Trials and Tribulations of Measuring Greenhouse Gas (CO$_2$, CH$_4$, H$_2$O) Fluxes over a Drained Peatland

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Methane Flux Team

• Joe Verfaillie, technician
• Jaclyn Hatala, grad student
• Matteo Detto, former postdoc
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• Ben Runkle, former grad student
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• Yit Teh, former postdoc, UCB/St Andrews
• Frank Anderson, DWR/USGS
• Ted Hehn, former technician
Preamble

- Methane is an important greenhouse gas, less studied than CO₂
- Sac/SJ Delta is an important ecosystem, lynchpin to California, and Potential Methane Source
  - Vulnerable, Subsiding and Unsustainable Ecosystem, Replete with Wetlands
  - Ecosystem Restoration is needed, but could come at the Unanticipated and Unexpected cost of Elevated Methane Emissions
  - I grew-up in the Delta and am interested in Studying its Biogeochemistry
- New generation of chemical sensors, e.g Tunable diode laser spectrometers, enable continuous measurements of methane and methane fluxes with eddy covariance
- Sac/SJ Delta is a Perfect site for Eddy Covariance Flux Measurements
  - fetch is extensive (kilometers), site is flat, winds are steady, strong winds and generally from the west, site is close to Berkeley for ready access and frequent study and servicing
- Complications:
  - TDLs and large pumps require ample AC power (1000W), restricting site selection
  - Methane production is microbial, so it is not ‘well-mixed’ and ‘uniform’ like CO₂ exchange which is dominated by wide-spread plants with similar physiology.
  - Flux Variability can exceed 3 orders of Magnitude within meters
  - Advection may occur from upwind, wetland complex
  - Boundary Layer Dynamics modulate Boundary Layer Depth and Elongation of Flux Footprint
  - Cows grazing on a pasture produce a large amount of methane
Contemporary Record in Methane, CH₄

- **Sources:** fermentation by methanogenic archaea in anaerobic environments
  - Cows
  - Termites
  - Rice
  - Wetlands
- **Sinks:** Oxidation by OH by aerobic soils

NASA Giss

ESPM 2, The Biosphere
Routes for Methane Production/Transport in a Wetland

Fluxes, Sources and Sinks of Methane

Air, O2

Xylem Transport

CH₄

Air-Water Exchange

Ebullition

CO₂

Anoxic Sediments

Oxidation: Methanotrophic Bacteria

Anaerobic Methanogenic Archaea
Methane Flux Measurements

Closed Chambers

Eddy Covariance

Auto Chambers
Histogram of Published Methane Fluxes

50% of Fluxes < 32 nmol m\(^{-2}\) s\(^{-1}\), but fluxes up to 600 nmol m\(^{-2}\) s\(^{-1}\) are possible.
Potential for Quasi-Continuous, Year-Round Methane Fluxes, via Eddy Covariance Fluxes

Fig. 3. Annual cycle of measured half-hourly methane fluxes. Positive sign indicates upward flux, i.e. emission from the fen.

Rinne et al, 2007 Tellus
Deltas Are Sinking, World-Wide

Syvitski et al. Nature Geoscience, 2009
San Francisco Bay-Sacramento/San Joaquin Delta Region
Delta Peatland is Indeed Subsiding!
Vulnerable Ecosystem via Severe Land Subsidence

Figure 2. Conceptual diagram illustrating evolution of Delta islands due to levee construction and island subsidence. Modified from Ingebritsen et al. (2000).
New Plans to Reverse Subsidence with Carbon Farming of Restored Tule Wetlands and Rice on Twitchell and Sherman Islands

What are the: Cost/Benefits?; Unintended Consequences?
Over-Arching Research Questions

• How Large are Methane Effluxes from Managed Peatlands on daily, seasonal, annual and inter-annual time scales?
• What is the Range of Methane Fluxes across Land Use Classes (drained peatlands, restored wetlands, crops, tidal marshlands) of the Delta?
• How Does Management for Carbon Sequestration affect Methane and Water Loss?
Delta Field Sites

Legend
- Micrometeorological tower
- Legal_Delta

Land use and land cover
- Water
- Urban
- Mixed Agriculture/Native Classes
- Mixed Agriculture/Urban

Delta Vision (http://deltavision.ca.gov/)
Ideal Micrometeorological Site:
Flat, with Extensive Fetch and Brisk Steady Winds from a Predominant Direction
Eddy Covariance,
Flux Density: mol m\(^{-2}\) s\(^{-1}\) or J m\(^{-2}\) s\(^{-1}\)

\[ F = \rho_a \, w \, s \sim \rho_a \cdot w' \, s' \]

\[ s = \left( \frac{\rho_c}{\rho_a} \right) \]
Eddy Covariance

- Direct Measure of the Trace Gas Flux Density between the atmosphere and biosphere, mole m^{-2} s^{-1}
- *In situ*
- Quasi-continuous
- Integrative of a Broad Area, 100s m^2
- Introduces No artifacts, like chambers
Eddy Covariance Tower
Sonic Anemometer, CO2/H2O IRGA,
inlet for CH4 Tunable diode laser spectrometer &
Meteorological Sensors
Drained Peatland Pasture, vegetated with Pepperweed, an invasive weed, 2007-present
Measuring Methane with Off-Axis Infrared Laser Spectrometer

Closed path
Moderate Cell Volume, 400 cc
Long path length, kilometers
High power Use:
Sensor, 80 W
Pump, 1000 W; 30-50 lpm
Low noise: 1 ppb at 1 Hz
Stable Calibration

Los Gatos Research
Complex Greenhouse Gas Site with Lots of Spatial Heterogeneity of Sources

Site Classes:
5% Ditches
22% Periodically Flooded
73% Drained
~ 100 Cows

Teh et al, Ecosystems, 2011
Even Over Perfect Flat Sites with Extensive Fetch
Advection can/does Occur with Methane:

Source Strength of Hot spots and Cold Spots can Differ by 1 to 2 orders of Magnitude (10x to 100x)

Such Advection is Less Pronounced for Water Vapor and CO₂ Fluxes Because Flux Differences Emanating from the Different Land Forms are Smaller
Results
Time Series at 10 Hz and 24 Hours

- CH₄ (ppm)
- CO₂ (mMol m⁻³)
- H₂O (mm)
- W (m/s)
Spectral Performance of Gas Sensors

Detto et al., AgForestMet, submitted
Zero-Flux Detection Limit, Detecting Signal from Noise

\[ F = w' c' \approx r_{wc} \sigma_w \sigma_c \]

- \( r_{wc} \approx 0.5 \)
- \( \sigma_{ch4} \approx 0.84 \text{ ppb @ 1 Hz sampling rate} \)
- \( \sigma_{co2} \approx 0.11 \text{ ppm} \)

<table>
<thead>
<tr>
<th>U* (m/s)</th>
<th>( \sigma_w ) (m/s)</th>
<th>( F_{min, \text{CH}_4} ) (nmol m(^{-2}) s(^{-1}))</th>
<th>( F_{min, \text{CO}_2} ) ((\mu\text{mol m}^{-2}) s(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>0.125</td>
<td>2.1</td>
<td>0.275</td>
</tr>
<tr>
<td>0.2</td>
<td>0.25</td>
<td>4.2</td>
<td>0.55</td>
</tr>
<tr>
<td>0.3</td>
<td>0.375</td>
<td>6.3</td>
<td>0.825</td>
</tr>
<tr>
<td>0.4</td>
<td>0.5</td>
<td>8.4</td>
<td>1.1</td>
</tr>
<tr>
<td>0.5</td>
<td>0.625</td>
<td>10.5</td>
<td>1.375</td>
</tr>
</tbody>
</table>

Methane Lab Calibration
Flux Detection Limit, based on 95% CI that correlation between W and C that is non-zero

0.035 mmol m\(^{-2}\) s\(^{-1}\), 0.31 μmol m\(^{-2}\) s\(^{-1}\) and 3.78 nmol m\(^{-2}\) s\(^{-1}\) for water vapour, carbon dioxide and methane flux,

Detto et al, AgForestMet, submitted
3 Years of Methane Flux Data from Sherman Island

Baldocchi et al AgForMet, in press
Methane Concentrations Experience Nocturnal Maximum

Boundary Layer Rectifier Effect?

Baldocchi et al AgForMet, in press
Emerging Mystery:

Strong, Unexpected Diurnal Pattern in Methane Efflux with a Nocturnal Efflux Maximum...

Baldocchi et al AgForMet, in press
No Diurnal Trend of Methane Efflux over sub-Arctic Peatland
Why are Large Methane Concentrations and Fluxes Observed at Night?

- **Microbial Mechanism:** ??
  - Temperature is cooler at night
  - Not observed in Literature, Nor at the Rice site
- **Tides Modulate Wetlands and Water table:** ??
  - Not always at night
  - Tidal Marsh too far upwind ??
  - Peatland is drained & water table fluctuations are weak
- **Advection:** ??
  - Collapse of the Convective Boundary Layer can increase [CH$_4$]
  - Wetlands are upwind and Maybe huge Sources of Methane ??
  - Elongation of Flux and Concentration Footprint can occur at Night under Stable Stratification
- **Cows:** ??
  - 100 cows over 38 ha
  - Strong source of methane
What to Do?; What to Believe?

• Measure Methane Flux over Rice, a known, uniform methane source, downwind 10 km
• Bound Problem and Check Advection with
  – PBL Box Model and Flux Footprint Model
  – Flux Divergence Studies
• Commando Field Campaigns to Measure Methane Effluxes from the Marshlands upwind of the Site
• Measure Methane Fluxes of Tidal Marshland Upwind on the Levee
  – Site not secure, power limited, 2\textsuperscript{nd} methane sensor not available
• Use Web Cam and Watch and Count Cows
Eddy Flux System at Rice
Rice Does Not Exhibit Diurnal Pattern in Methane Efflux; Fetch is Uniform and Extensive

Rice Experiences Strong diurnal Pattern in Methane Concentration

Baldocchi et al AgForMet, in press
Is the Tule Wetland, Upwind of Sherman Island, a Large CH4 source?
Observed increase in [CH4] after Sunset is too fast to be explained by the PBL Box, which infers a complex source due to wetlands, wet fields and ditches.
Elevated [CH4] (> 2500 ppb) corresponds with Low Boundary Layers (< 200 m) and High Effluxes (50 to 250 nmol m⁻² s⁻¹).

Figure 5 Computation of CH₄ concentrations using a one-dimensional box model for a stable and steady nocturnal boundary layer. The figure is plotted as a function of flux density ($F_{CH4}$, nmol m⁻² s⁻¹) and height of the planetary boundary layer. The color contours represent methane concentration. These computations were derived after a time integral of 10 hours.
Commando Raids into the Tules with Methane Flux Chambers!
Pilot Study on Sherman Lake

- Average CH$_4$ fluxes for the flooded site were 6381 nmol m$^{-2}$ s$^{-1}$ and peak rates exceeded 13000 nmol m$^{-2}$ s$^{-1}$

- At flooded site, the presence or absence of vegetation in the chamber footprint didn't seem to have a significant effect of CH4 emissions

- Average CH$_4$ fluxes for the drier site were on the order of 10 nmol/m2/s
Daytime Footprint, drained ditches and paddock
Night Footprint, wetter fields and ditches

Night-time Flux Footprint Does Not Extend to the Wetlands
Chamber Fluxes Across Landscape Features
Ditches, upland hummocks, wet areas
Chamber Fluxes by Land Form
Mean Methane Fluxes vary by 2 orders of Magnitude,
Extremes by 3 orders of Magnitude

Teh et al, Ecosystems, 2011
Sniff Methane from the Levee, Upwind from Cows, Downwind from the Wetland
Natural Tule Wetland, upwind of Paddock, Does NOT experience diurnal pattern in methane Efflux

Natural Tule Wetland, upwind of Paddock, Experiences lower methane concentrations than grazed paddock, downwind, and No Diurnal Variation

Baldocchi et al AgForMet, in press
Are Pheasants and Cows Releasing Methane in the Near Field?
24 Hour Time Series of 10 Hz Data, Vertical Velocity (w) and Methane (CH$_4$) Concentration

Sherman Island, CA: data of Detto and Baldocchi
Cows and Methane emissions

10 to 30 mol/cow/day is reasonable bound for a number of studies

100 cows over 0.38 km² and 24*3600 s

Bounded flux density averaged over landscape

\[ 10 \times \frac{100}{(380000 \times 24 \times 60 \times 60)} = 30 \text{ nmol m}^{-2} \text{ s}^{-1} \]
\[ 30 \times \frac{100}{(380000 \times 24 \times 60 \times 60)} = 90 \text{ nmol m}^{-2} \text{ s}^{-1} \]
Cow Cam

Oliver Sonnentag, analyst
The Wonders of MatLab and Inspecting Raw Data
Cows, Near-Field Diffusion and CH₄ Spikes

![Graph of CH₄ (PPM) vs. hour of day]

- CH₄ (PPM) values range from 2.0 to 3.5.
- The graph shows spikes in CH₄ concentrations at certain hours.
- The hours of data collection are highlighted in red boxes.

### Data Collection Times
- 8:15
- 8:45
- 9:15
- 9:45
- 10:15
- 10:45
- 11:15
- 11:45
- 12:15
- 12:45
- 13:15
- 13:45
- 14:15
- 14:45
- 15:15
- 15:45
- 16:15
- 16:45
Jan 5, 2010

**Methane (ppb), 10 s average**

- **Time, hours:** 0 4 8 12 16 20 24
- **Methane (ppb):**
  - **x-axis:** 2000 to 4000
  - **y-axis:** 0 to 4000

**[w\(\text{CH}_4\)] (nmol m\(^{-2}\) s\(^{-1}\))**

- **Time, hours:** 0 4 8 12 16 20 24
- **[w\(\text{CH}_4\)] (nmol m\(^{-2}\) s\(^{-1}\)):**
  - **x-axis:** -200 to 200
Cow-Cam Climatology

Oliver Sonnentag, analyst
Diurnal Variation in Cow-Cam Index

Sherman Island, Westerly Winds

![Graph showing diurnal variation in cow-cam index.]

- **Day > 100 and Day < 300**
- **Day < 100 or Day > 300**

The graph illustrates the diurnal variation in cow-cam index for Sherman Island under Westerly Winds. The data is grouped into two categories based on day range, showing distinct patterns throughout the day.
Night-time Maximum in CH4 Flux Persists with No Cows in Fetch

Peatland Pasture, No Cows, West Winds
## Annual Budgets of Methane Efflux

<table>
<thead>
<tr>
<th></th>
<th>Variable footprint</th>
<th>Small footprint</th>
<th>Large footprint</th>
<th>Large-small footprint: flooded portion of the field</th>
<th>Small footprint: Dry portion of the field</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Day and Night, with cows</strong></td>
<td>8.66 +/- 6.65</td>
<td>4.2 +/- 1.93</td>
<td>13.1 +/- 6.67</td>
<td>8.77</td>
<td>2.68 +/- 1.42</td>
</tr>
<tr>
<td><strong>gC m⁻² y⁻¹</strong></td>
<td></td>
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<tr>
<td><strong>mol m⁻² y⁻¹</strong></td>
<td>0.721 +/- 0.554</td>
<td>0.353 +/- 0.161</td>
<td>1.08 +/- 0.556</td>
<td>0.73</td>
<td>0.223 +/- 0.119</td>
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Interim Summary

• Elevated Methane Effluxes at night are Real, but Distinct from the Drained Footprint of the paddock observed during the Day

• Elevated Nocturnal Effluxes Represent a combination of methane emitted by cows, ditches and wet portions of the field
  – But not the wetland complex upwind of the site
  • Too far away..
Drained Peatland Pastures are Huge Sources of CO2 as they continue to Subside.

CO2 efflux at night from Peatland pasture

CO2 efflux [µmol m⁻² s⁻¹]

day after Jan 2007
Strong CO2 emissions, supporting mechanism for soil subsidence
Weak methane fluxes, methane produced at the water table is oxidized as it diffuses through the soil
Twitchell Island Rice
CO₂: Pasture vs Rice

Sherman Island pasture daily CO₂ fluxes

Twitchell Island rice paddy daily CO₂ fluxes

Hatala, Baldocchi, Detto and Verfaillie, unpublished
CO$_2$: Annual budgets

Hatala and Baldocchi

<table>
<thead>
<tr>
<th></th>
<th>2009</th>
<th>2010</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pasture</td>
<td>+308 g-C m$^{-2}$</td>
<td>+50 g-C m$^{-2}$</td>
</tr>
<tr>
<td>Rice paddy</td>
<td>-412 g-C m$^{-2}$</td>
<td>-316 g-C m$^{-2}$</td>
</tr>
</tbody>
</table>
New Licor 7700 Open Path Methane Spectrometer:
Low Power, NO PUMPS
New Studies, Off the Grid!

Restored Wetland, Mayberry Ranch on Sherman Island
Conclusion

• Measuring Methane Fluxes Is Much Harder and More Complex than measuring CO2 and Water Fluxes
• Be Patient, Persistent and Adaptable
• Conduct Numerous Scoping Studies to Identify Artifacts, especially if Site is Non-Ideal, which most Are.

• Planting Rice may be a Viable strategy for Stopping or Reversing Subsidence; but it has the cost of water use and methane production
Phenology of Invasive Pepperweed

Sonnentag et al, AgForestMet, submitted
Fluxes: daily averaged

- $H_2O$ fluxes (mmol/m²/s)
- $CO_2$ fluxes ($\mu$mol/m²/s)
- $CH_4$ fluxes (nmol/m²/s)

Day of the year 2009