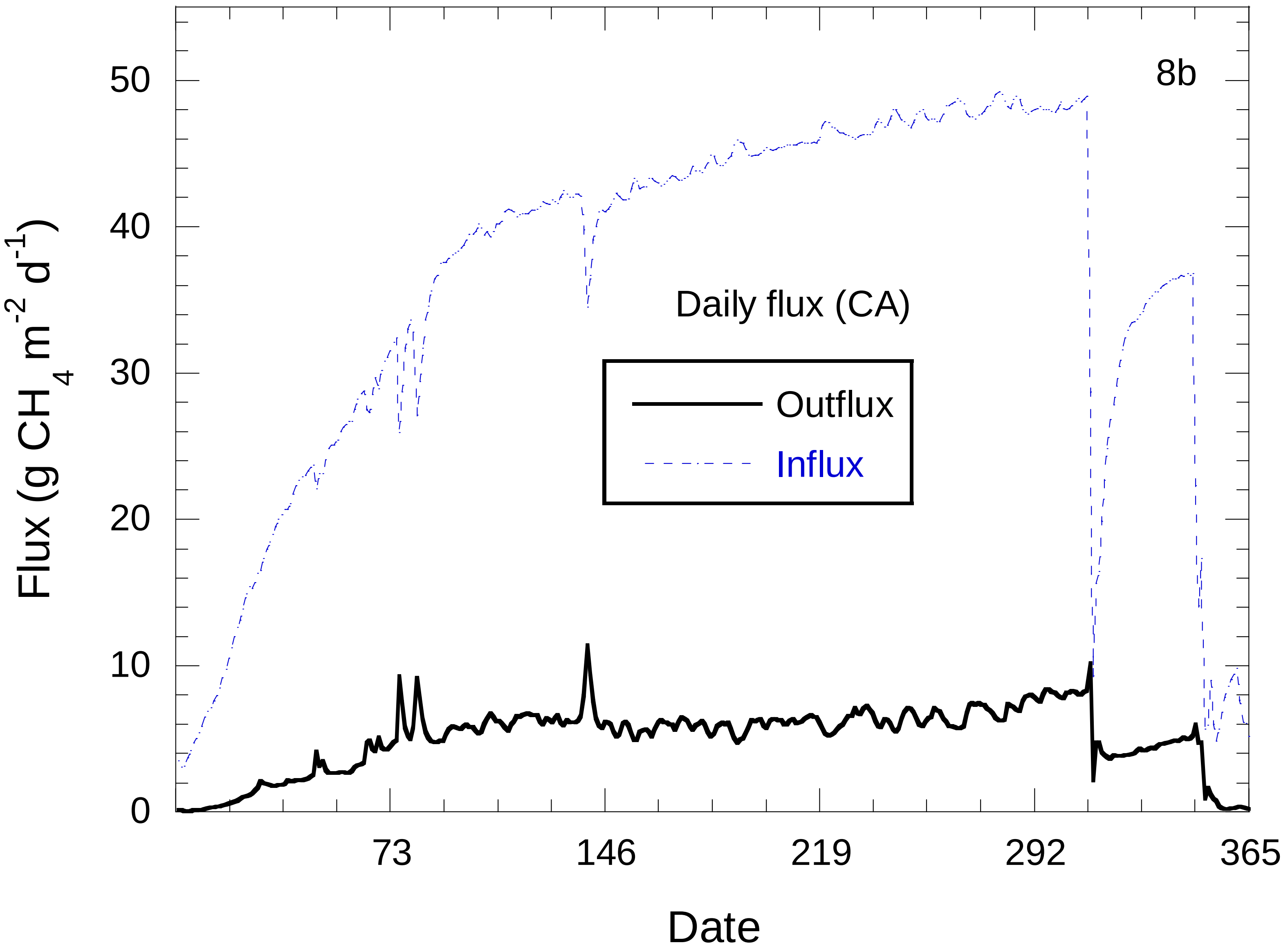
Water balance (10 years)

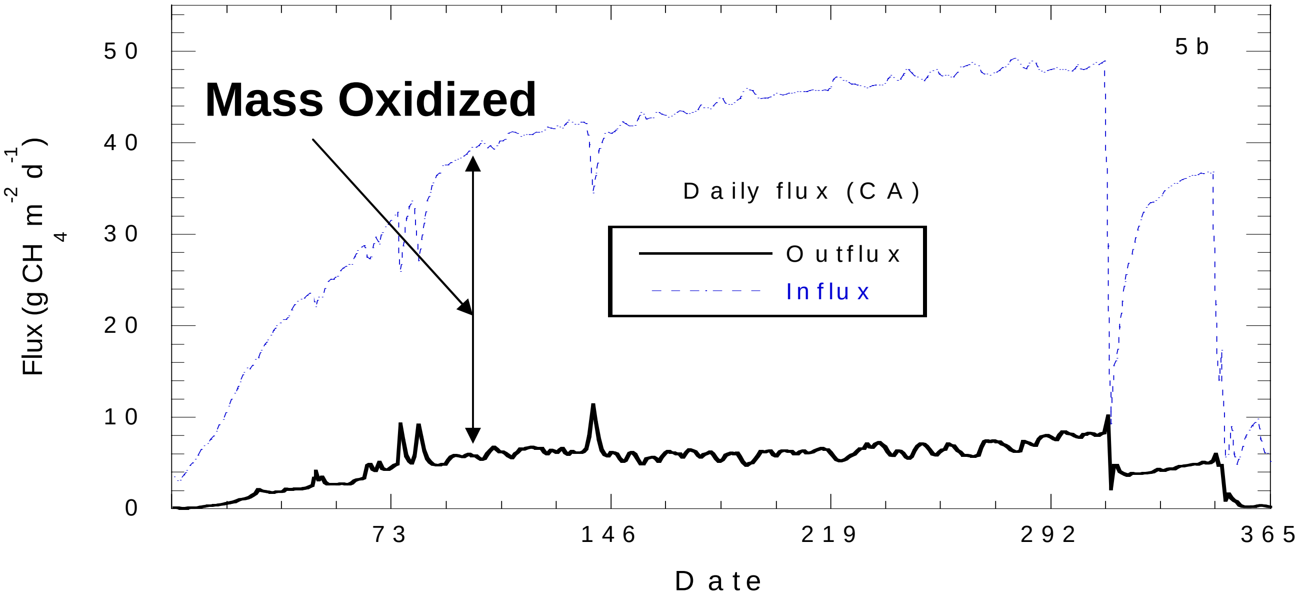
Water balance (cm)	**CA**	**MT**
Precipitation	503	357.9
Runoff	0	0
Evaporation	255.9	211.6
Transpiration	217.9	140.5
Percolation	29.1	15.6
Percolation (% precip)	5.78%	4.36%

Obtained Water content and temperature at every depth during for Year 10

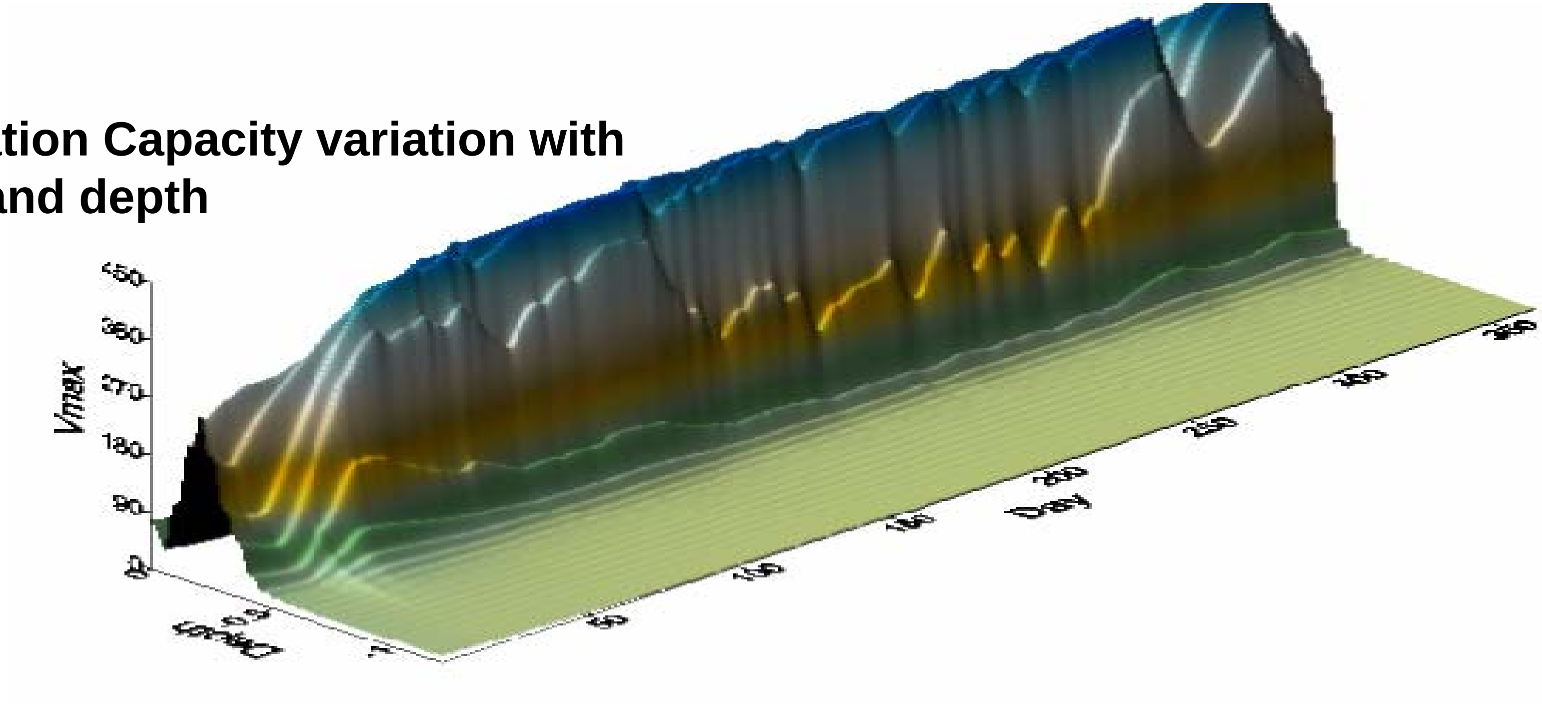


Obtained daily methane flux from the waste into the cover (Influx) and daily surface emissions (Outflux) during Year 10.





Oxidation Capacity variation with time and depth



Summary of Yearly emissions and oxidation

g/m^2/Year

	Pressure		CA	MT
High Vmaxmax (compost rich soil)	**High**	**Influx**	42795.6	62726.3
		outflux	13724	30339
		mass removed	29071.6	32387.3
		oxidation	**67.93%**	**51.63%**
	Medium	**Influx**	21208.6	32744.4
		outflux	3014.5	10657
		mass removed	18194.1	22087.4
		oxidation	**85.79%**	**67.45%**
	Zero	**Influx**	15254.6	20954
		outflux	1056.8	4943.4
		mass removed	14197.8	16010.6
		oxidation	**93.07%**	**76.41%**
	Vacuum	**Influx**	10307.3	16412.2
		outflux	466	2877.1
		mass removed	9841.3	13535.1
		oxidation	**95.48%**	**82.47%**

Summary of Yearly emissions and oxidation

g/m²/Year

	Pressure		CA	MT
Low Vmaxmax (typical soil)	**High**	**Influx**	42359	63566.5
		outflux	24152.6	44904.1
		mass removed	18206.4	18662.4
		oxidation	**42.98%**	**29.36%**
	Medium	**Influx**	21049	32277.8
		outflux	6534.6	16274.6
		mass removed	14514.4	16003.2
		oxidation	**68.96%**	**49.58%**
	Zero	**Influx**	15199.2	20759.5
		outflux	2030.8	7195
		mass removed	13168.4	13564.5
		oxidation	**86.64%**	**65.34%**
	Vacuum	**Influx**	10286	16300.4
		outflux	785.5	4039
		mass removed	9500.5	12261.4
		oxidation	**92.36%**	**75.22%**

CONCLUSIONS (model)

- Methane oxidation occurs in landfill cover
- Covers can be designed better to take advantage of oxidation
- Preliminary simulations show that our model captures how variations in climatic condition affect methane emissions from landfill surfaces.
- The model is being calibrated using data collected from the landfills in FL, IA, CO, and CA
- Model can be an effective tool to compare emissions and oxidation of methane through different landfill cover designs
- Model can be used to predict gas through landfill covers similar to water balance

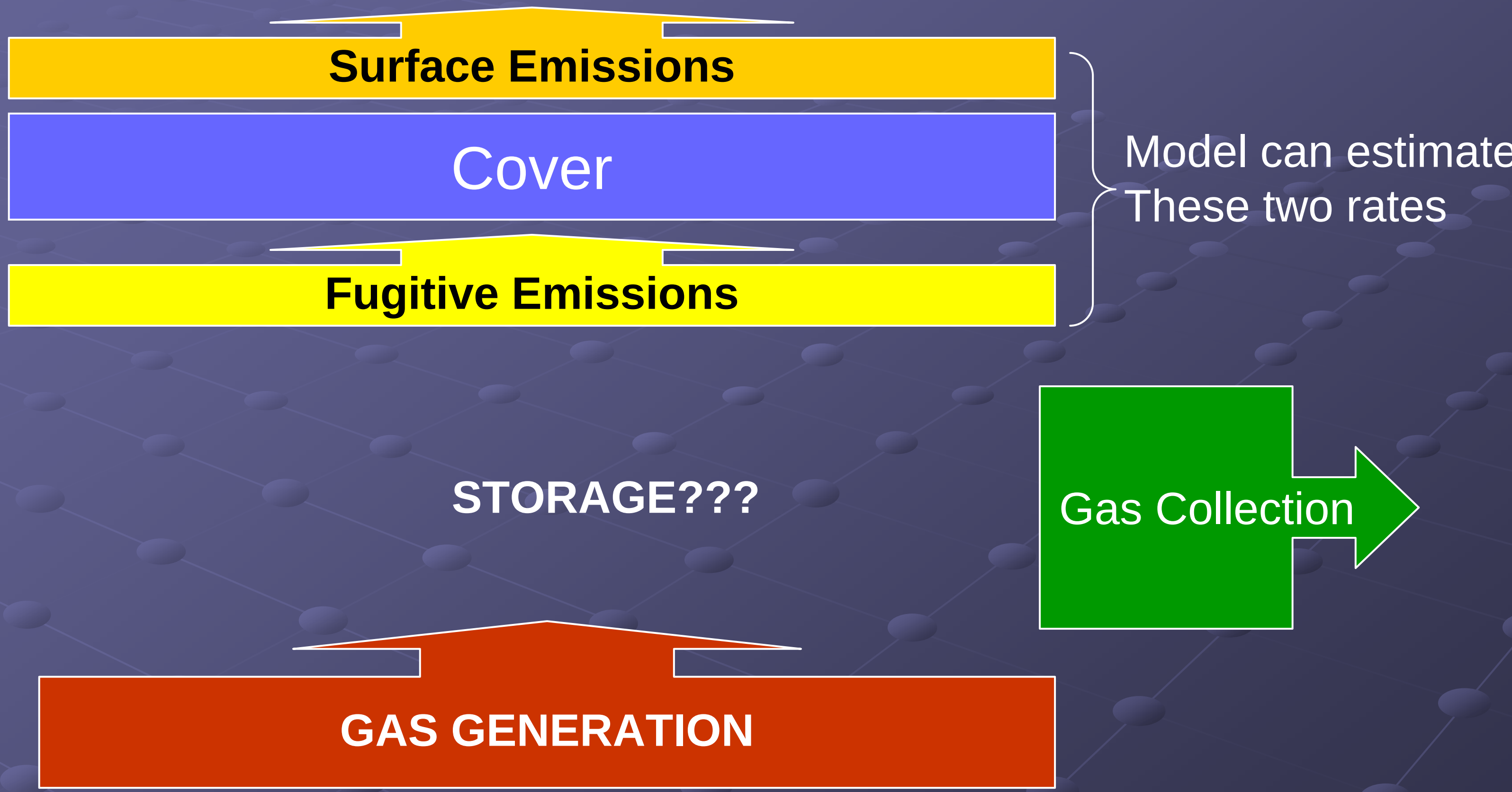
Limitations

- Model running time (maximum 80hr for 1 year simulation)
- Need field measurement bottom pressures to get better estimation of methane emission
- Soil oxidation capacity dependence on water content, nutrient content, organic content, etc…We are working on correlating this property to geotechnical properties

Other applications of the model:

Another Application of Model:

- Given climate and cover data, estimate daily emissions throughout post closure life of landfill
- Combine with collection data and better estimate Generation



GENERATION = Collection + Fugitive Emission + Storage??

OXIDATION BY COVER = Fugitive Emissions – Surface Emissions

One more of Model:

- Improve controlled mass emissions equation, USEPA Equation (5) AP-42, SECTION 2.4
- Introduce Emission Reduction Factors **(ERF)** into the first term of the following equation

Controlled CH_4, NMOC, and speciated emissions can be calculated with equation 5. It is assumed that the landfill gas collection and control system operates 100 percent of the time. Minor durations of system downtime associated with routine maintenance and repair (i.e., 5 to 7 percent) will not appreciably effect emission estimates. The first term in equation 5 accounts for emissions from uncollected landfill gas, while the second term accounts for emissions of the pollutant that were collected but not combusted in the control or utilization device:

$$CM_P = \left[UM_P * \left(1 - \frac{\eta_{col}}{100}\right)\right] + \left[UM_P * \frac{\eta_{col}}{100} * \left(1 - \frac{\eta_{cnt}}{100}\right)\right] \qquad (5)$$

where:

CM_P = Controlled mass emissions of pollutant P, kg/yr;
UM_P = Uncontrolled mass emissions of P, kg/yr (from equation 4 or the Landfill Air Emissions Estimation Model);
η_{col} = Collection efficiency of the landfill gas collection system, percent; and
η_{cnt} = Control efficiency of the landfill gas control or utilization device, percent.

Collection System Efficiency

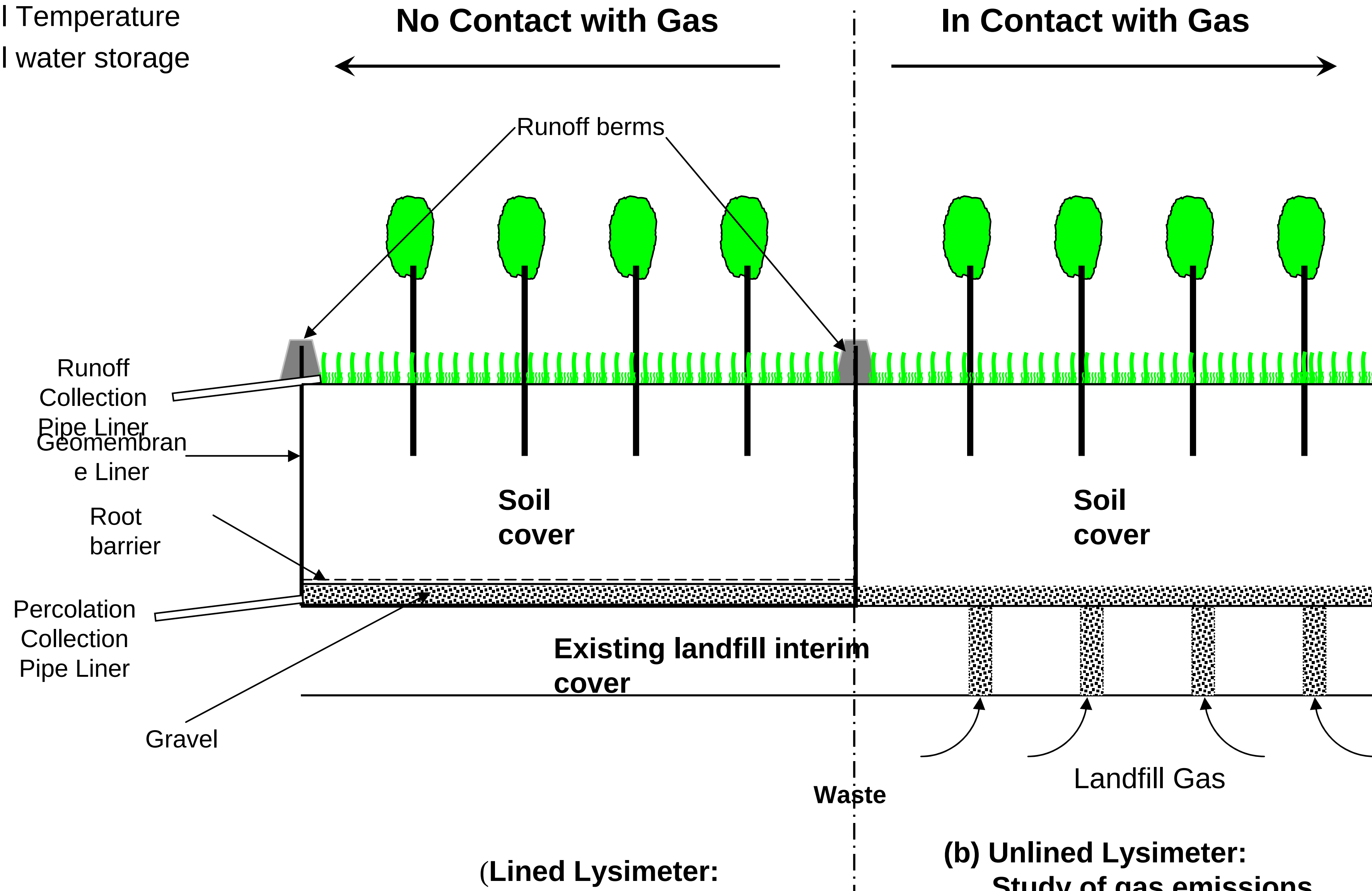
Treatment System Efficiency

UM_P is basically the generation rate

Next slides present additional materials dealing with a case study on effect of gas on tree growth

Effect of landfill gas on vegetation growth (case study, Tallahassee FL)

- Trees growth (height and DBH)
  - Tree heights were measured in August 2004 and December 2005
  - DBH was measure in December 2005
- Soil Temperature
- Soil water storage



Tree Growth: Lysimeter & Unlined Test Section (Height of Eucalyptus Trees)

Date	Note	Lysimeter		Unlined Test Section		Significantly Different	P-Value
		Height (mm)	Std Dev (mm)	Height (mm)	Std Dev (mm)		
4-May-2004	Planting	305	-	305	-	-	-
18-Aug-2004	-	2543	737	2853	661	NO	0.061
19-Dec-2005	-	15930	3458	16739	3355	NO	0.311
Change in Height	Aug -04 to Dec-05	13387	3088	13885	2897	NO	0.477

Tree Growth: Lysimeter & Unlined Test Section (Height of Cottonwood Trees)

Date	Note	Lysimeter		Unlined Test Section		Significantly Different	P-Value
		Height (mm)	Std Dev (mm)	Height (mm)	Std Dev (mm)		
4-May-2004	Planting	305	-	305	-	-	-
18-Aug-2004	-	3881	1474	5237	1063	YES	<0.05
19-Dec-2005	-	19355	1916	19664	3802	NO	0.689
Change in Height	Aug -04 to Dec-05	15474	1154	14427	3499	NO	0.128

Tree Growth: Lysimeter & Unlined Test Section (Diameter at Breast Height - DBH)

Date	Trees Type	Lysimeter		Unlined Test Section		Significantly Different	P-Value
		DBH (mm)	Std Dev (mm)	DBH (mm)	Std Dev (mm)		
19-Dec-2005	Eucalyptus	359	118	409	128	NO	0.082
	Cottonwood	364	86	434	131	YES	0.015

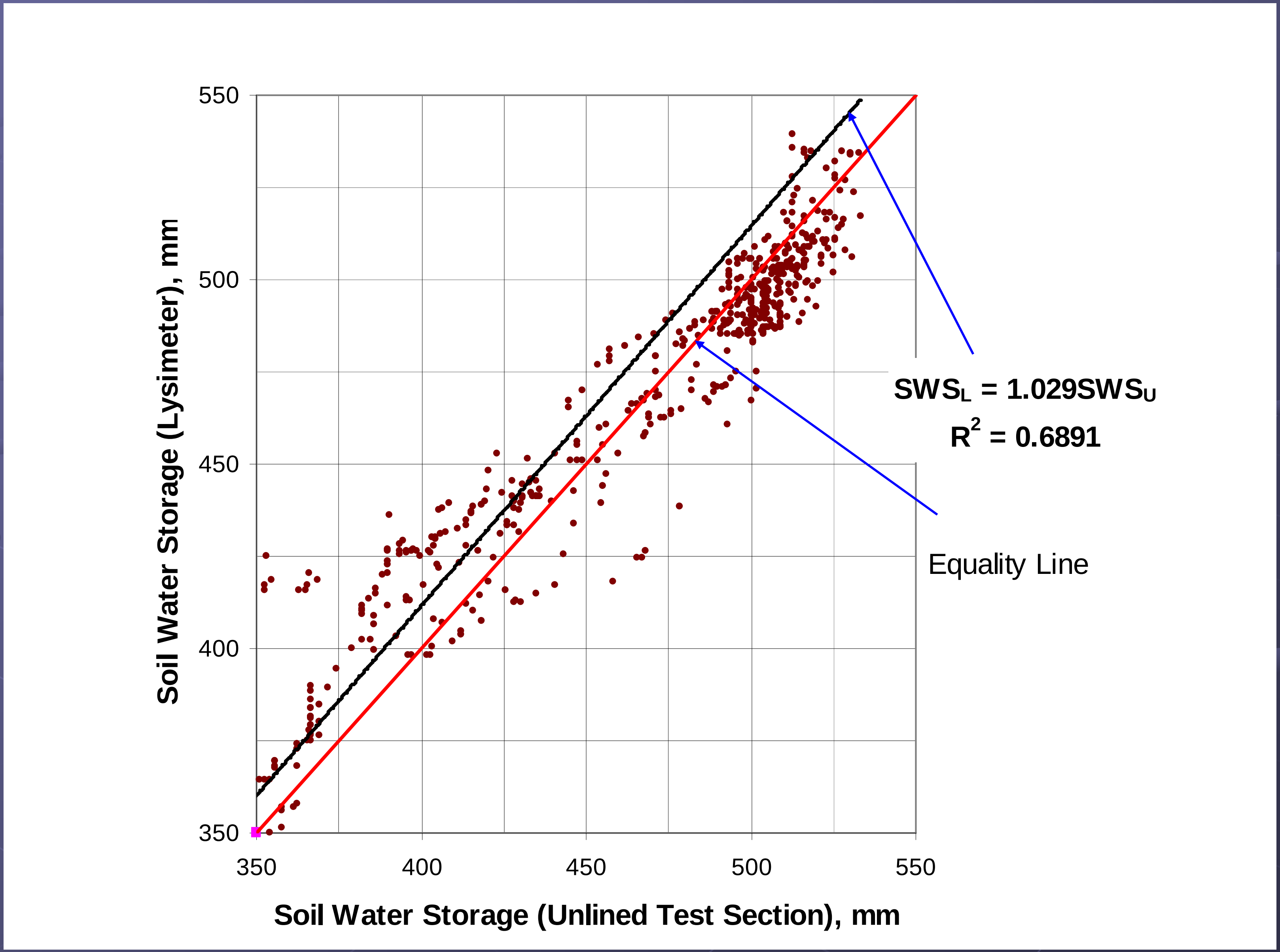
Tree Growth: Lysimeter & Unlined Test Section (Diameter at Breast Height - DBH)

Date	Trees Type	Lysimeter		Unlined Test Section		Significantly Different	P-Value
		DBH (mm)	Std Dev (mm)	DBH (mm)	Std Dev (mm)		
19-Dec-2005	Eucalyptus	359	118	409	128	NO	0.082
	Cottonwood	364	86	434	131	YES	0.015

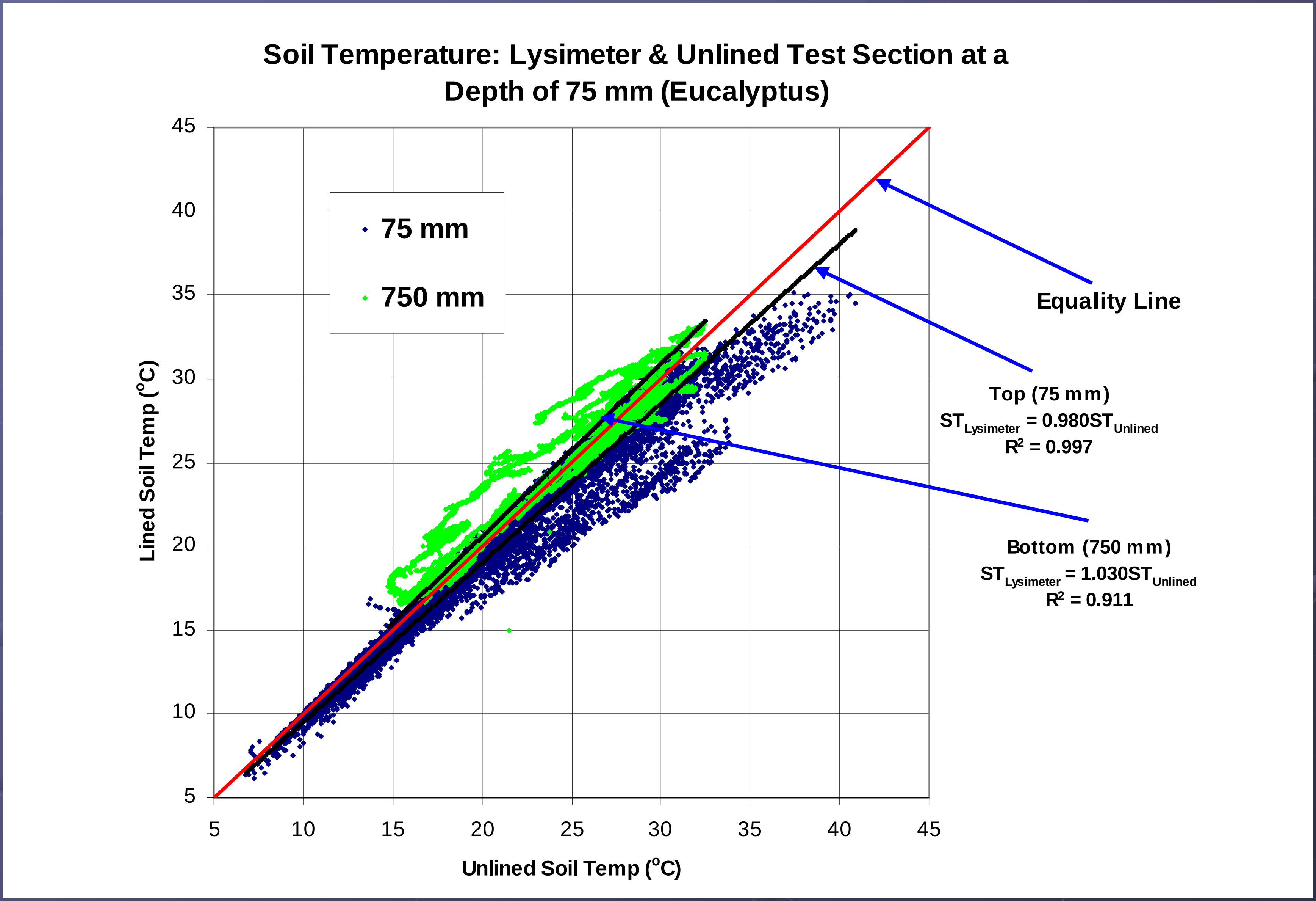
Tree Growth: Lysimeter & Unlined Test Section (Diameter at Breast Height - DBH)

- Analysis of variance of Height of eucalyptus and DBH data showed that there is no significant difference between tree height and DBH inside and outside the lysimeter
- This suggests that landfill gases did not impact tree growth rates
- In August 2004, height of cottonwood inside the lysimeter was significantly different than outside the lysimeter
- However the difference was not significant when the height of the trees was measured in December 2005
- No significant difference was observed between the change in tree height inside and outside the lysimeter for both types of trees.

Comparison of Soil Water Storage: Eucalyptus Lysimeter & Unlined Test Section



Comparison of Soil Temperature: Lysimeters & Unlined Test Sections



Comparison of SWS and Soil Temperature in the Lysimeter & Unlined Test Section

- Generally, SWS in the lysimeter is slightly higher (about 3%) than that in the unlined test section
- The higher soil water storage in the lysimeter may be due to the presence of the geocomposite at the bottom boundary. The presence of geocomposite may induce capillary effects and increase the water content right above it.
- The slight difference in soil water storage and temperature between the inside of the lysimeter and the unlined test section did not however lead to difference in vegetation growth