Session Overview :

Controlling CH_4 Emissions from Waste

Total waste sector emissions:

2.9 % of 49 Gt total [CO_2 eq.] anthropogenic GHG emissions for 2010
(IPCC AR5 WG3 Table 10.3)

89% of sectoral total = CH_4 from landfills & wastewater

We know how to:

Control CH_4 emissions from landfills:

Engineered landfills with recovery & use of biogas.
Horizontal gas collectors installed concurrent with filling.
Installation of thicker soil covers or "biocovers" to optimize soil oxidation of CH_4.
Diversion of biodegradable waste from landfills.

Control CH_4 emissions from wastewater:

Engineered wastewater collection & treatment.
Reduce anaerobic retention times.
Fix systemic leaks.
Add biofilters.

Time

However…

millenium

century

decade

year

day

minute

second

Current IPCC (1996, 2006) National GHG Inventory Methods

…do not reflect current scientific understanding.

…exclude major drivers for emissions.

… do not match field measurements at various spatial & temporal scales.

Field measurements indicate wide range of values:

Landfill emissions: <0.001 to >1000 g CH_4 $m^2 d^{-1}$ [chambers]

<10 to >100 mol CH_4 sec^{-1}

[whole site aircraft mass balance]

Wastewater emissions: primary tanks 0.72* to 96** g CH_4 m^{-2} d^{-1}

digesters negligible *** to 2400**** g CH_4 m^{-2} d^{-1}

*mechanized scraper flights ** Imhoff tanks

***membrane capped ****floating cover

Space

mm cm m 10m 100m km national

Scales for processes, measurements, & IPCC models…

geologic time

millennium

century

Temporal

decade

year

day

minute

second

weather

micromet. tower

Scale of Current Field Methods

chambers

aircraft

mass balance

Scale of biogenic methane processes

NGGIP

IPCC national GHG inventory methodologies

Spatial

mm cm m 10m 100m km national global

geologic time

millennium

century

Temporal

decade

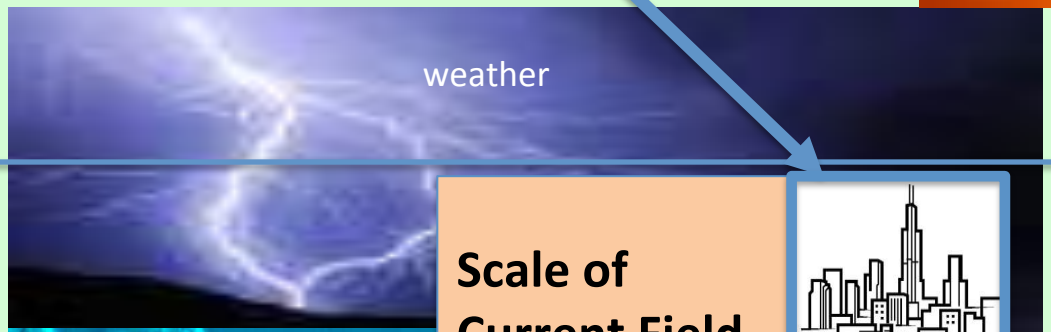
year

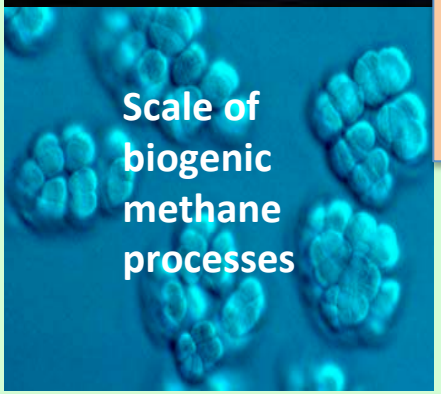
day

minute

second

…Increasing importance of site-specific CH_4 emissions for URBAN-scale inventories.





Scale of Current Field Methods

NGGIP

IPCC national GHG inventory methodologies

Spatial

mm cm m 10m 100m km national global

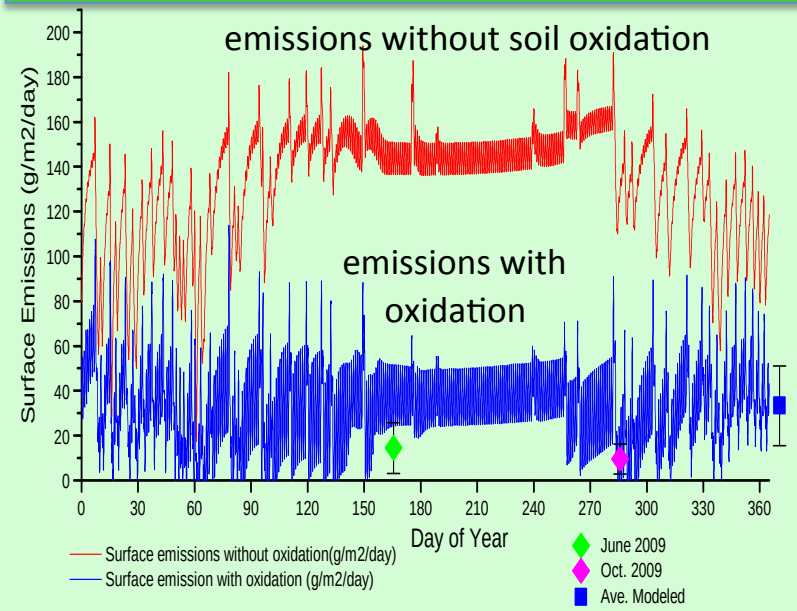
Session will include:

J. Bogner: "No More California Dreaming: Applying Science-Based Modeling Tools to CH_4 Emissions from Waste"

- *Overview & shortcomings of current IPCC methodologies/ models [IPCC, 2006] compared to California field data.*
- *New field-validated method [CALMIM] for site-specific landfill CH_4 emissions inclusive of spatial & temporal variability in soils & climate at any global location.*
- *Some CALMIM applications.*

- *Landfill CH_4 case studies:*
  - *J. Fernandez [Latin America]*
  - *J. Parkin [South Africa]*

Annual cycle for CH_4 emissions:
Intermediate Cover (45 cm sandy loam)
N. California landfill



No More California Dreaming: Applying Science-Based Modeling Tools to CH_4 Emissions from Waste

Jean Bogner
Kurt Spokas

J. Bogner
University of Illinois at Chicago

K. Spokas
U.S. Dept. of Agriculture
Agricultural Research Service, St. Paul, MN

Note:

- Current NGGIP landfill & wastewater methodologies:

  [IPCC, 1996, 2006]: industrial mass balance approach w/ primary dependencies on CH_4 generation from landfilled waste or wastewater BOD w/ fraction emitted.

Will Include:

- Focus on landfill methods/focus on California:

  Overview & shortcomings of current IPCC methodologies/ models [IPCC, 2006] compared to California data.

- "Science-based" modeling approach [CALMIM]:

  Site-specific landfill CH_4 emissions inclusive of spatial & temporal variability in soils & climate at any global location.

  Validation. Applications.

ALL landfill CH_4 pathways and CH_4 mass balance

$$a = b + c + d + e + \Delta f$$

(a)Methane generated in anaerobic waste (methanogens) = ***the sum of***

(b) Methane recovered by engineered systems

+

(c) Methane oxidized to CO_2 in cover soils [*methanotrophs*]

+

(d) Methane emitted to atmosphere through cover soils

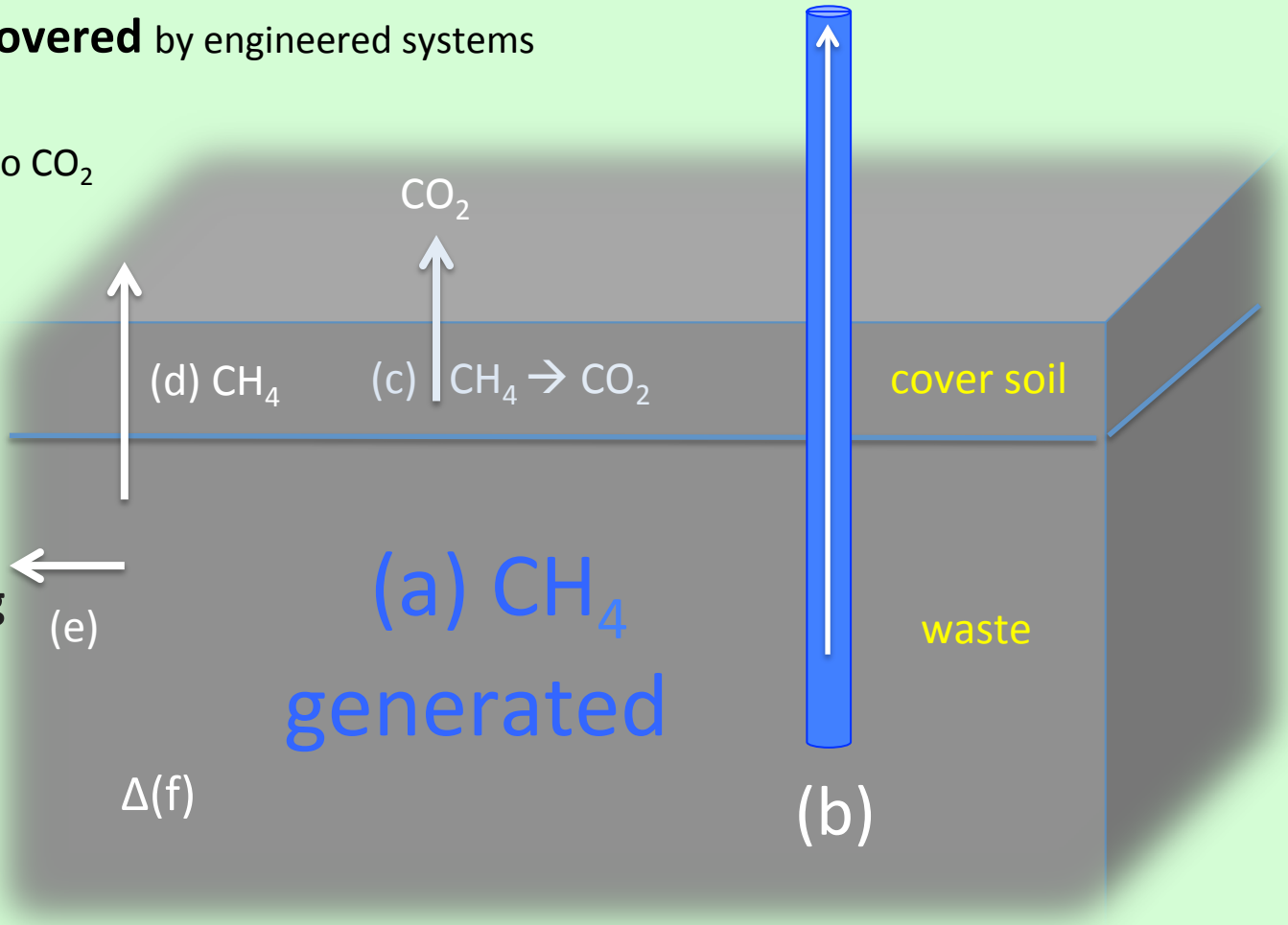
+

(e) Methane migrating *laterally* to external soils;

+

(f) Change in CH_4 storage

units = mass/time



- Current IPCC (2006) GHG inventory methodology uses a simplified mass balance where…

Modeled CH_4 emissions = [modeled CH_4 generation – estimated or *measured CH_4 recovery] * 0.9*

- *Estimate total annual LFG generation from waste-in-place using*

  1st order kinetic model

- *Determine the % CH_4 (often assumed to be 50%),*
- *Subtract or estimate CH_4 recovered (if engineered system exists),*
- *Subtract an additional 10% for oxidation in cover soils at well-managed sites,*
- *Assume the remainder = CH_4 emissions.*

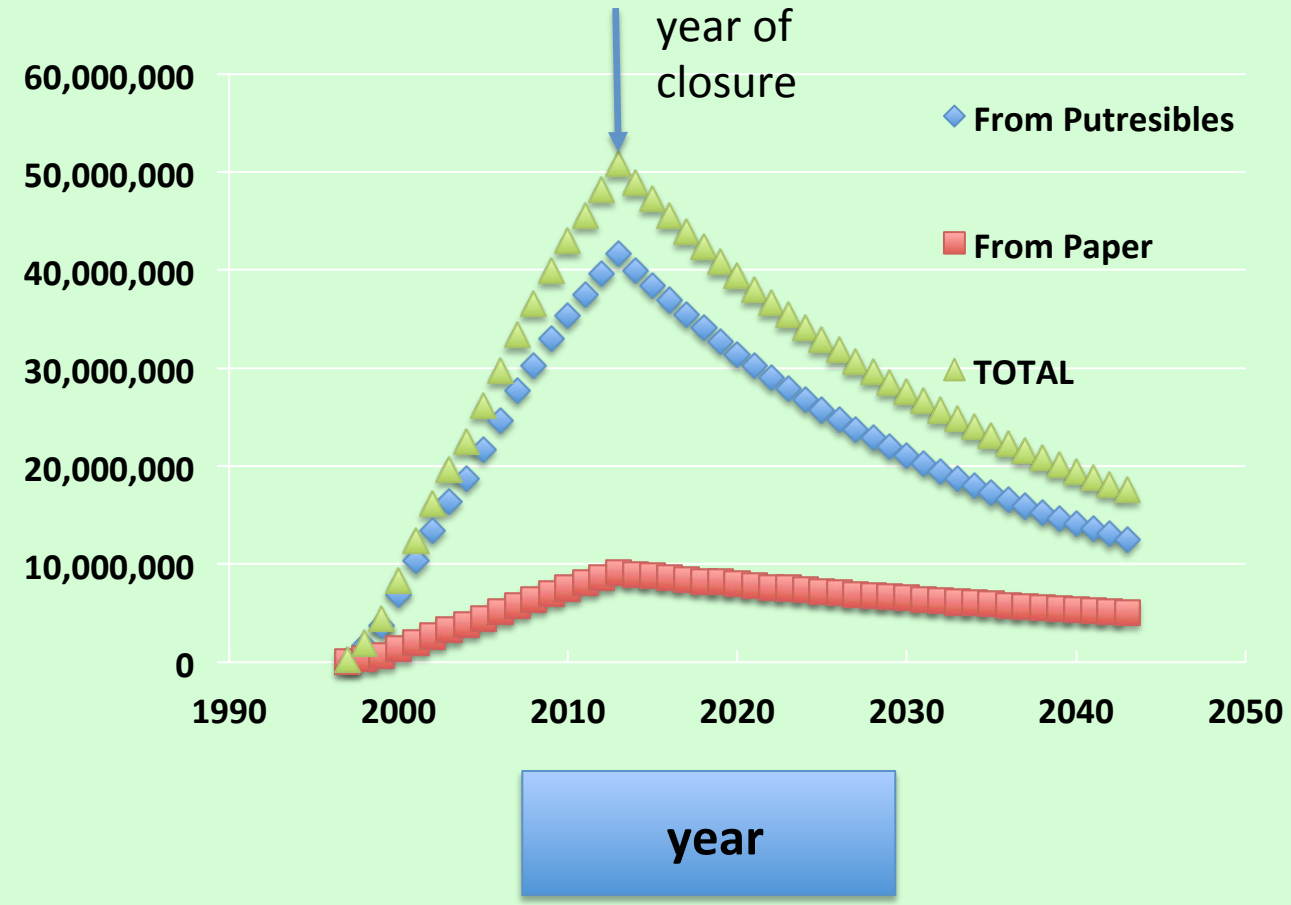
  - IPCC, 2006 [multicomponent model for decomposition of organic carbon in various waste fractions].

Example for modeled generation using current IPCC (2006) multicomponent first order kinetic "FOD" Model:

- **Here using 2 components only…**
- **Kinetic constant (k) values ranging from 0.02 to 0.4, assumed to be related to climate…**

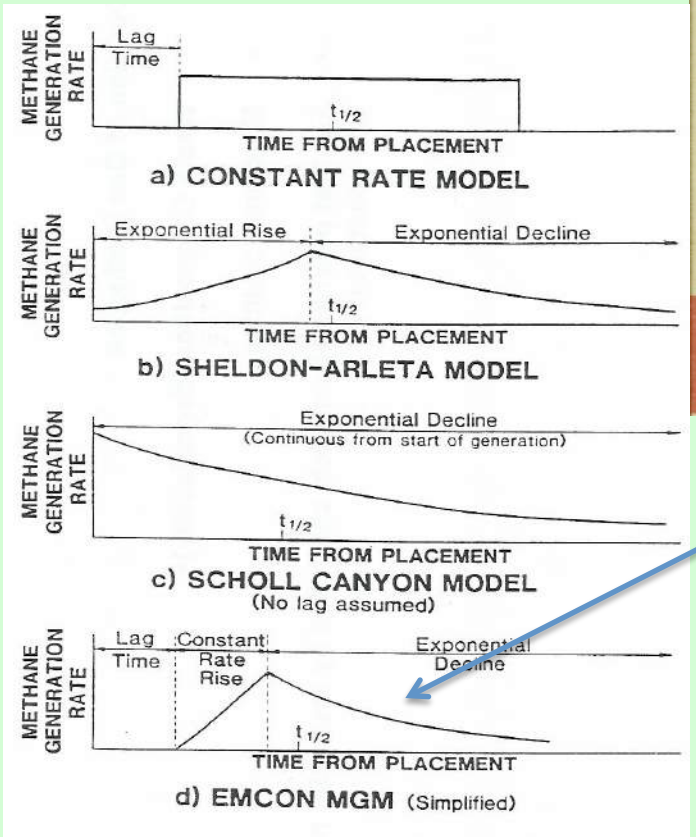
For each component, the degradable organic carbon [DOC] converted to biogas at time t = decomposable $DOC_{t=0} \bullet (e^{-k(t-1)} - e^{-kt})$

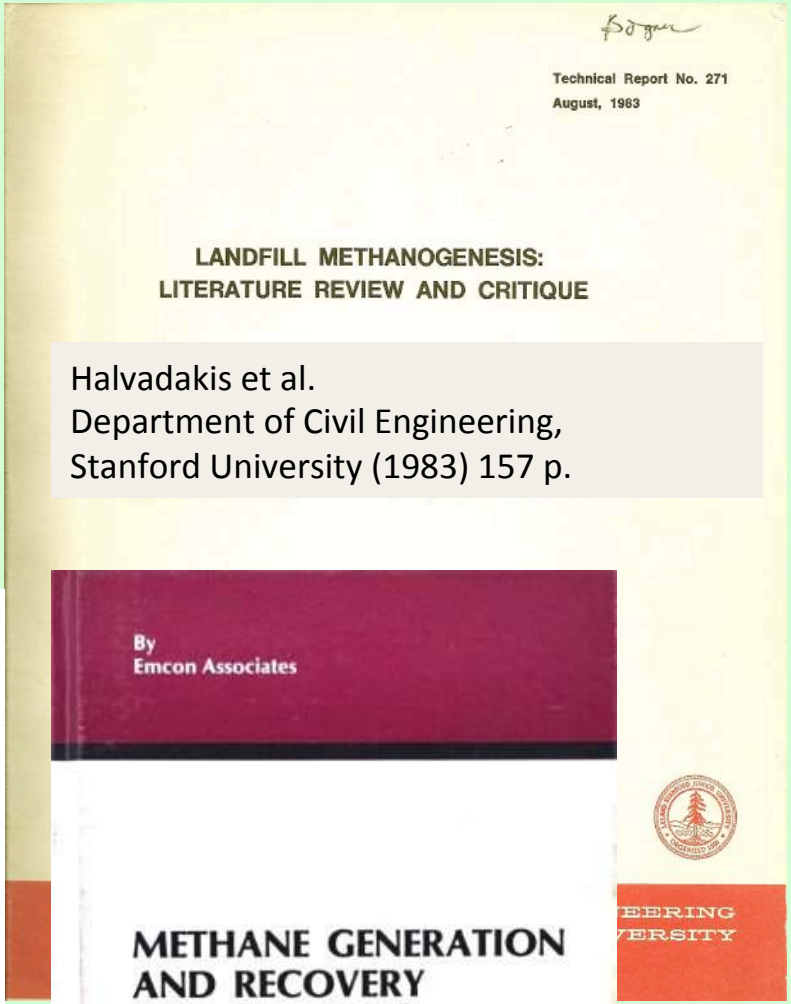
Total modeled biogas generation ($Nm^3\ y^{-1}$)



Source of kinetic model?: one of many applied to 1st commercial landfill biogas utilization projects in California:

- ✓ Goal was to predict future recovery from past performance.
- ✓ Now IPCC (1996, 2006) applied to every landfill.





Halvadakis et al.
Department of Civil Engineering,
Stanford University (1983) 157 p.

EMCON Associates (1980)
150 p.

What's wrong with these models for predicting landfill CH_4 emissions?

- **Models never field-validated for CH_4 emissions**. ["Validation" consisted of comparing *measured recovery* to *modeled generation* at limited # sites]
- **Model results do not match a growing database of field measurements for CH_4 emissions.**
- **Assumption of 10% oxidation is based on a single study:** First study in the literature addressing annual oxidation at a small NH landfill (Czepiel et al., 1996). ***Oxidation is a variable***, not a constant, with unique seasonal trends in each cover soil at each site.
- **Models exclude the 3 major drivers for emissions**:

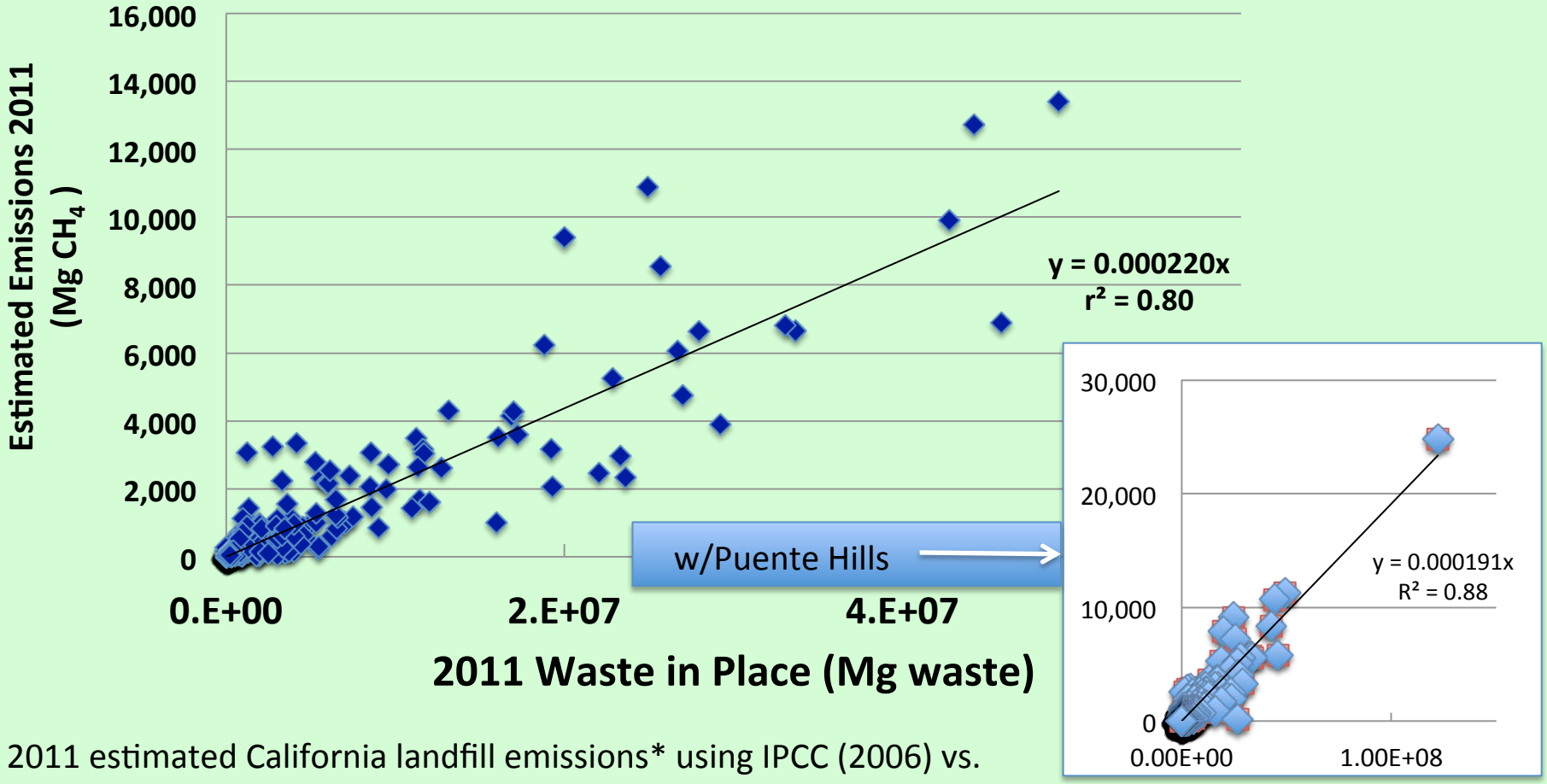
  1) area, composition, and thickness of ***cover soils***.

  2) **climate trends** unique to both the global location (lat./ long.) & individual cover soils w/ seasonally variable gaseous transport & CH_4 oxidation rates.

  3) physical effect of **LFG recovery system** on soil gas CH_4 concentrations.

What else is wrong with the application of IPCC (2006) to site-specific landfill CH_4 emissions?

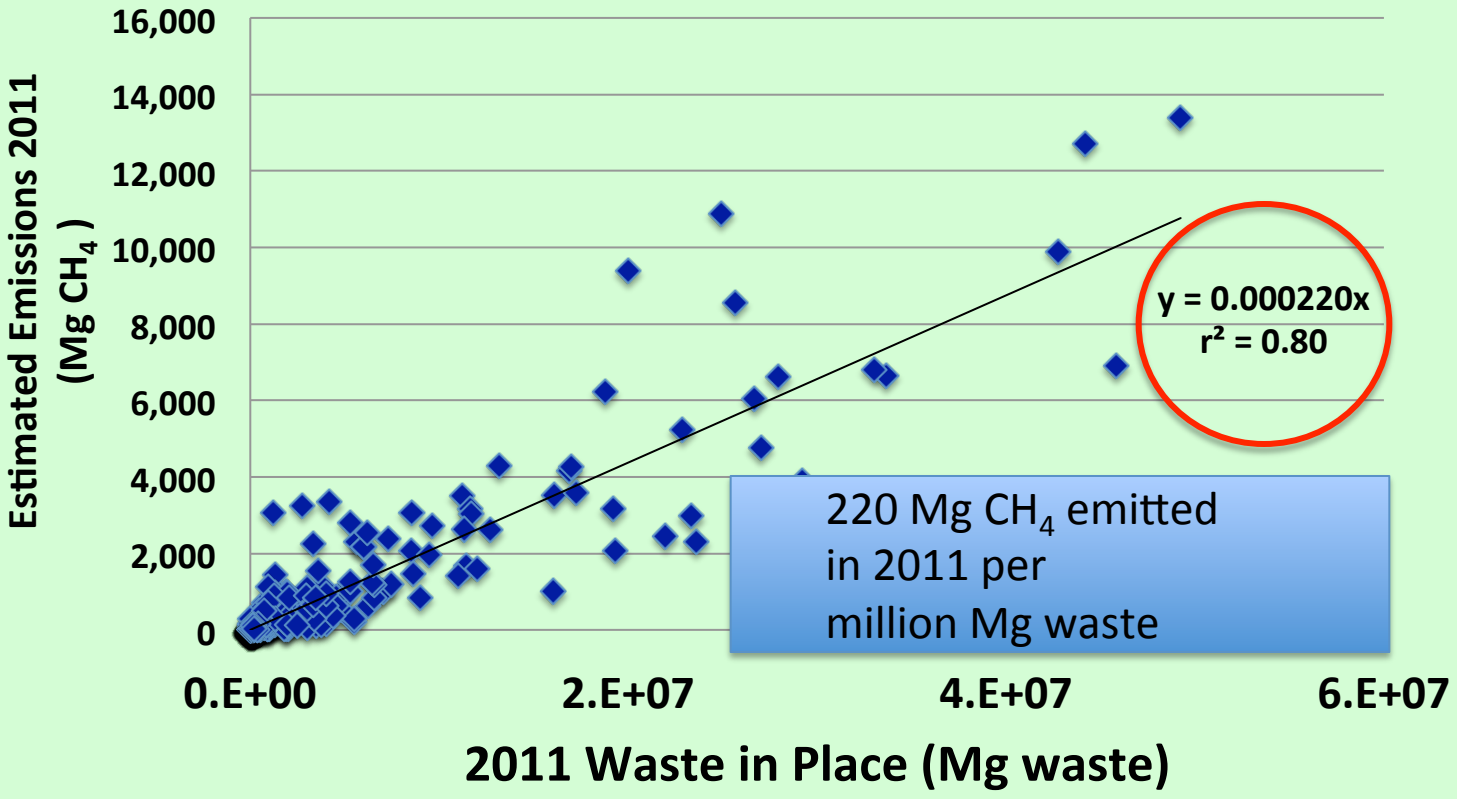
- <u>Results in a primary dependency of emissions on WIP.</u>
- <u>Example</u>: 2011 California landfill CH_4 inventory values using IPCC (2006) "FOD" model w/assumed 75% biogas "collection efficiency", where applicable. 371 sites.



2011 estimated California landfill emissions* using IPCC (2006) vs. 2011 Waste-in-Place. 371 sites excluding Puente Hills. Source of data: California Air Resources Board.

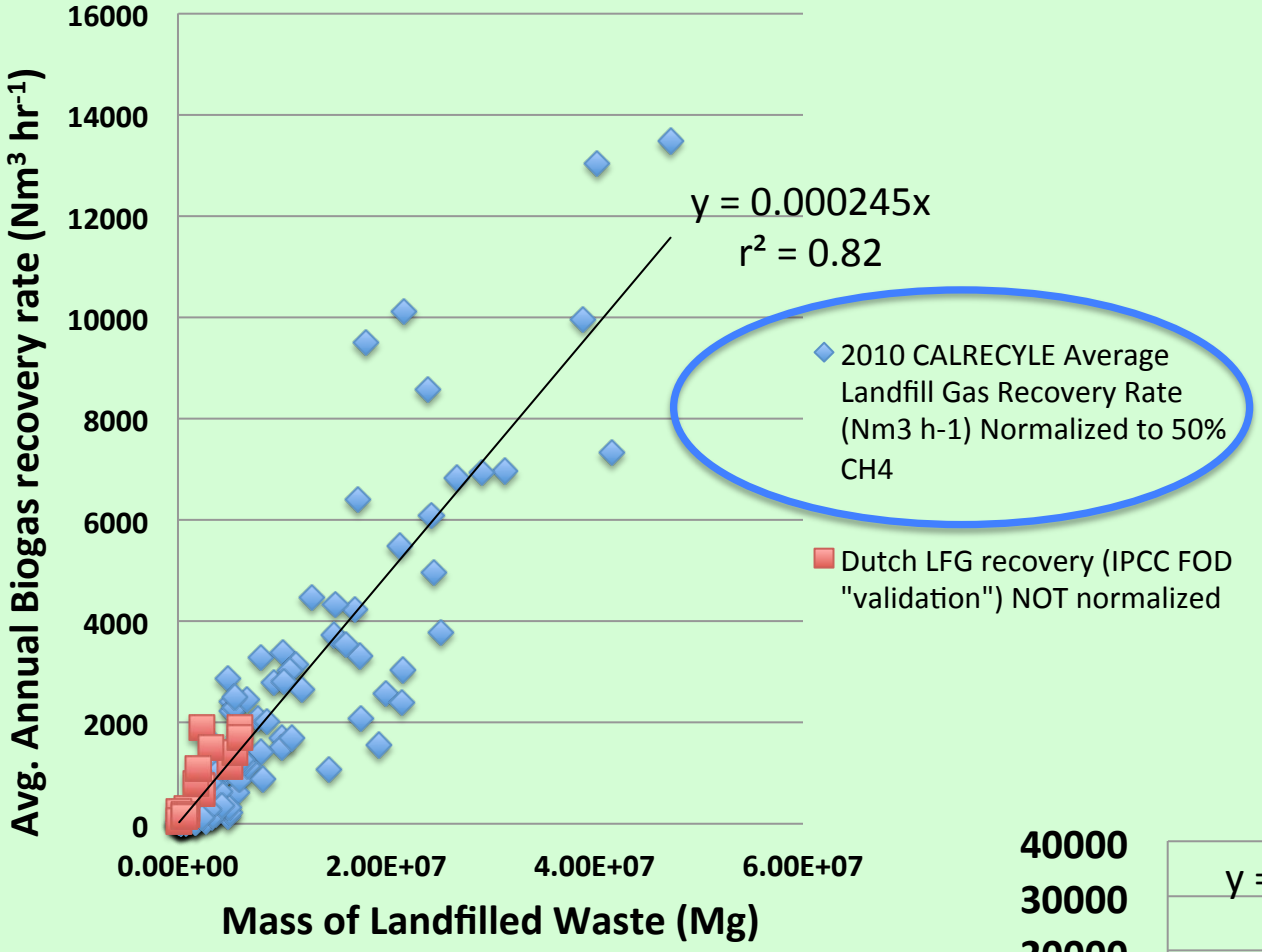
What is the result?

- ✓ Impossible for sites to reduce emissions below a certain threshold…
- ✓ Discourages proven engineering solutions to reduce emissions
  [no concurrent "credit"… Australian carbon tax example…]
- ✓ Tends to reward "non-optimized" gas recovery [assigned collection efficiency…]



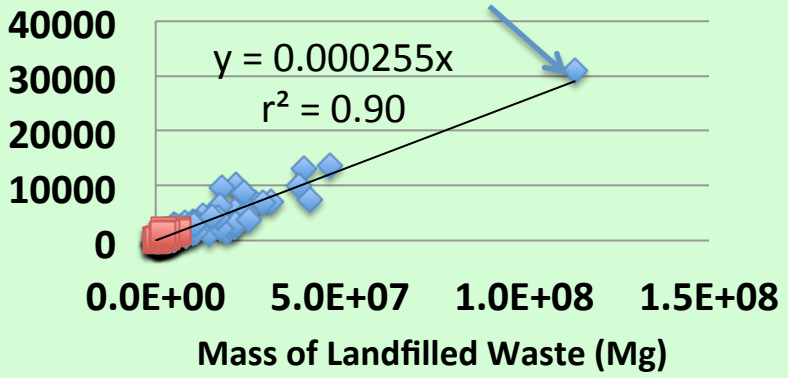
2011 estimated California landfill emissions* using IPCC (2006) vs.
2011 Waste-in-Place. 371 sites excluding Puente Hills [ARB data, 2012].

Linear dependence of 2010 avg. annual biogas recovery rate on 2010 mass of landfilled waste [128 landfills]



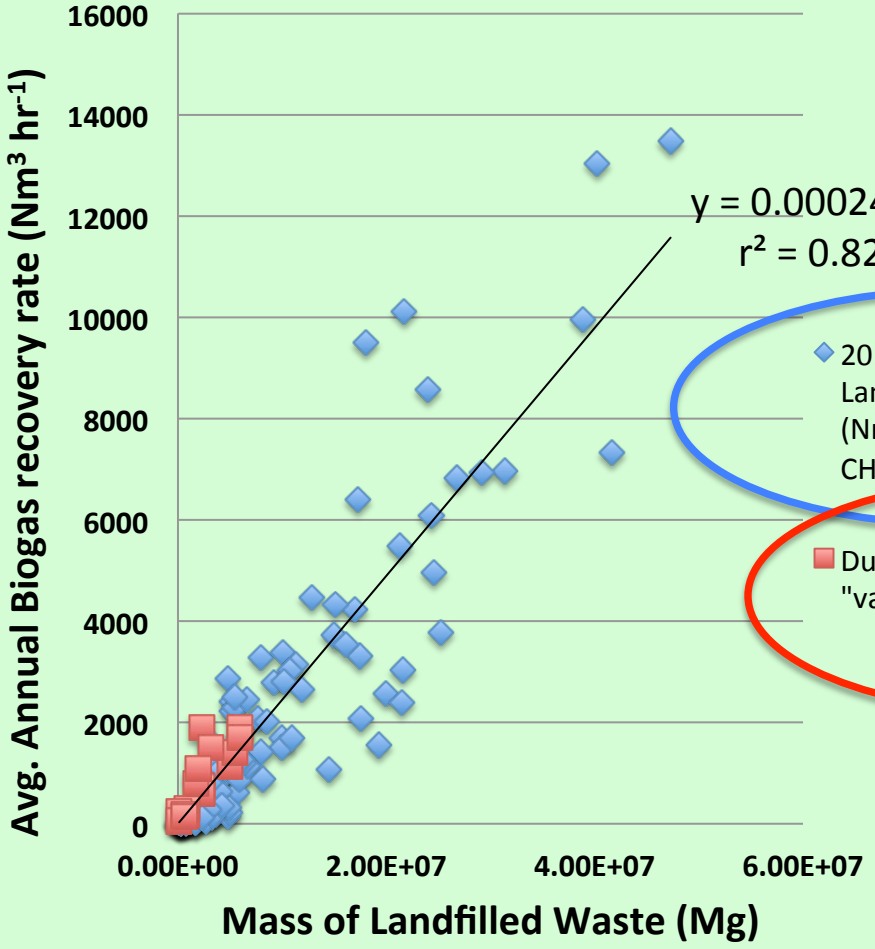
California biogas recovery sites: Empirical relationship w/ constant rate of biogas recovery per unit mass of waste…independent of site age, size, status (open or closed), or climate.

129 California landfills [Puente Hills]



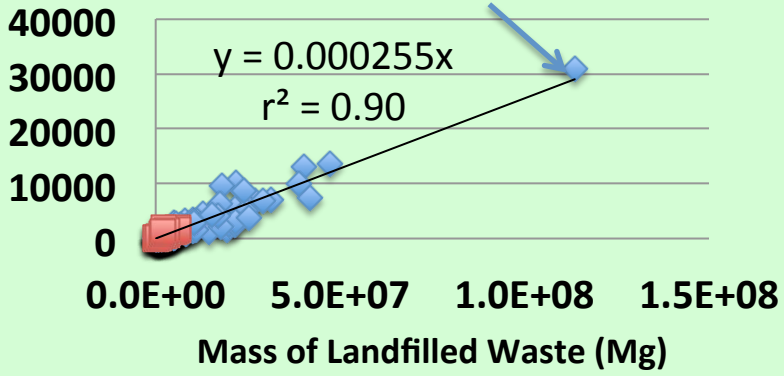
Source of data: Walker et al., 2012 California Dept of Resources Recovery & Recycling [Calrecycle]

Linear dependence of 2010 avg. annual biogas recovery rate on 2010 mass of landfilled waste [128 landfills]



Also plotted original IPCC FOD model "validation data": 9 Dutch Landfills.

129 California landfills [Puente Hills]

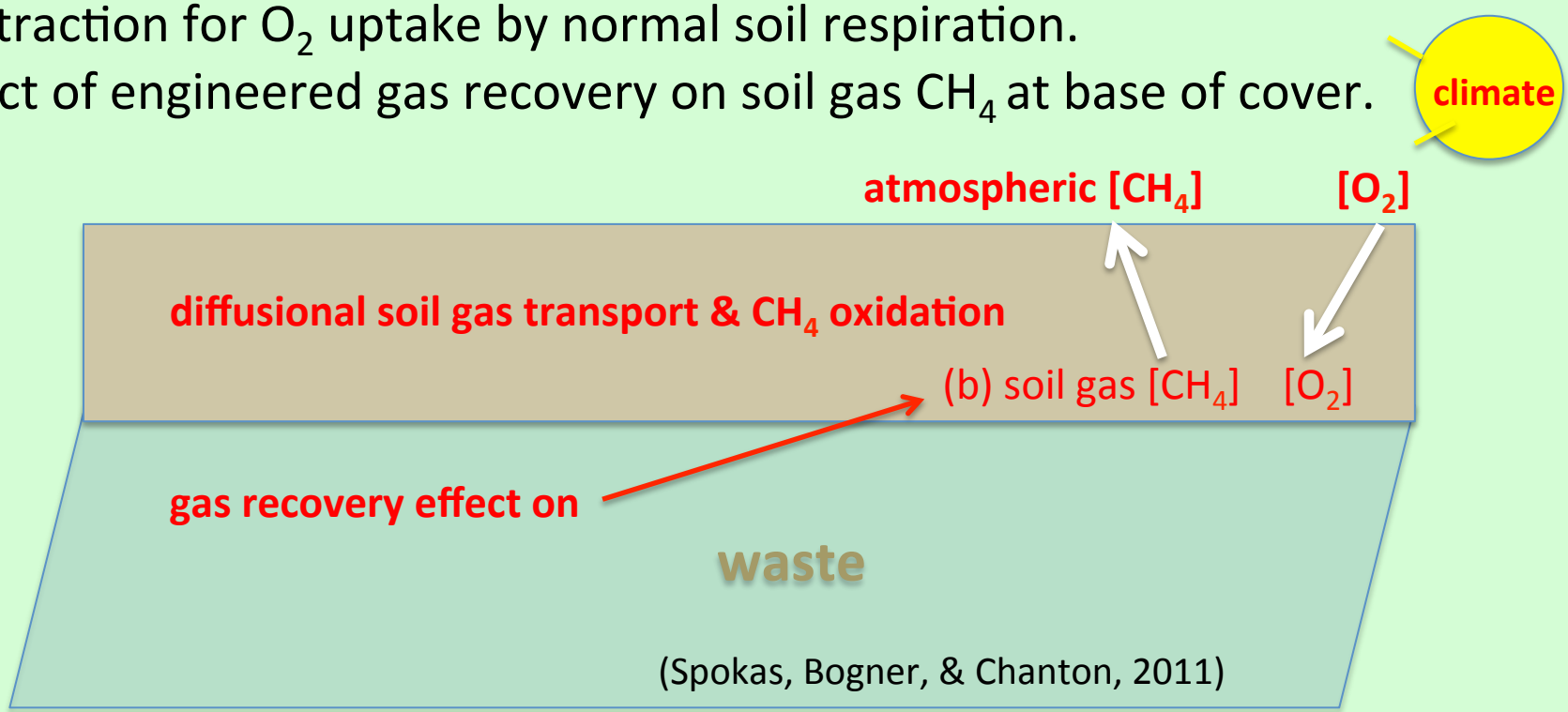


Source of data: Walker et al., 2012
California Dept of Resources Recovery & Recycling [Calrecycle]

CAlifornia Landfill Methane Inventory Model (CALMIM, v 5.4)

Summary of major processes & dependencies:

- Climate effects on soil moisture & temperature in individual cover soils.
- Heat, water, and gaseous transport [1-D diffusional soil gas CH_4 and O_2 transport in individual cover soils].
- Soil moisture & temperature effects on temporal oxidation rates.
- Subtraction for O_2 uptake by normal soil respiration.
- Effect of engineered gas recovery on soil gas CH_4 at base of cover.



CAlifornia Landfill Methane Inventory Model

(CALMIM, v 5.4): JAVA model freely available at ars.usda.gov.

- INPUTs: Site latitude & longitude; surface area, thickness, and texture of each cover soil or alternative materials; % of each cover area with gas recovery & seasonal vegetation.

- Embedded USDA climate models for air temp, pcp, surface energy balance, soil temperature & moisture. Globally-validated with 0.5 deg latitude/longitude reliability OR can input site-specific weather.

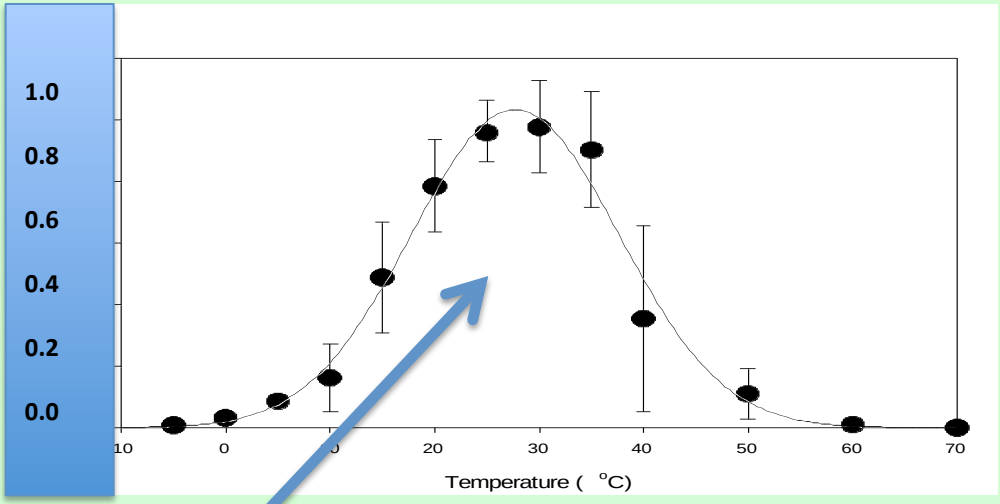
- Soil gas transport: Developed from first principles→1-D diffusional transport model for CH_4 and O_2 [Moldrup et al., 1998; 2004; Campbell, 1985]. Default concentrations for daily, intermediate, & final covers for inventory applications OR can input site-specific soil gas data.

- Variable CH_4 oxidation rates: Scaled to a maximum rate based on modeled soil temperature and soil moisture potential (Spokas & Bogner, 2011).

- OUTPUTs: CH_4 emissions for **each cover** w/oxidation and w/o oxidation over "typical annual cycle "[365 days] for 10-min timesteps and 2.5-cm depth increments. Annual emissions summary. Graphs. Backup EXCEL files.

How CALMIM calculates oxidation…

- Rate calculated every 10-min for 2.5 cm depth increments for 365 days.
- All rates scaled to a maximum rate for modeled soil temperature & SMP [soil moisture potential] using these relationships…

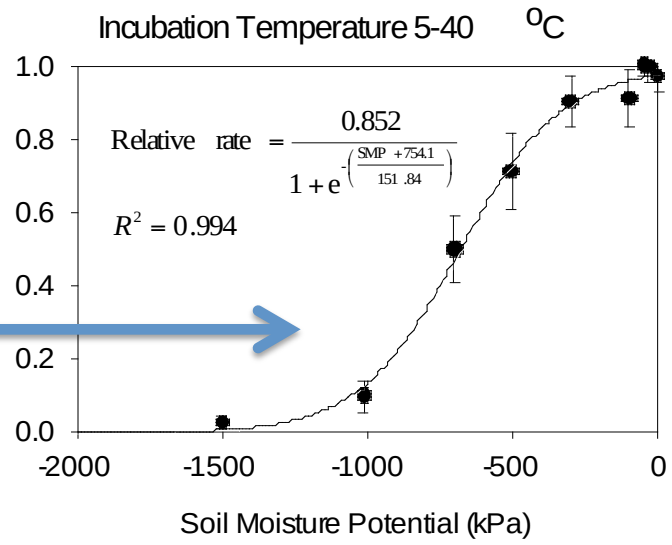


Optimum Conditions?

(Spokas & Bogner, 2011)

Gaussian function for rate at specific temperature divided by maximum rate for the corresponding SMP…

Sigmoid functions for rate at SMP divided by maximum rate for the corresponding temperature.

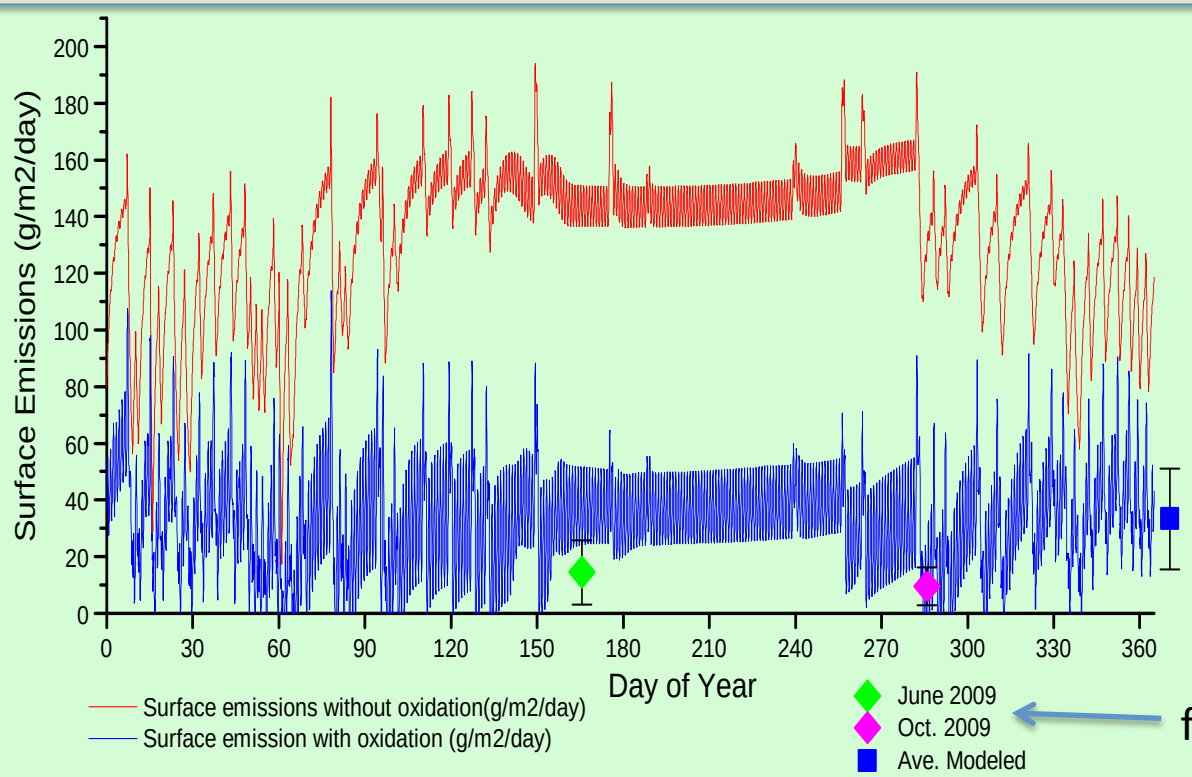


>2000 laboratory incubations

Standard CALMIM output:

10-min. surface CH_4 emissions w/ & w/o oxidation over "Typical Annual Cycle"

Here: Intermediate Cover (45 cm sandy loam) at N. California site



DIRECT COMPARISON of:
"modeled emissions without oxidation" IN RED
to
"modeled emissions with oxidation" & annual "average" emissions IN BLUE.

field measurements

Why so many "squiggles"?: Daily soil temperature & soil moisture variability...

Note here: ≈75% reduction in emissions due to oxidation during warm [dry] summer conditions with variable & sporadically negligible emissions during wetter parts of the year…

Other standard CALMIM outputs: Complete EXCEL files & automatically-generated graphs

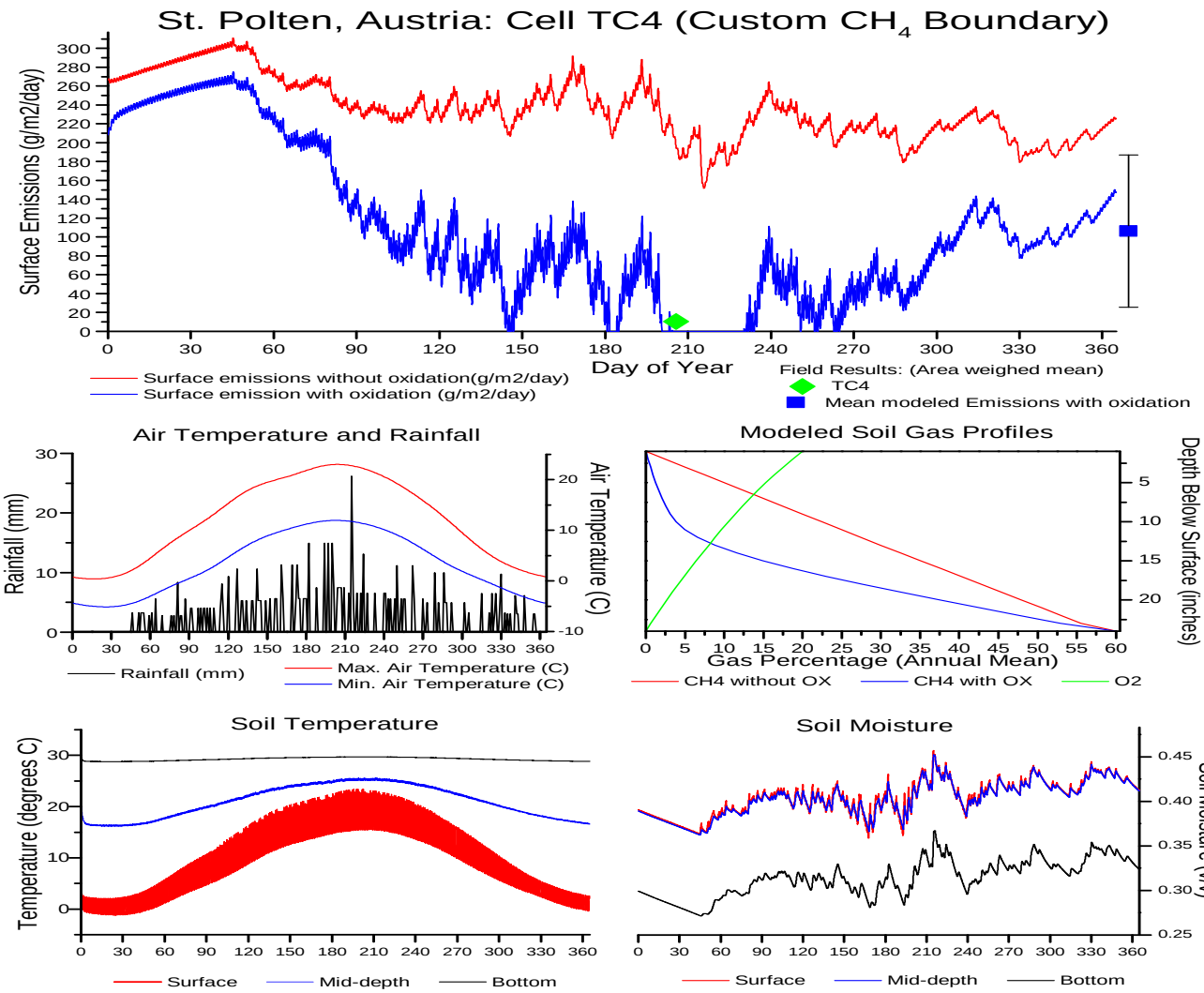
[CH_4 emissions with and without oxidation, soil temperature, soil moisture, gas-filled porosity, soil gas CH_4 and O_2, CH_4 oxidation rate, % oxidation, relative oxidation with depth.]

Example: CALMIM output for a contrasting climate & cover (Austria)

including examples of automatically-generated graphs

30 cm compost/
30 cm loam
biocover
test cell

<u>NOTE:</u>
High emissions during cold winter temperatures with low oxidation…

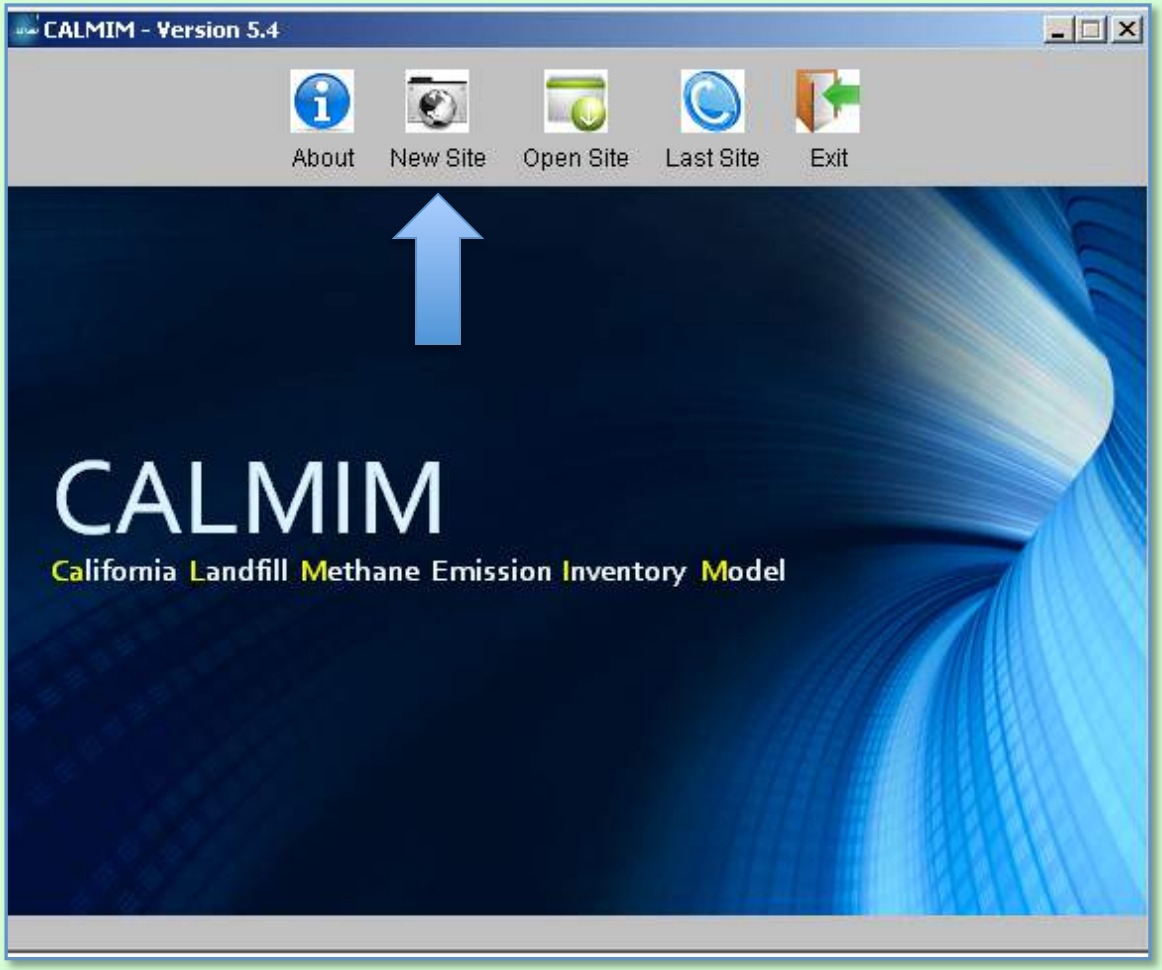


(Bogner, Spokas, & Corcoran, 2014, w/ thanks to BOKU Univ., Vienna)

CALMIM – Quick Tour:

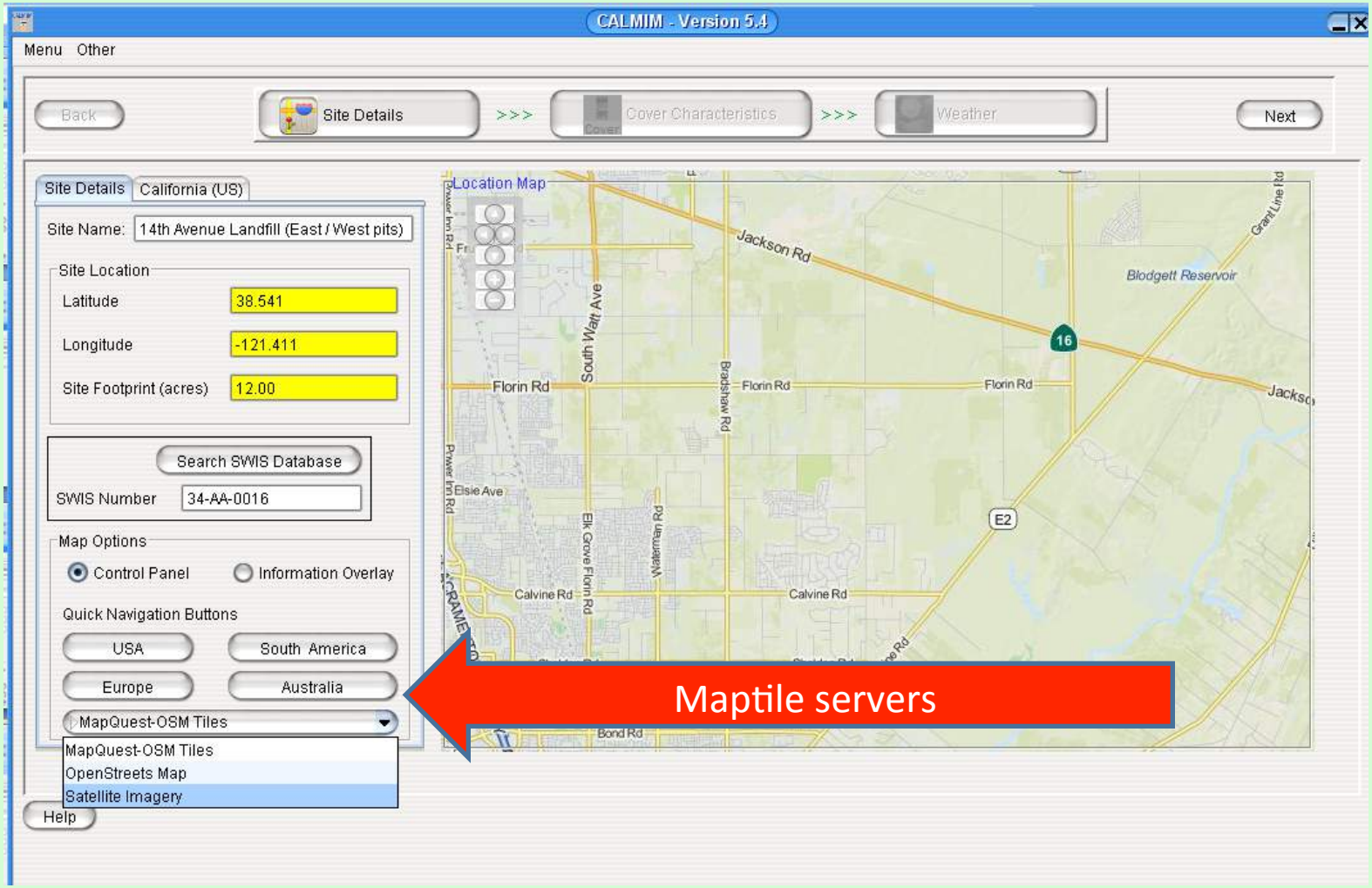
JAVA tool: compatible w/PC, MAC, UNIX

download at: *www.ars.usda.gov*



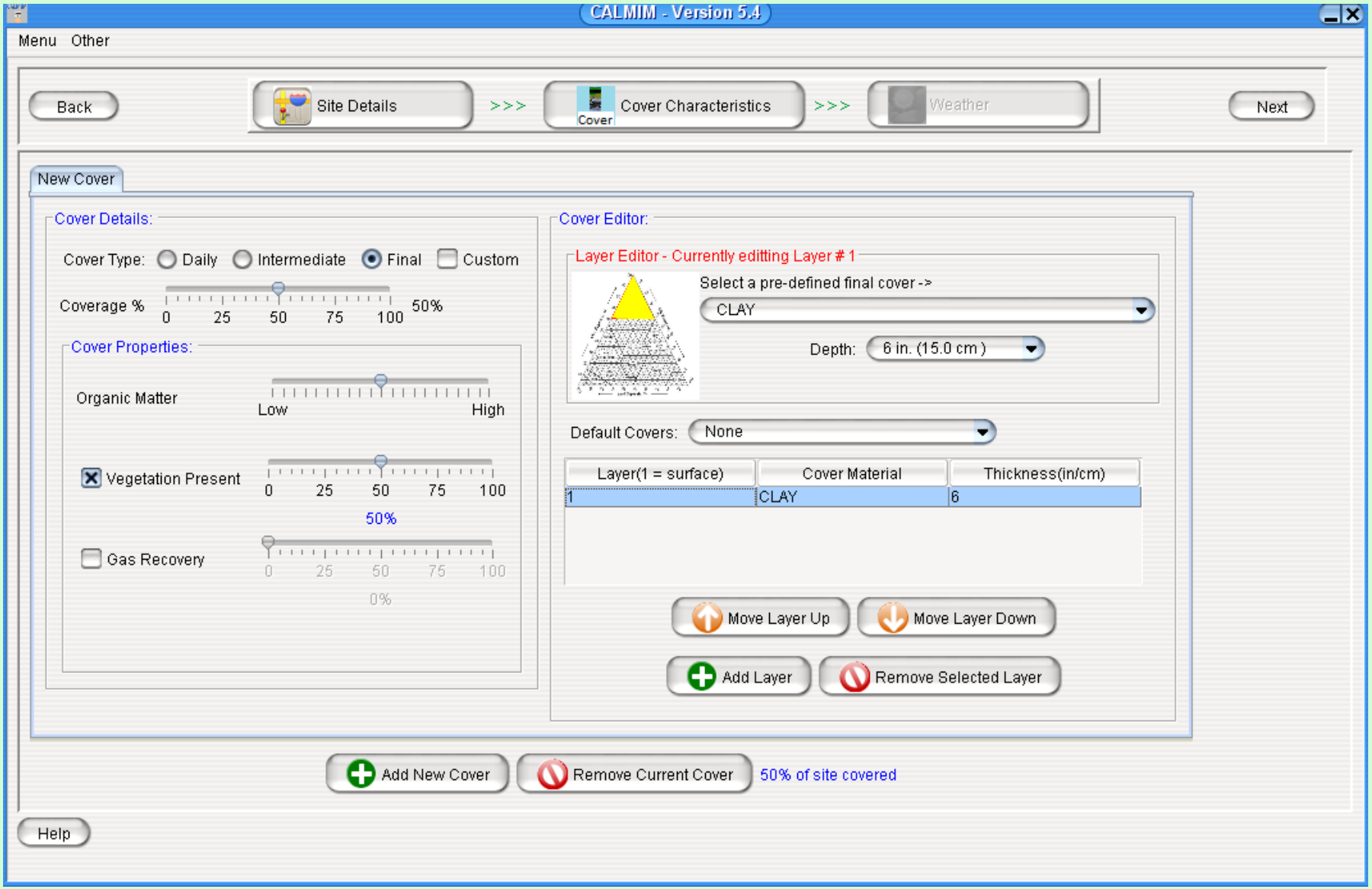
CALMIM 5.4

Two input screens: (1) site location, waste footprint



CALMIM 5.4

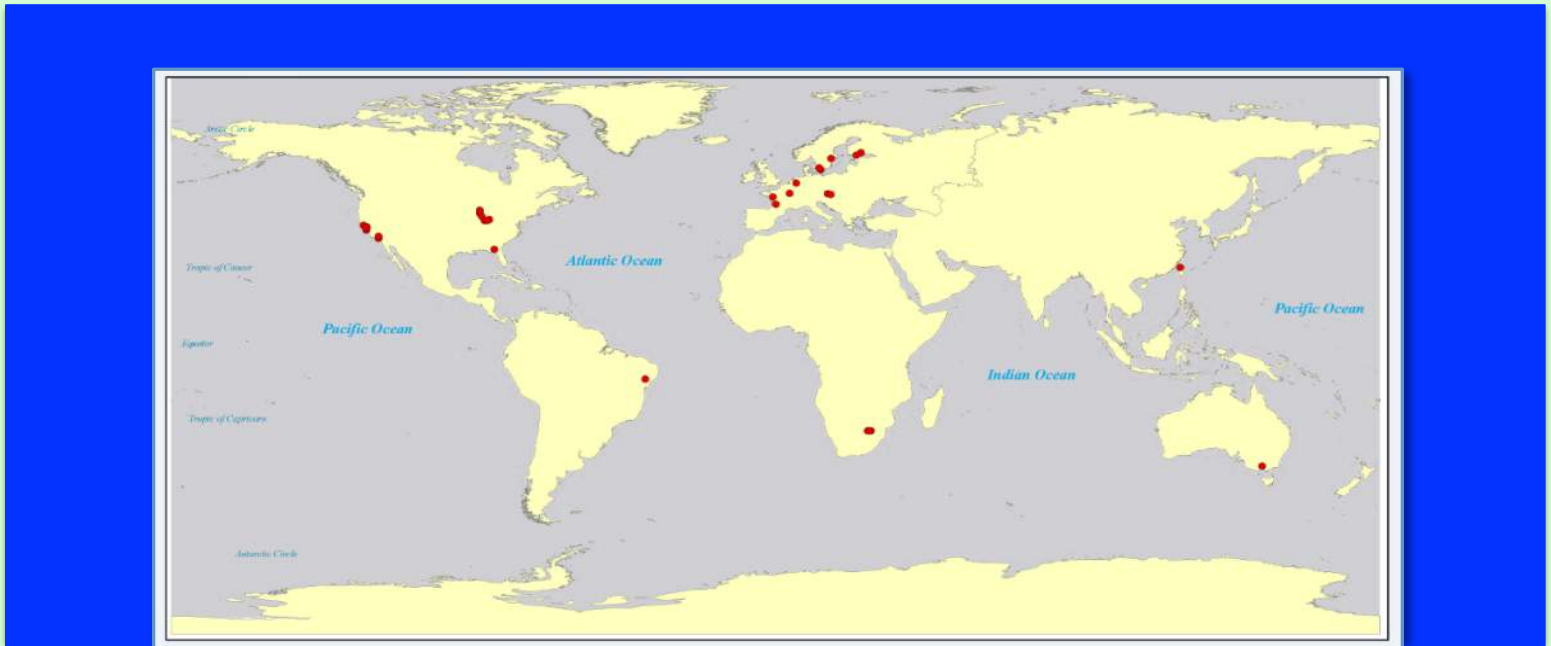
Two input screens: (2) cover type, soil, % area with gas recovery…



Field validation of CALMIM [independent of model development]:

(1) First project for California [2006-2010 project]: Seasonal campaigns at 2 California landfills over 2 years w/ additional data from 5 other California sites.

(2) Second CALMIM project [2011-2014 project]: Field measurements for 40 covers from 29 international sites in North & South America, Europe, Asia, Australia, and Africa:

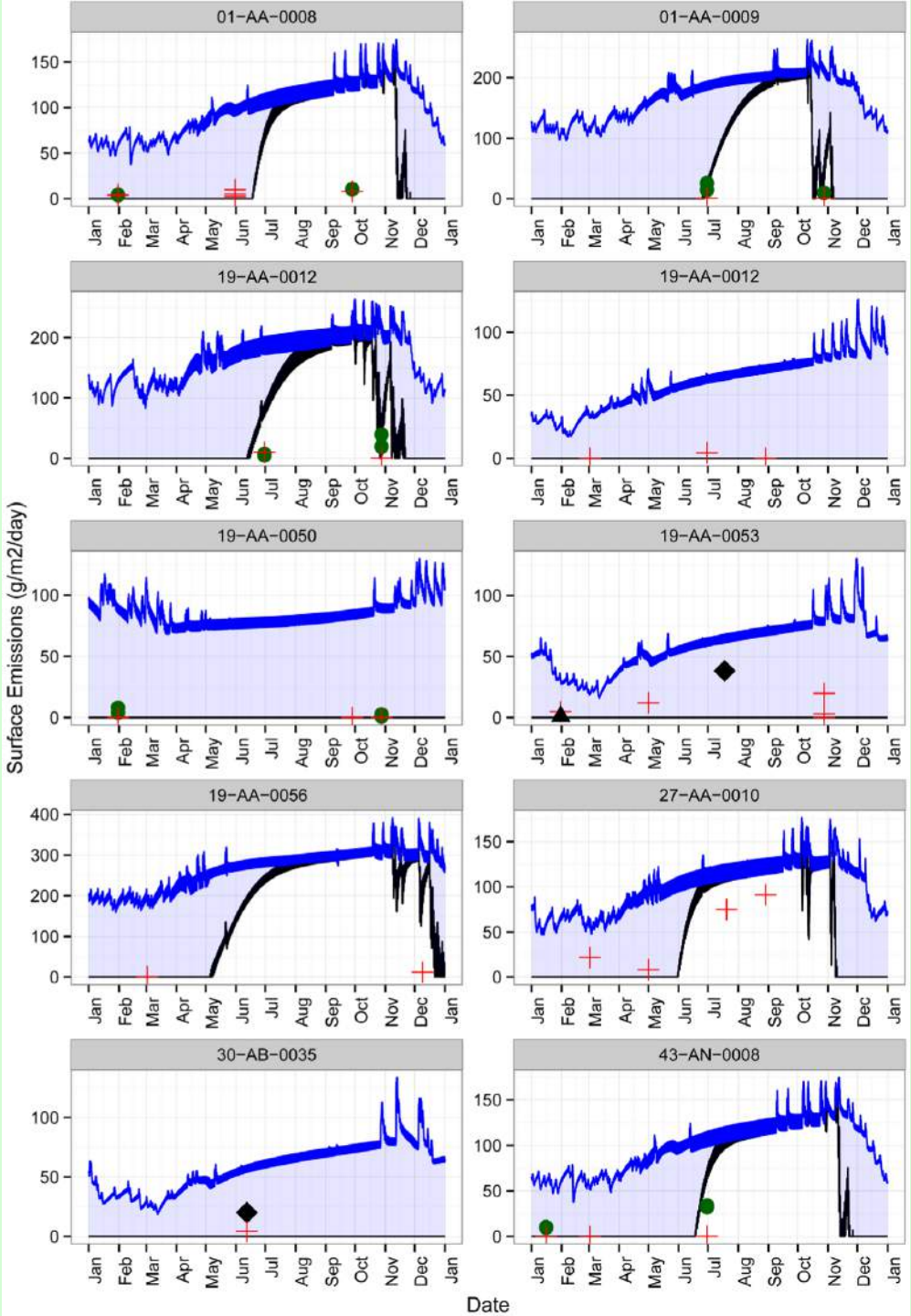


Comparison of CALMIM modeling to field measurements at 10 California landfills.

All units are in g CH_4 m^{-2} d^{-1}.
For CALMIM results, BLUE LINE = surface emissions without oxidation.
BLACK LINE = emissions with oxidation,
Region between is shaded in light blue.

Field results are plotted for the month of measurement with different symbols for different techniques:
Red plus sign indicates surface chambers (Spokas et al, 2011; Shan et al, 2012), black diamond/triangles indicate aircraft plume measurements (Peischl et al, 2013; Tratt et al, 2014; Turner et al, 2015), and the green circle indicates vertical radial plume mapping (Goldsmith et al, 2012).

(Spokas, Bogner, Corcoran, Walker, 2015)



HOW to USE CALMIM? ➔ 2 different modes

Annual GHG inventory [DEFAULT mode]:

Uses 30-year average climate data & default soil gas profiles for each cover type (daily, intermediate, final).

Uses a standardized reduction in soil gas CH_4 at base of each cover type relative to the extent of engineered gas recovery.

"CUSTOM ["Research mode"] applications:

- ✓ "What if"? modeling for alternative cover designs to minimize emissions.
- ✓ Scheduling of field campaigns to capture annual variability.
- ✓ Emissions along latitudinal gradients & for future climate change scenarios.
- ✓ Annual framework for research and field measurement applications.

Typically uses site-specific annual weather (daily min/max temp, daily pcp)

Typically uses site-specific soil gas profiles.

(1) <u>"Default Mode" example for annual GHG inventory:</u>
Re-did the 2010 California GHG inventory
using CALMIM, then compared results
to the 2010 California ARB
(Air Resources Board) inventory
using IPCC (2006)…

<u>CALMIM input data included:</u>

a) 2010 site-specific cover areas from CalRecycles
(California Dept. of Resources Recovery and Recycling,
Walker et al., 2012).

b) Most common 2010 California cover soils:

Daily Cover: 15 cm green waste

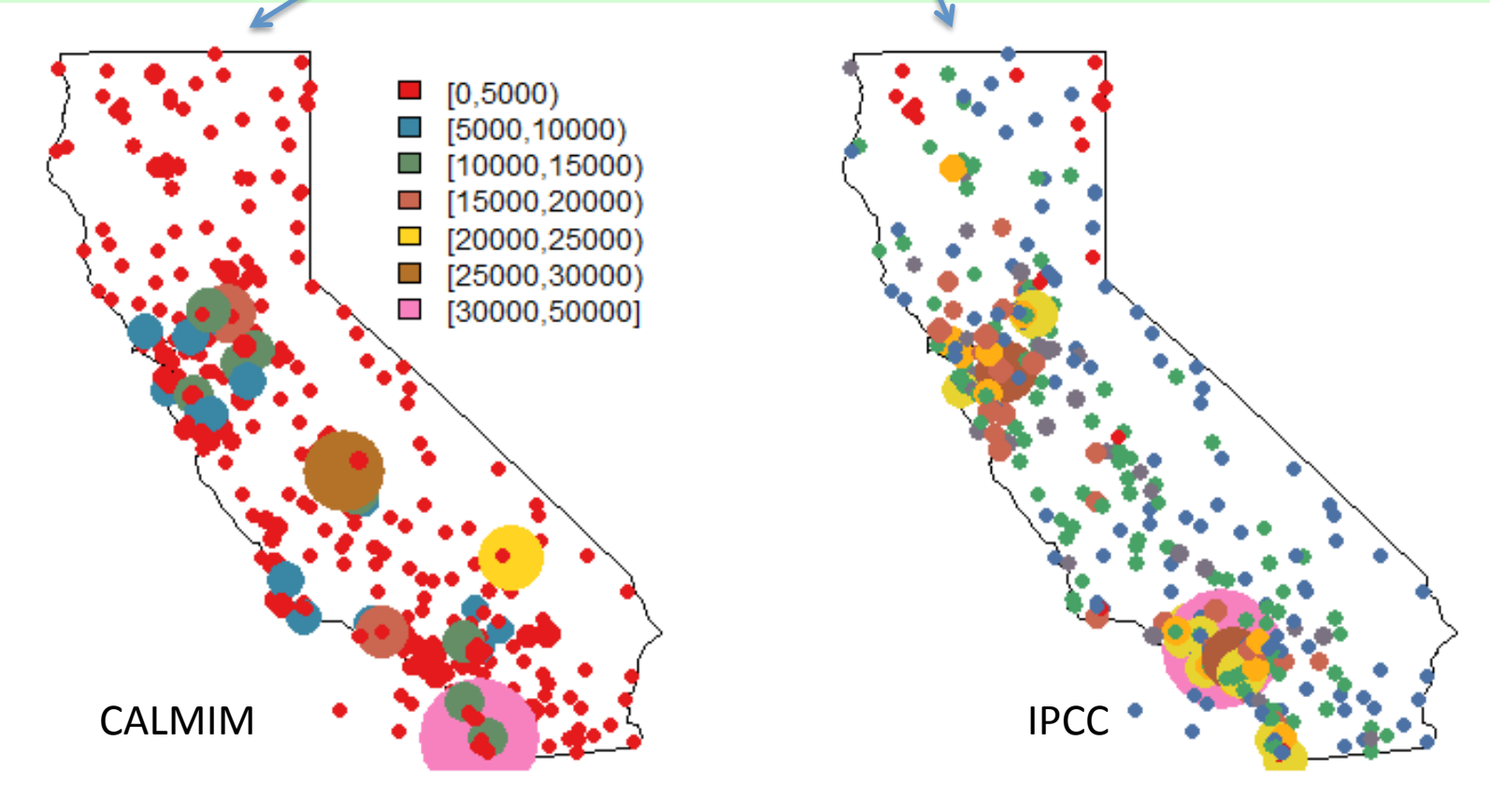
Intermediate Cover: 90 cm sandy loam

Final Cover: 30 cm loam/30 cm clay/60 cm silty clay loam

[California Code of Regulations/CCR Title 27]

Results: New 2010 California Inventory

using CALMIM 5.4 compared to ARB (using IPCC, 2006)



Annual state-wide total (Mg CH_4/year):

337,430 301,748

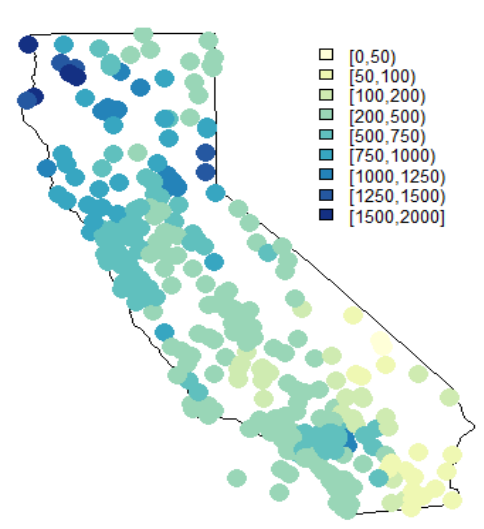
Similar totals but very different regional distribution

WHY?: Major differences between California inventories…

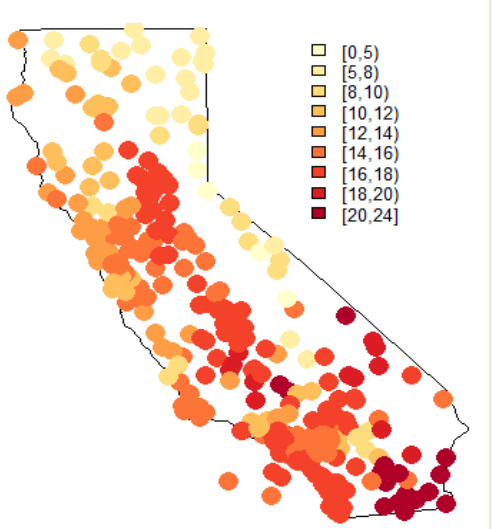
IPCC (2006): Highest-emitting sites correlated with sites containing largest mass of waste.

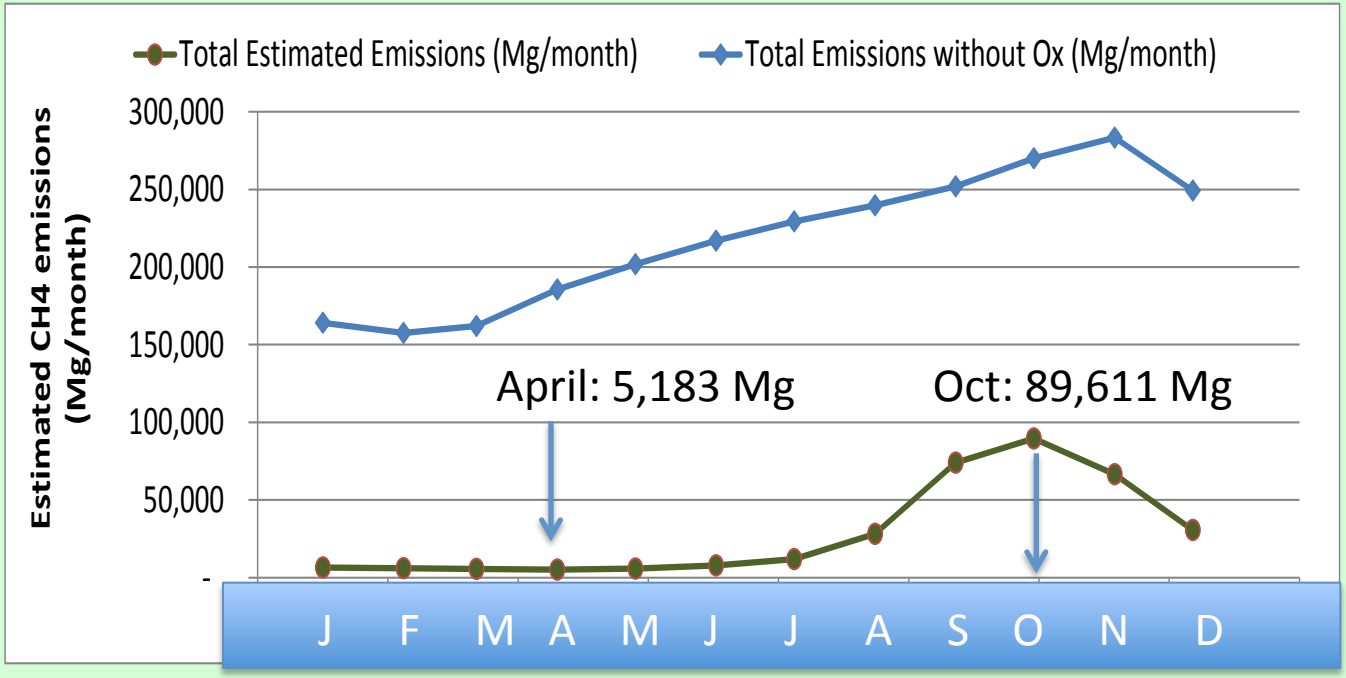
CALMIM inventory: Highest-emitting sites associated with large areas of thinner intermediate cover (96% of emissions) and low seasonal oxidation rates (too dry/hot) ➔ strong climate dependency:

mean annual precipitation (mm) at California landfills



mean annual temperature (deg. C) at California landfills





max/min:

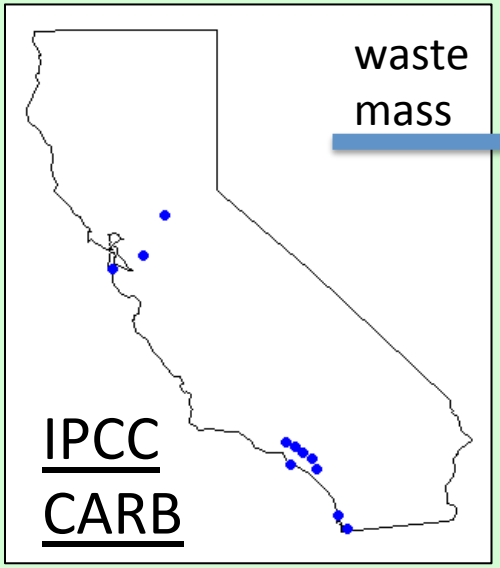
<u>w/o oxidation:</u>
<2–fold difference

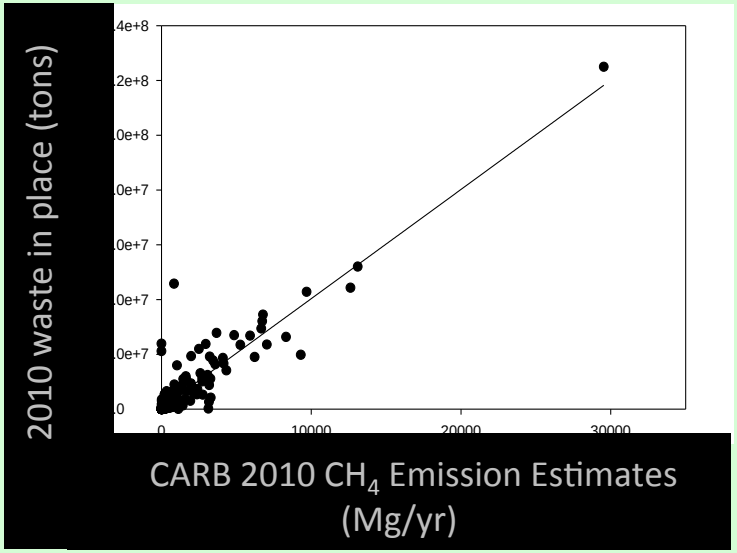
<u>w/oxidation:</u>
17–fold difference

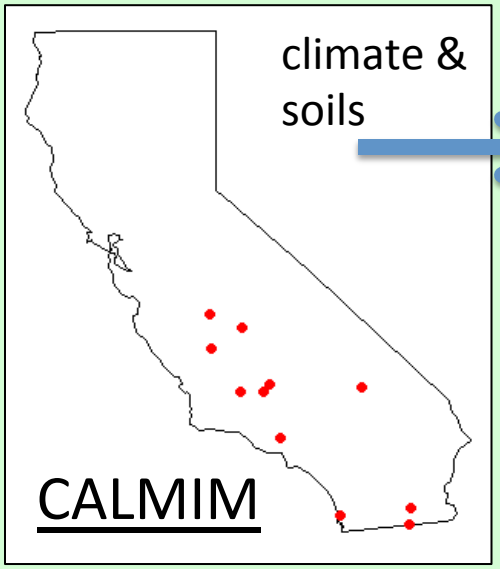
<u>Seasonality of monthly California emissions & oxidation [CALMIM]</u>

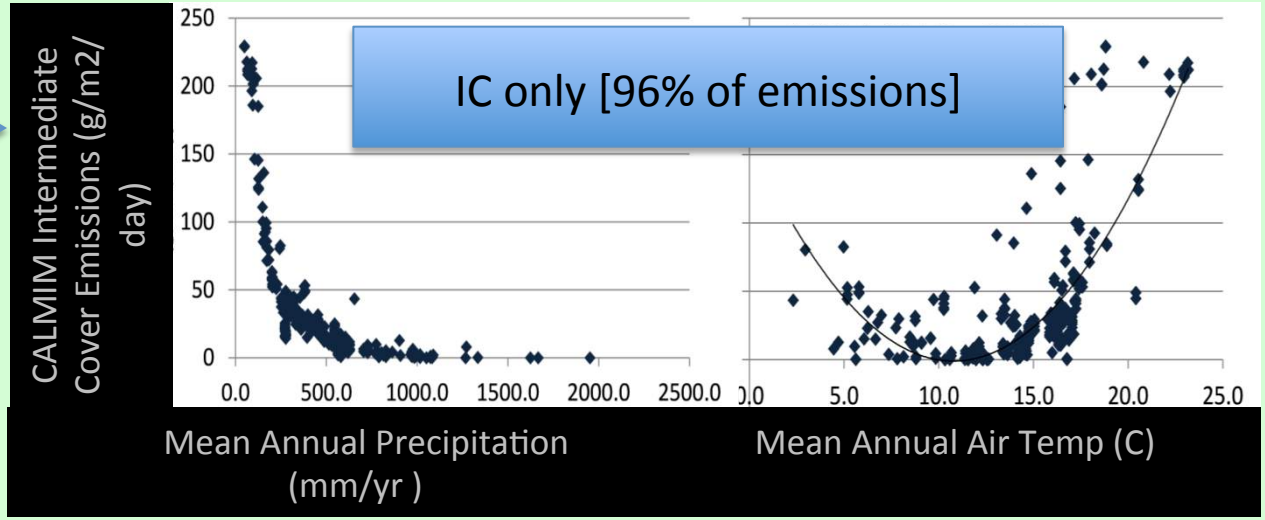
Different drivers for different methods

and the 11 highest emitting sites from each method:



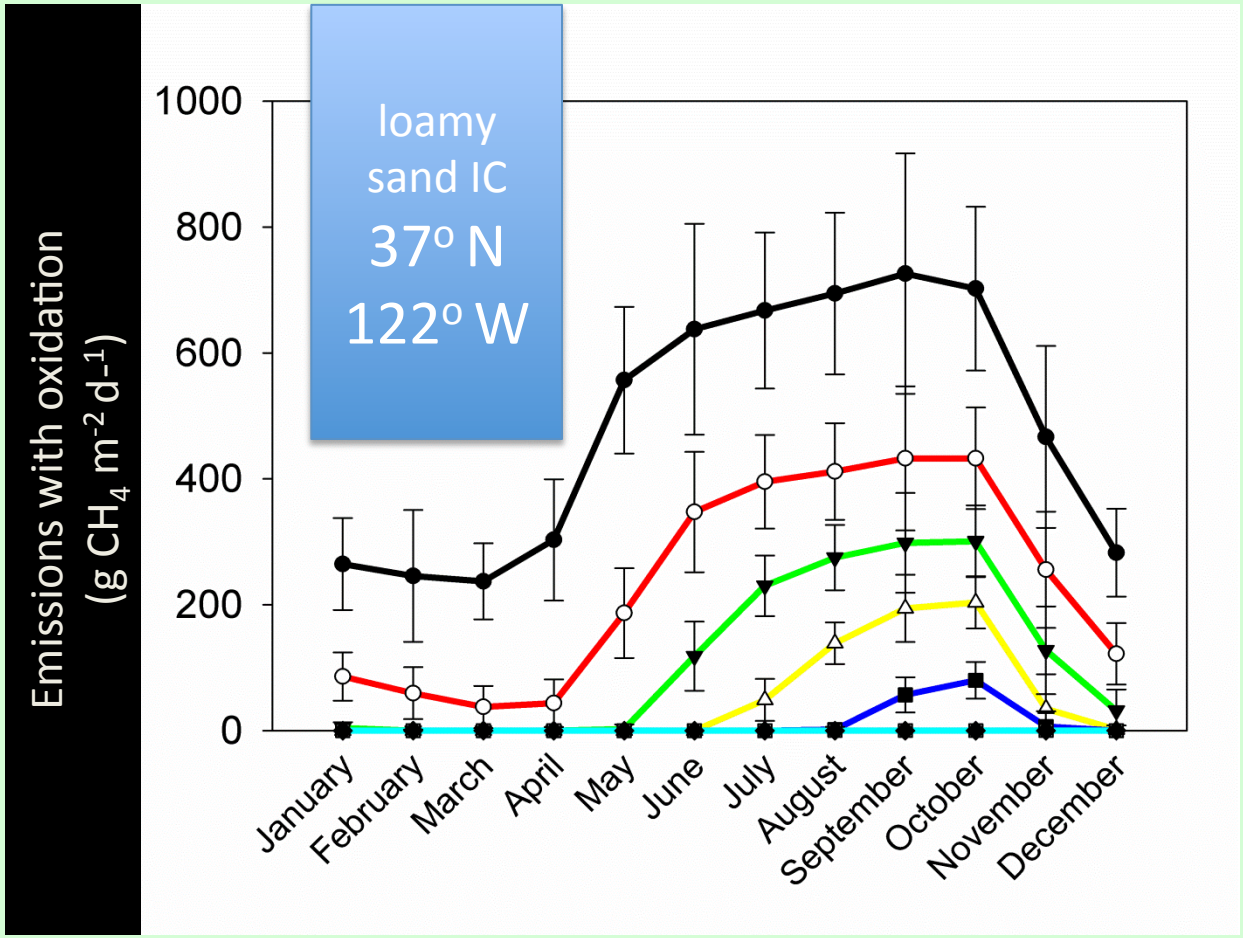






Custom CALMIM applications: "What if?" modeling of alternative soils & thicknesses.

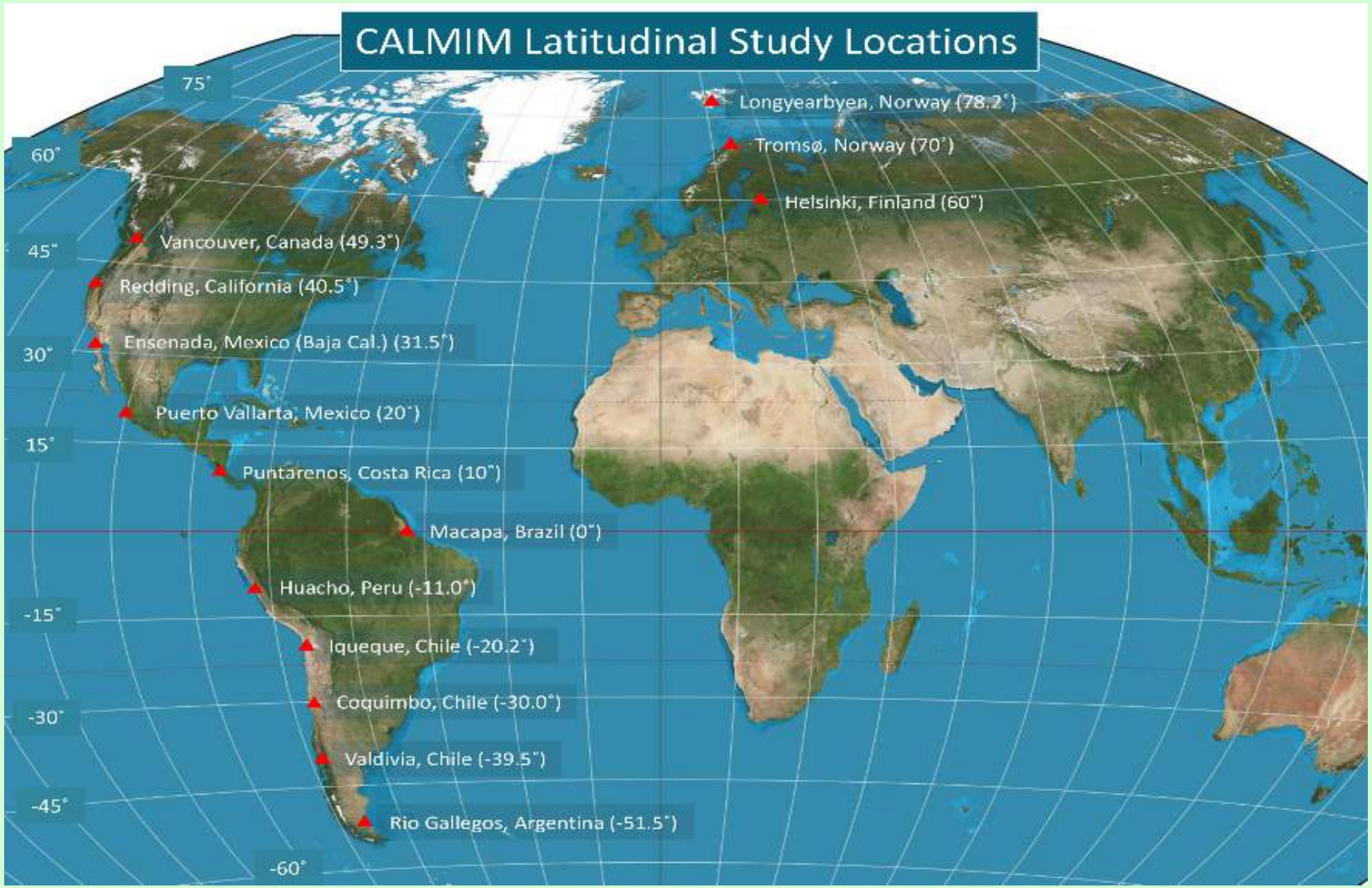
Below: emissions for range of cover thicknesses at specific site



black: 30 cm
orange: 45 cm
green: 60 cm
yellow: 75 cm
blue: 90 cm
turquoise: 120 cm

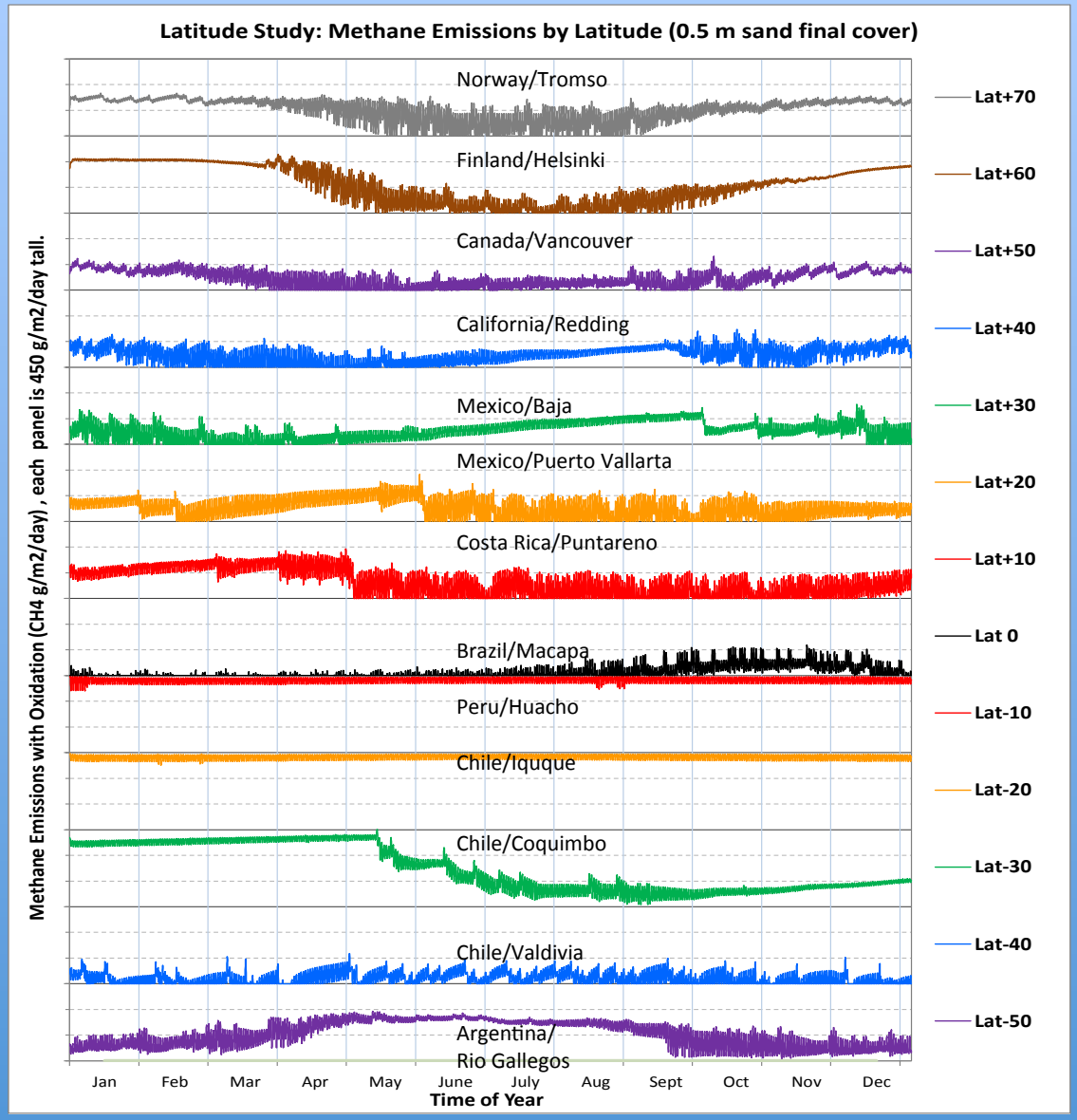
Note: negligible seasonal emissions with thicker covers.

Effect of Climate: Latitudinal Study

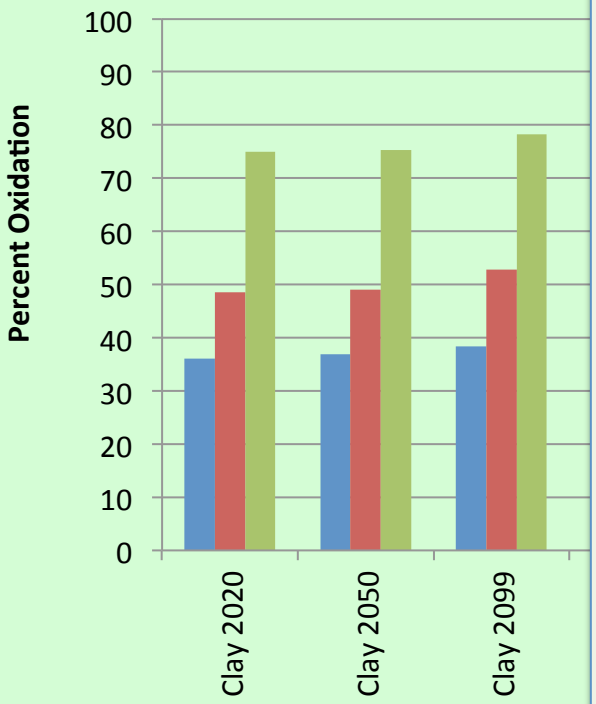


Latitudinal study using CALMIM assuming "minimum" final cover of 0.5 m sand

Latitudinal study for “minimum” 50 cm sand final cover: each site using same scale (0-450 g m^{-2} d^{-1}).



Simulation of emissions under future climate change scenarios at various latitudes…



Projection for increased % oxidation in clay final cover soil, Lulea, Sweden: 2020, 2050, 2099
due to warmer temperatures…
using SRES* B1 scenario.

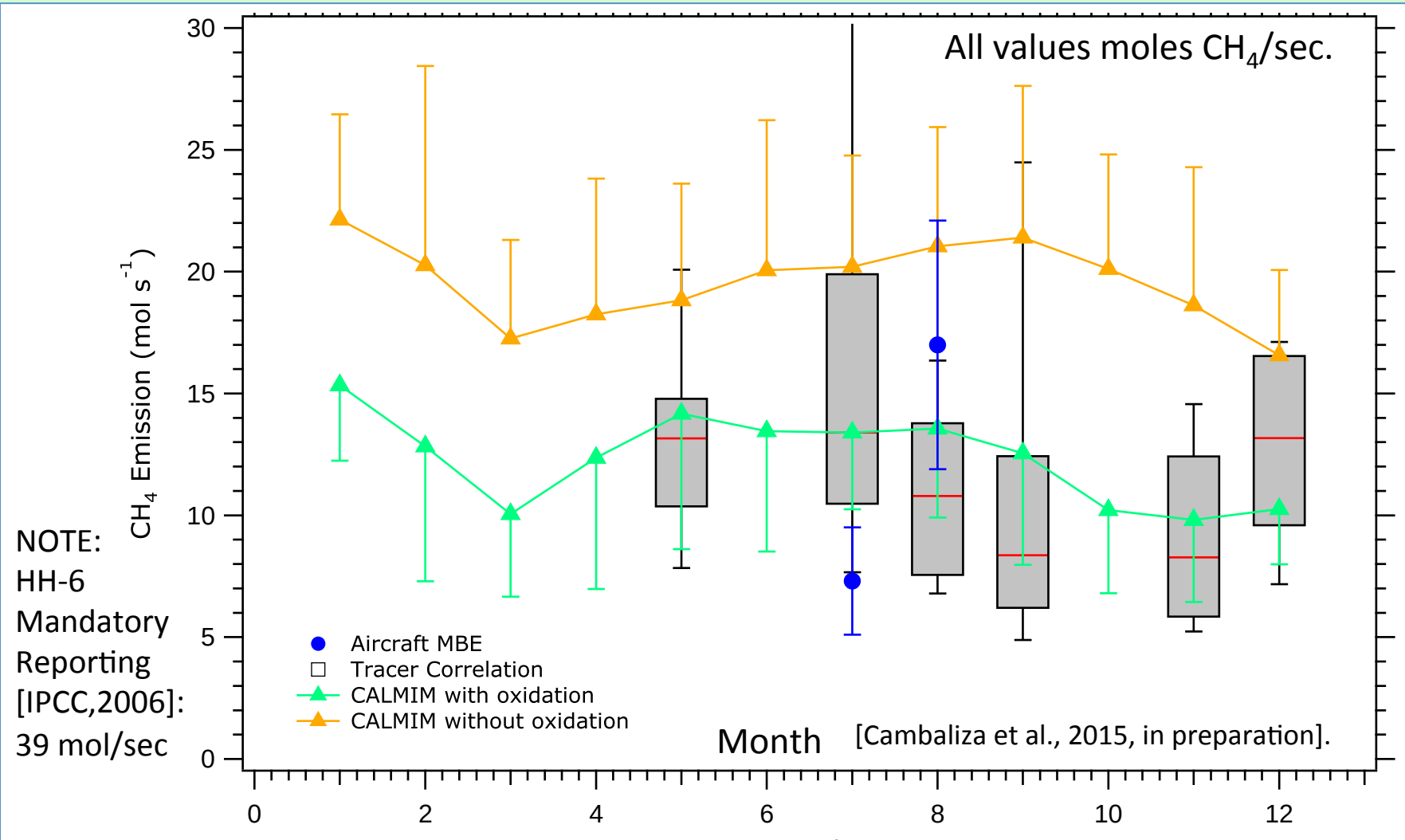
Cover thickness:
blue 25 cm
red 50 cm
green 100 cm

Bogner, Spokas, Corcoran, 2014

*IPCC, 2000, Special Report on Emission Scenarios

Annual "framework" for field measurements using "whole landfill" techniques—Indiana landfill.

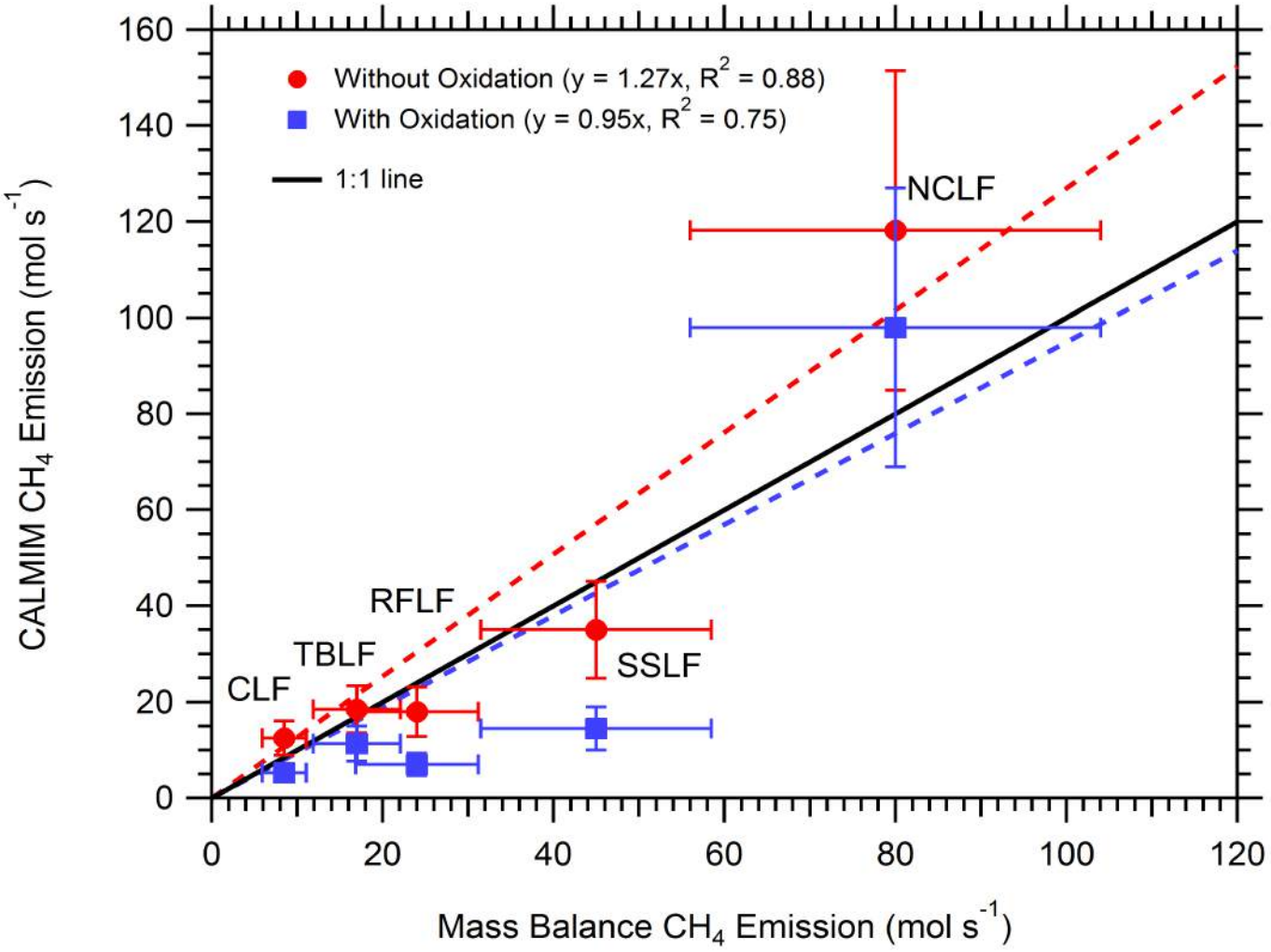
GREEN: CALMIM average monthly emissions w/ oxidation + SD; **YELLOW:** CALMIM without oxidation - SD ; **GRAY:** box & whisker plots for measured emissions in specific months using aircraft mass balance technique; **BLUE**: measured using tracer correlation approach.



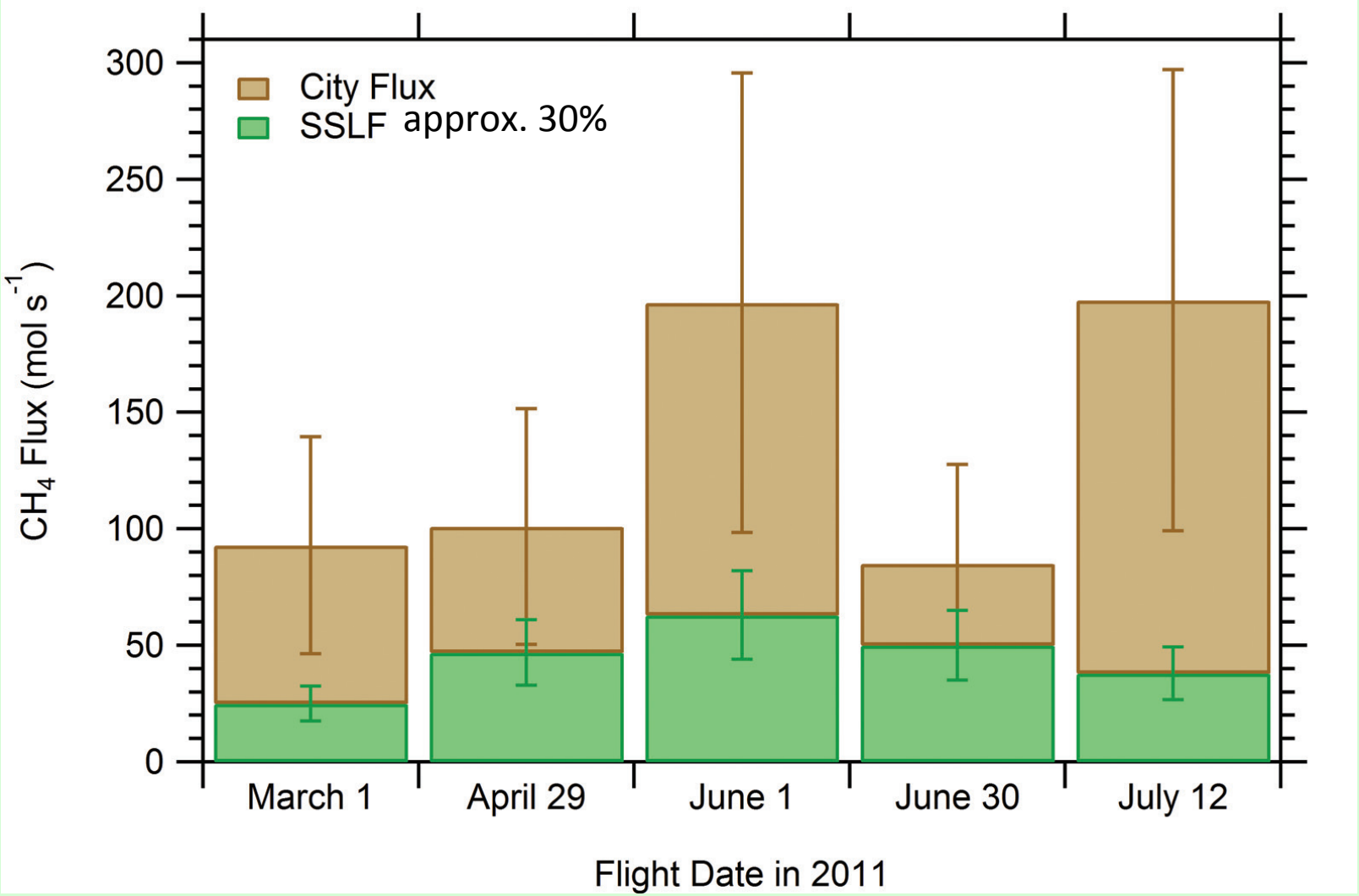
NOTE:
HH-6 Mandatory Reporting [IPCC,2006]: 39 mol/sec

Uncertainty comparisons-Modeling vs. Field measurements at 5 Indiana landfills: Least squares linear regression comparing CALMIM modeling [y-axis; Uncertainty = SD of monthly avg emissions, 10-min timesteps] to aircraft mass balance results [x-axis; uncertainty = ± 30%]. Units = mol CH_4 sec^{-1}

[Fig. 6, Cambaliza et al., 2015].

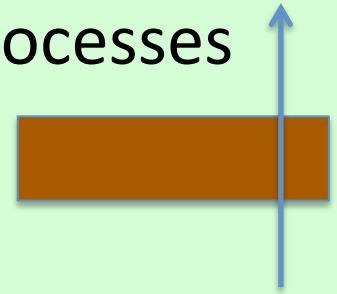


Indianapolis: **Southside Landfill emissions** as a fraction of total city CH_4 emissions for 5 aircraft mass-balance field campaigns in 2011 [Cambaliza et al., 2015]



To conclude:

- CALMIM is a science-based, field-validated, user-friendly inventory method focusing on the major processes which control landfill CH_4 emissions.



- Better numbers are needed…

…for GHG inventory & management decisions regarding landfill CH_4 emissions at a specific global location.

…to reduce uncertainties for urban, regional, and national CH_4 inventories.

Merci Beaucoup!

Project sponsors:

- Environmental Research & Education Foundation (EREF) 2011-2014
- California Energy Commission PIER Program 2006-2010

Also:

- California Dept. of Resources Recycling and Recovery (CallRecycle) & Air Resources Board (ARB)
- Los Angeles County Sanitation Districts
- Monterey Bay Regional Waste Management Authority
- J. Chanton (Florida State Univ.) & M. Cambaliza, P. Shepson (Purdue Univ.)
- Waste Management, Inc.
- USDA field and laboratory personnel, including C. Rollofson, M. duSaire, D. Peterson
- UIC students, including M. Corcoran, P. Roots, T. Badger, P. Pilosi

…And many field research groups who provided measurements of landfill CH_4 emissions…

Jean Bogner jbogner@uic.edu
Kurt Spokas kurt.spokas@ars.usda.gov

To download CALMIM: search ars.usda.gov for "CALMIM"

CALMIM—Selected Bibliography/journal articles & EREF final report:

Spokas, K., Bogner, J., Corcoran, M., and Walker, S. From California Dreaming to California Data: Challenging Historic Models for Landfill CH_4 emissions, Elementa: Science of the Anthropocene *[Elem. Sci. Anth.]* **3**: 000051 doi: 10.12952/journal.elementa.000051 (2015). Available at: *https://www.elementascience.org/articles/51/*

Cambaliza, M.O., Shepson, P.B., Bogner, J., Daulton, D., Stirm, B., Sweeney, C., Montzka, S., Gurney, K., Spokas, K., Salmon, O., Lavoie, T., Hendricks, A., Mays, K., Turnbull, J., Miller, B., Lauvaux, T., Davis, K., Karion, A., Moser, B., Miller, C., Obermeyer, C., Whetstone, J., Prasad, K., Crosson, E., Miles, N., and Richardson, S., Quantification and Source Apportionment of the Methane Emission Flux from the City of Indianapolis, Elementa: Science of the Anthropocene, 3:000037, doi: 10.12952 (2015). Available at: *https://www.elementascience.org/articles/37/*

Spokas, K., Bogner J., and Chanton, J., A Process-Based Inventory Model for Landfill CH_4 Emissions Inclusive of Soil Microclimate and Seasonal Methane Oxidation, J. Geophysical Research-Biogeosciences, 116: paper G04017, 19 p. (2011).

Bogner, J., Spokas, K., and Chanton, J., Seasonal Greenhouse Gas Emissions (methane, carbon dioxide, nitrous oxide) from Engineered Landfills: Daily, Intermediate, and Final California Landfill Cover Soils, J. Environ. Quality 40:1010-1020 (2011).

Spokas, K., and Bogner, J., Limits and dynamics of methane oxidation in landfill cover soils, Waste Management 31:823-832 (2011).

EREF final report: Bogner, J., Spokas, K., and Corcoran, M., **International Field Validation of CALMIM: A Site-Specific Process-Based Model for Landfill Methane (CH_4) Emissions Inclusive of Seasonal CH_4 Oxidation**. Final Report. 413 p. (2014). http://erefdn.org/index.php/grants/fundedresearchinfo/international_field_validation_of_a_new_ipcc_model_for_landfill_methane_emi/.