Trials and Tribulations of Measuring Greenhouse Gas (CO_2, CH_4, H_2O) Fluxes over a Drained Peatland

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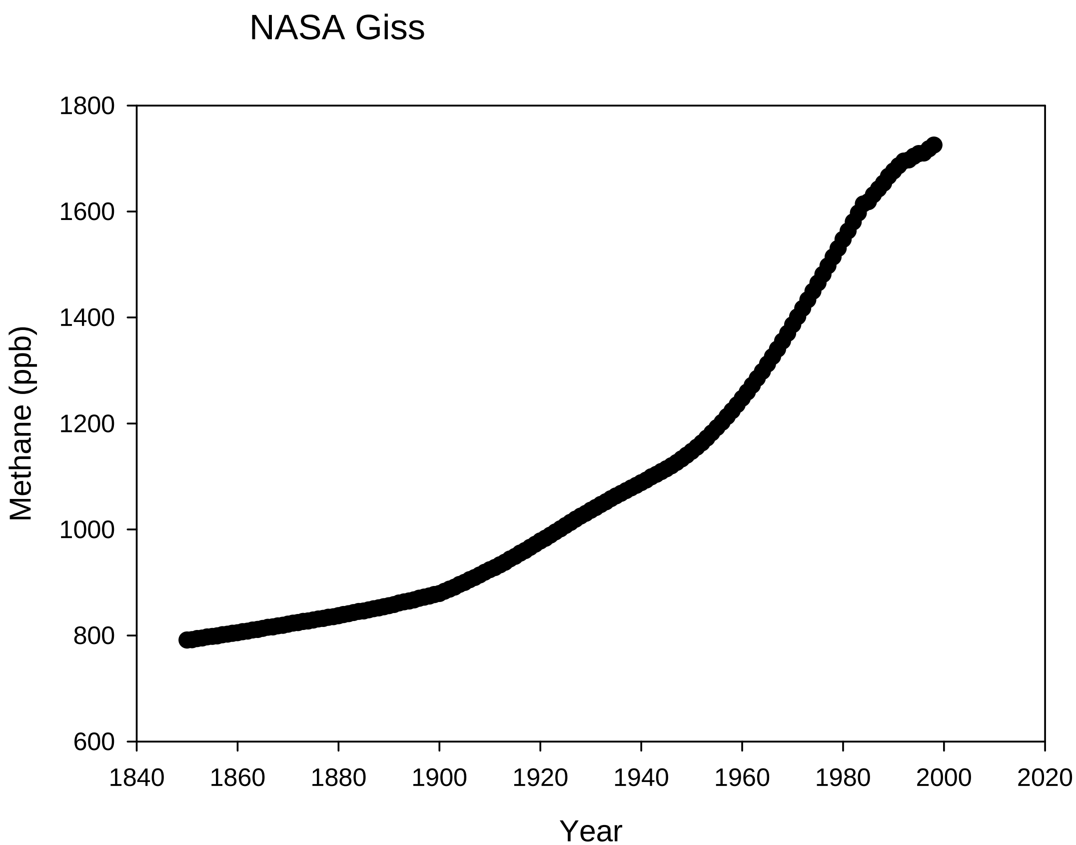
Methane Flux Team

- Joe Verfaillie, technician
- Jaclyn Hatala, grad student
- Matteo Detto, former postdoc
- Oliver Sonnentag, former postdoc
- Ben Runkle, former grad student
- Whendee Silver, UCB Prof
- Maggie Kelly, UCB Prof
- Yit Teh, former postoc, UCB/St Andrews
- Frank Anderson, DWR/USGS
- Ted Hehn, former technician

Preamble

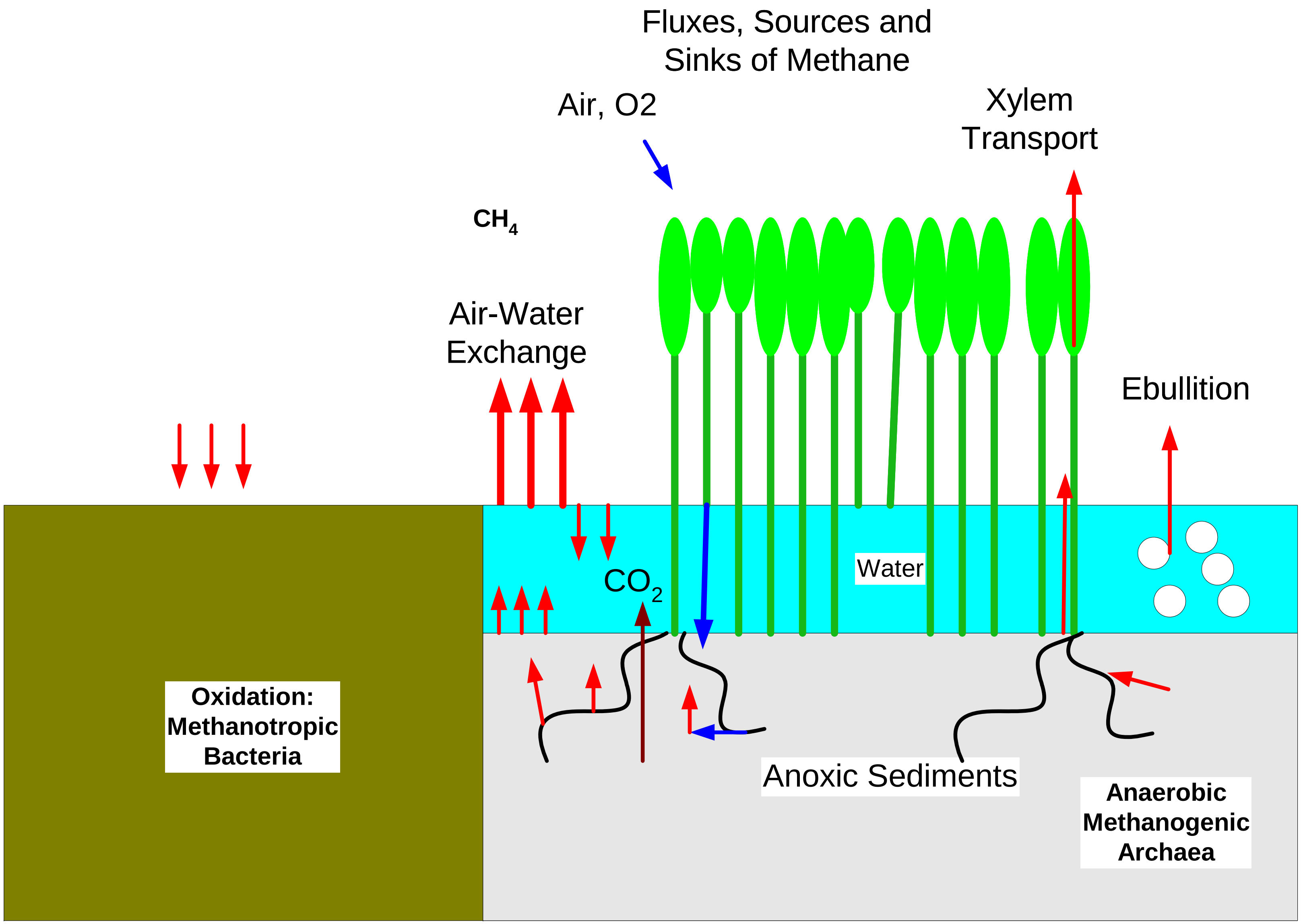
- Methane is an important greenhouse gas, less studied than CO_2
- Sac/SJ Delta is an important ecosystem, lynchpin to California, and Potential Methane Source
  - Vulnerable, Subsiding and Unsustainable Ecosystem, Replete with Wetlands
  - Ecosystem Restoration is needed, but could come at the Unanticipated 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, CH_4



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

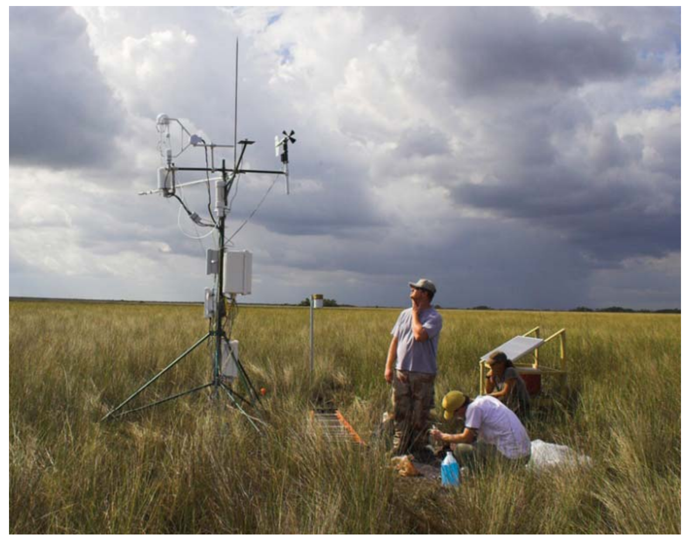
Routes for Methane Production/Transport in a Wetland



Methane Flux Measurements

Closed Chambers

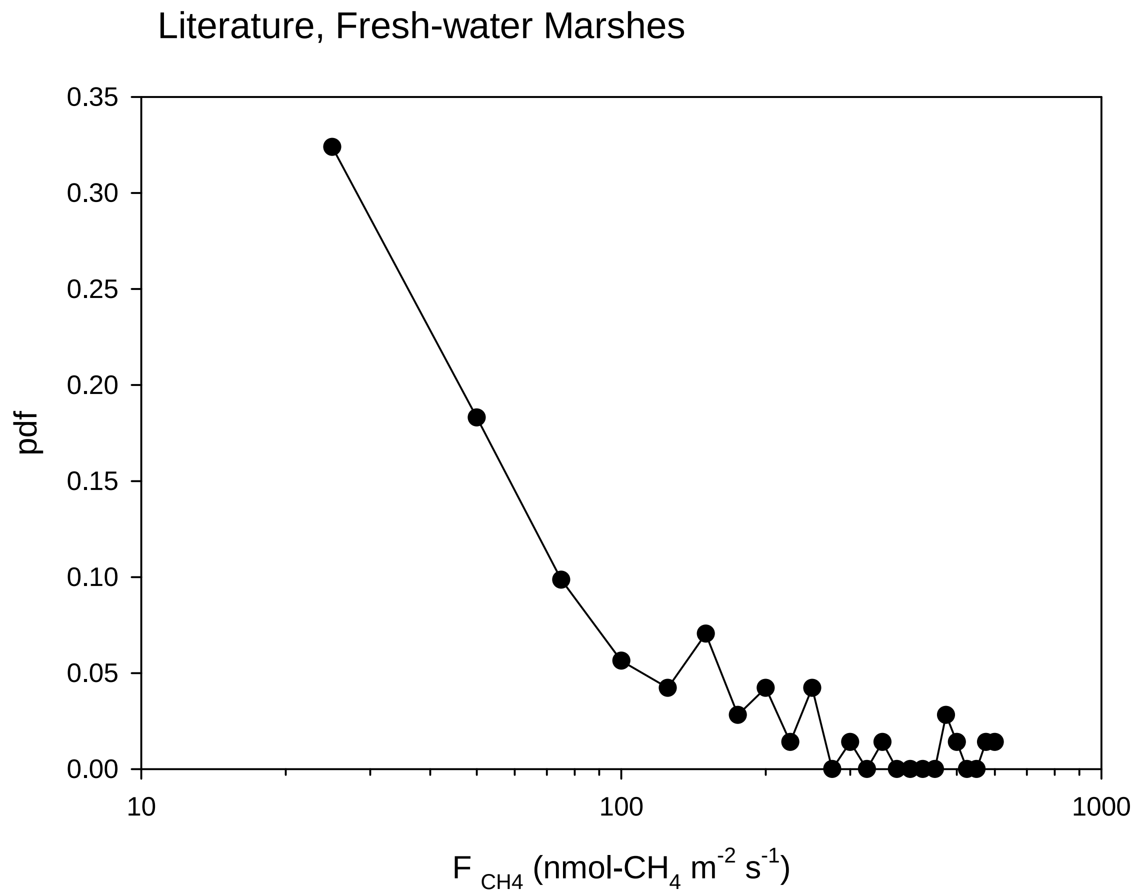
Eddy Covariance



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

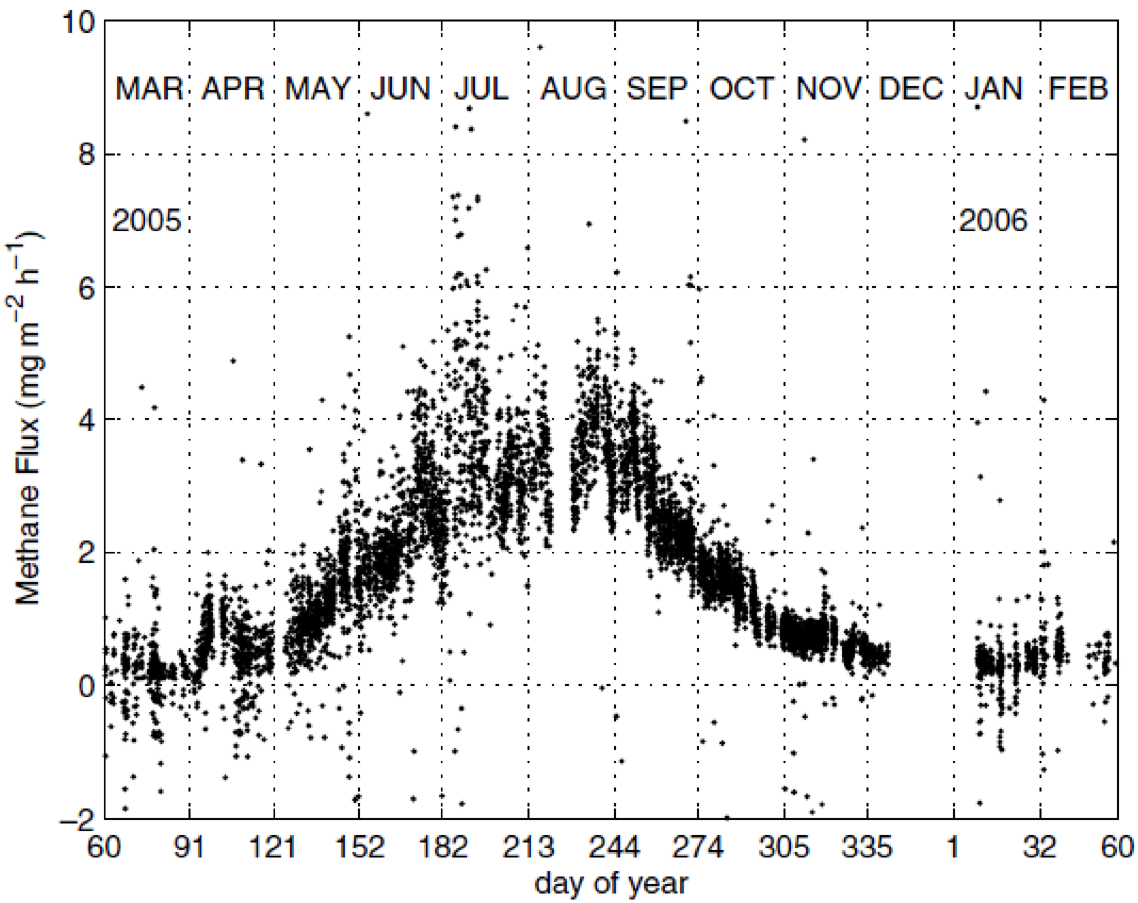
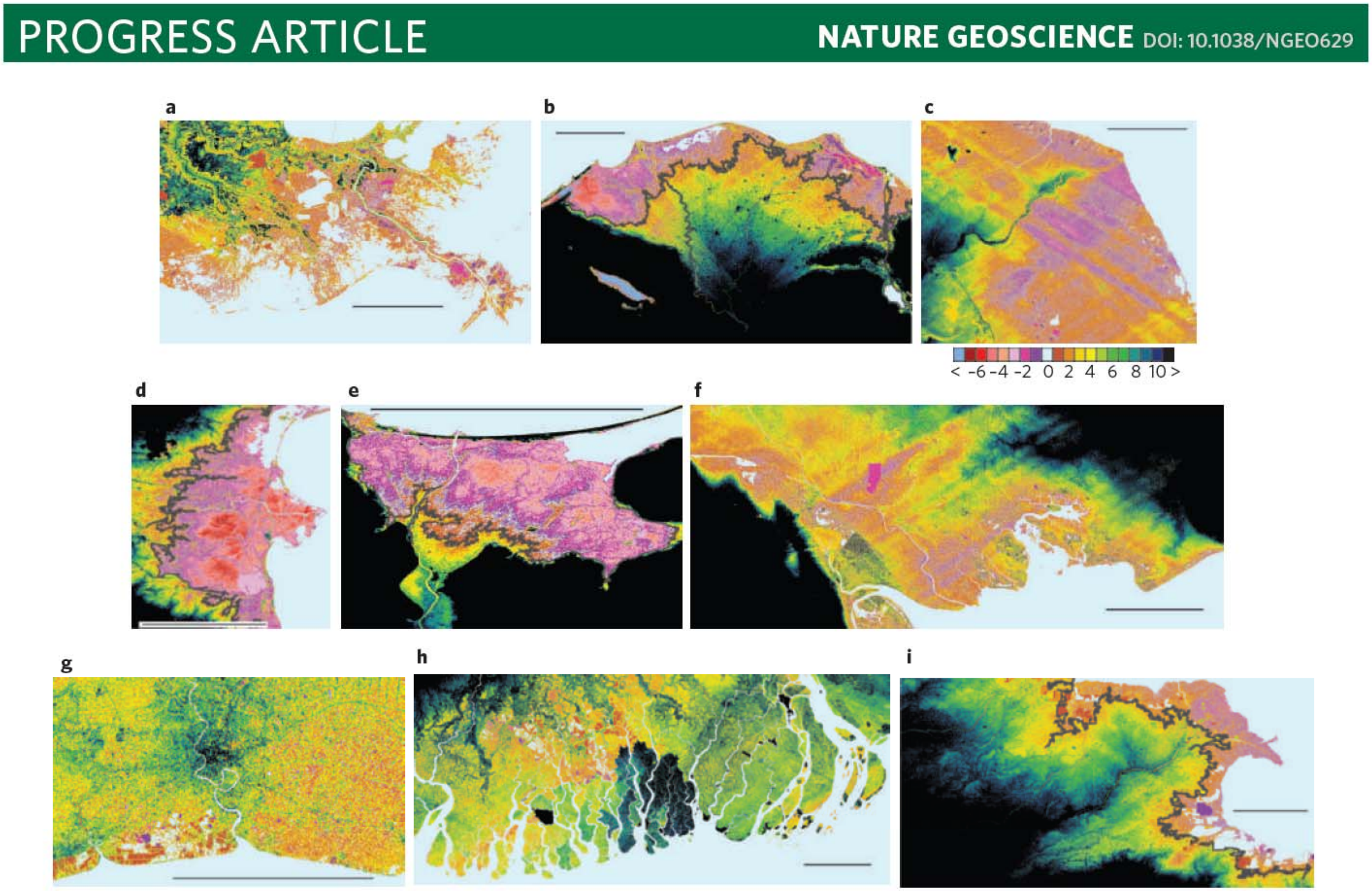


Fig. 3. Annual cycle of measured half-hourly methane fluxes. Positive sign indicates upward flux, i.e. emission from the fen.

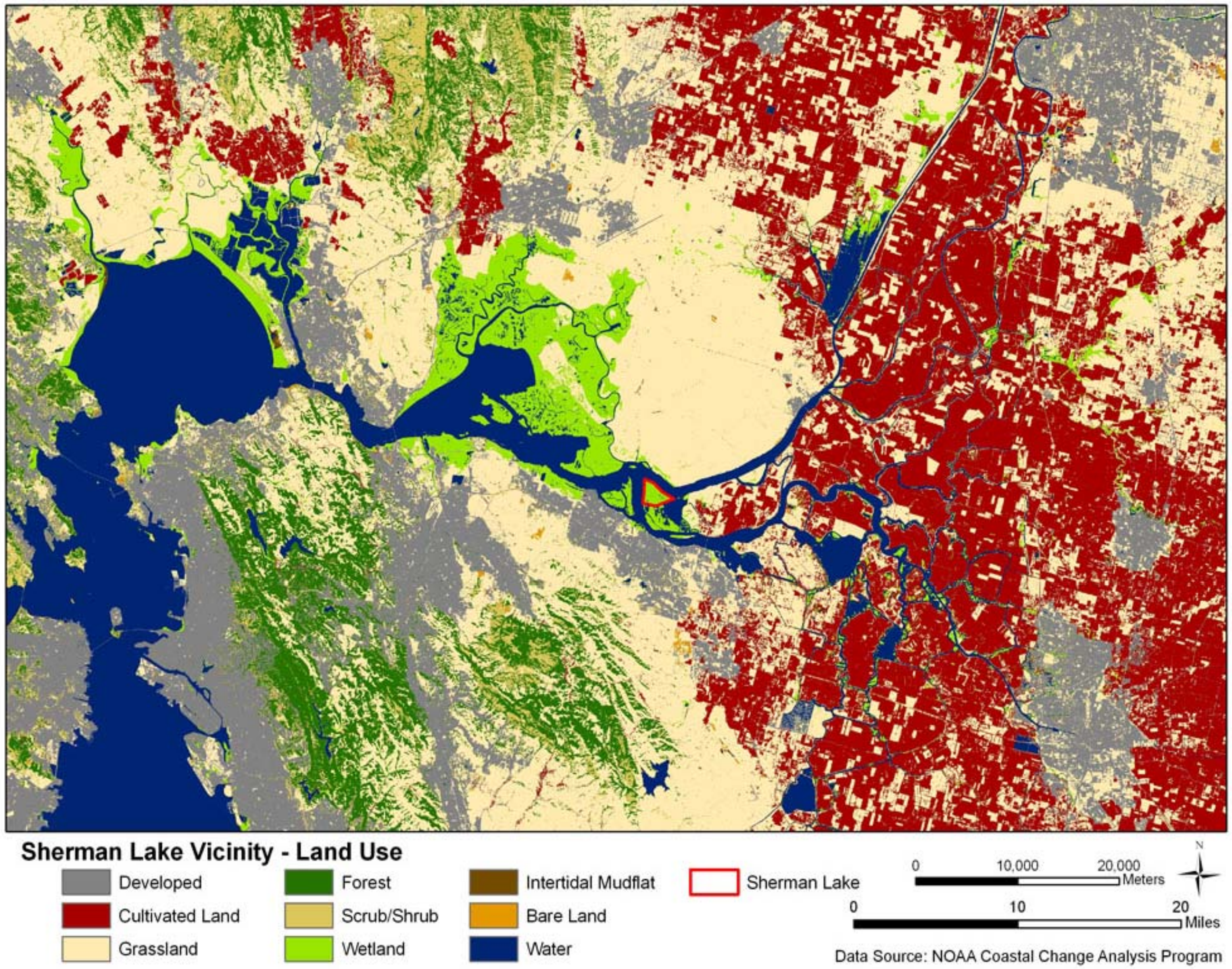
Rinne et al, 2007 Tellus

Deltas Are Sinking, World-Wide

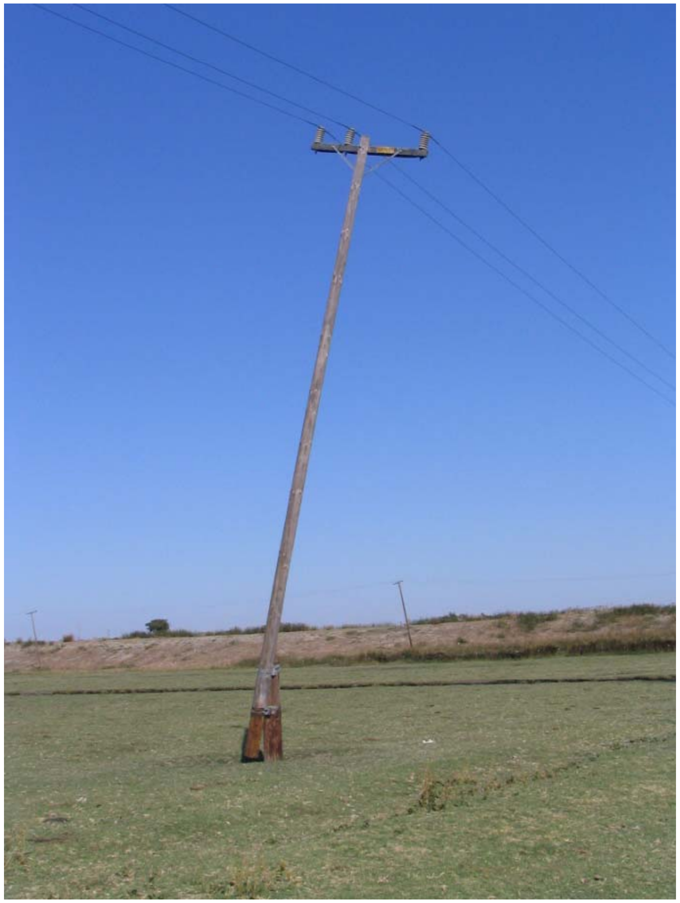


Syvitski et al. Nature Geoscience, 2009

San Francisco Bay-Sacramento/San Joaquin Delta Region



Delta Peatland is Indeed Subsiding!



Vulnerable Ecosystem via Severe Land Subsidence

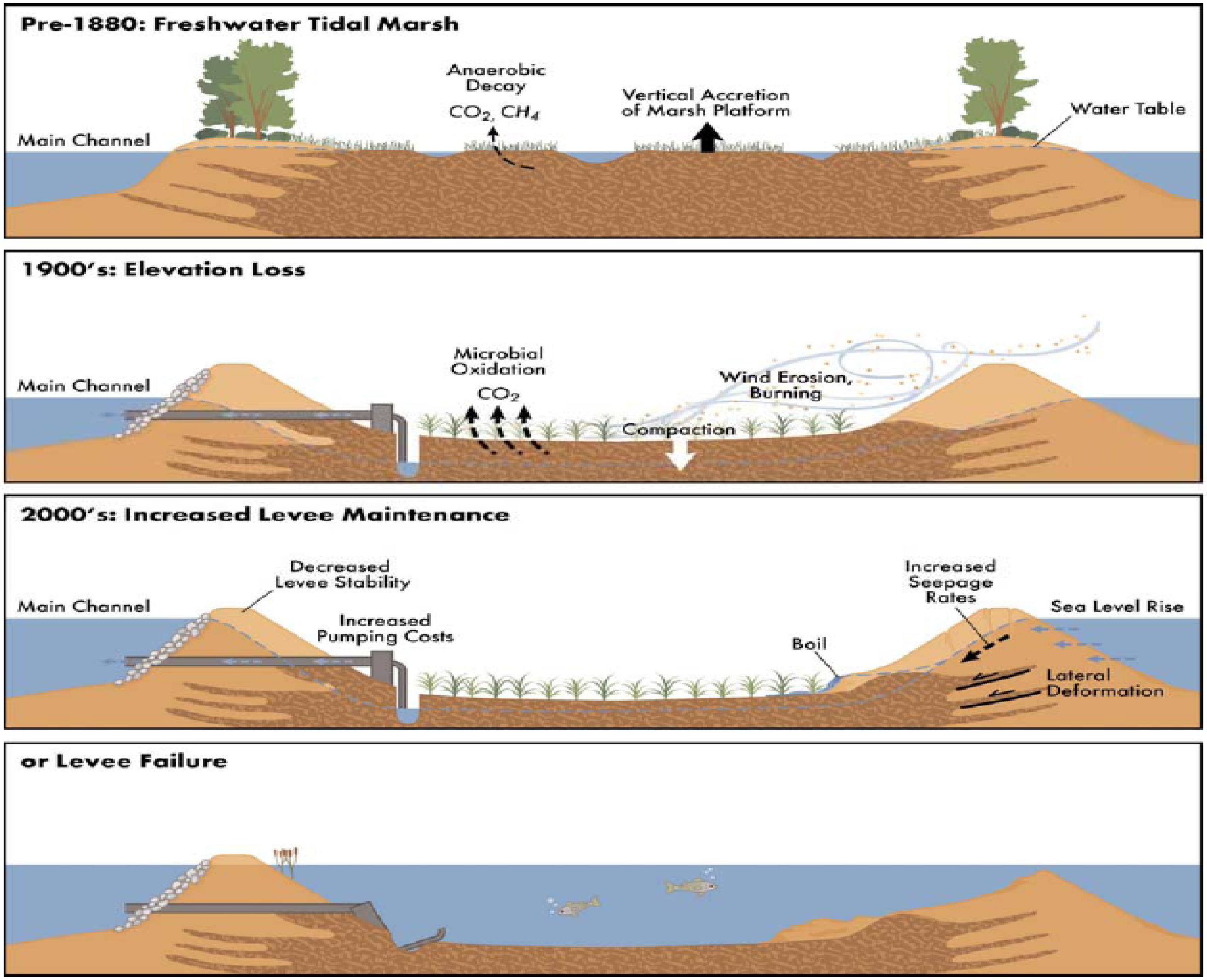


Figure 2. Conceptual diagram illustrating evolution of Delta islands due to levee construction and island subsidence. Modified from Ingebritsen et al. (2000).

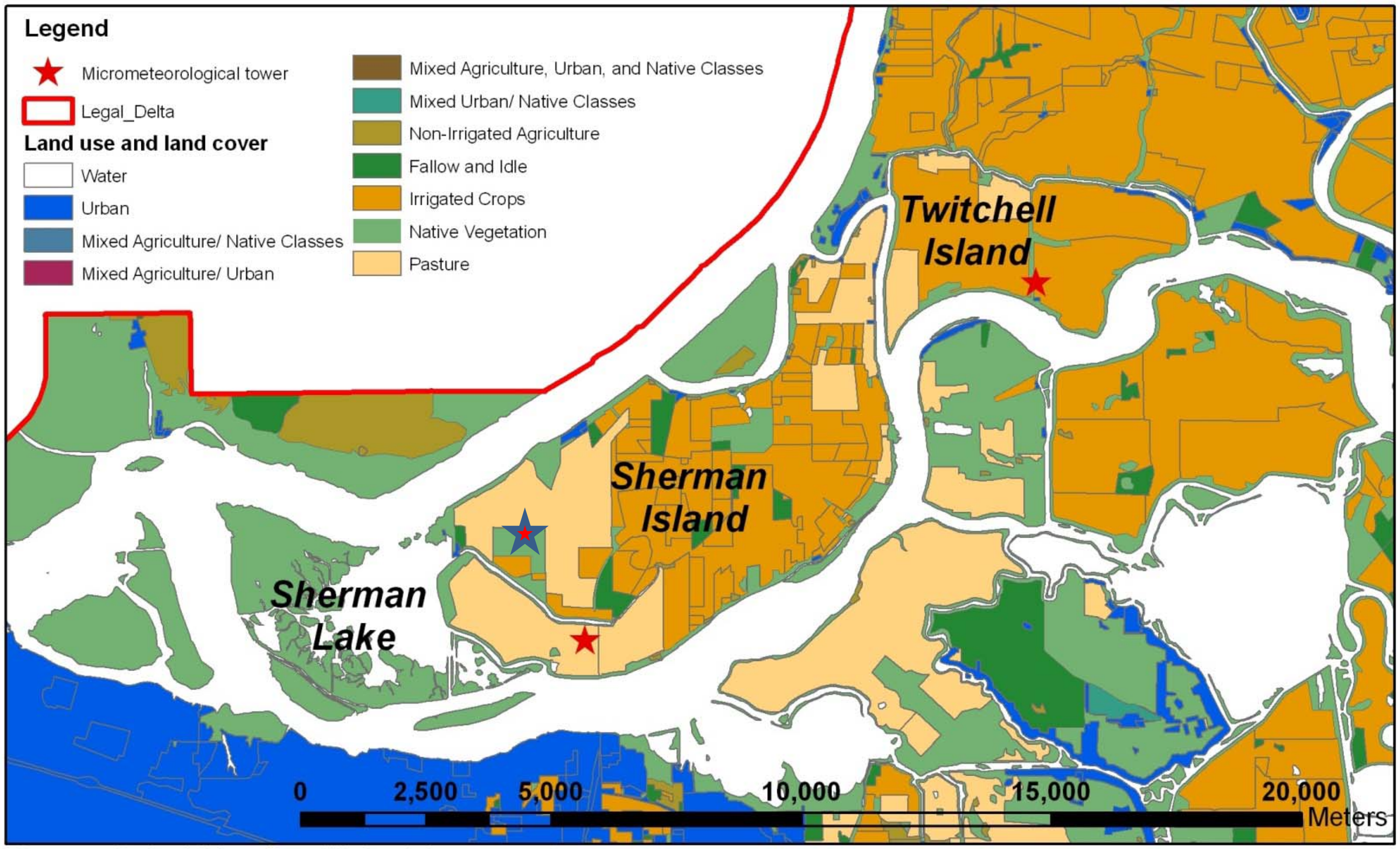
New Plans to Reverse Subsidence with Carbon Farming of
Restored Tule Wetlands and Rice on
Twitchell and Sherman Islands

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



Source: Delta Vision (http://deltavision.ca.gov/)

Ideal Micrometeorological Site:
Flat, with Extensive Fetch and Brisk Steady Winds from a Predominant Direction

Eddy Covariance,

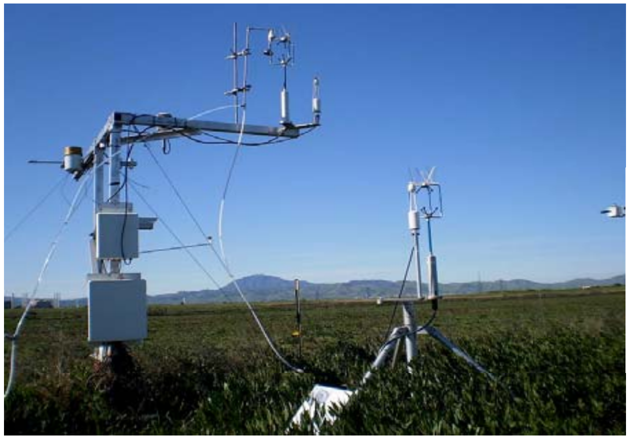
Flux Density: mol m^{-2} s^{-1} or J m^{-2} s^{-1}

$$F = \overline{\rho_a w s} \sim \overline{\rho_a} \cdot \overline{w's'}$$

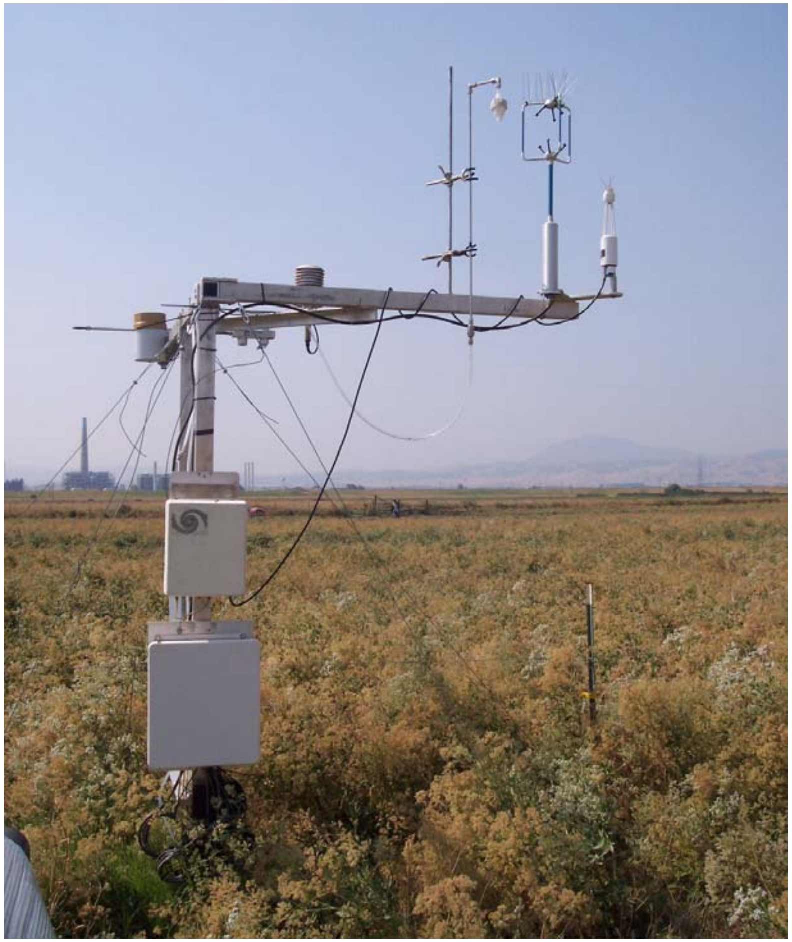
$$s = (\frac{\rho_c}{\rho_a})$$

Eddy Covariance

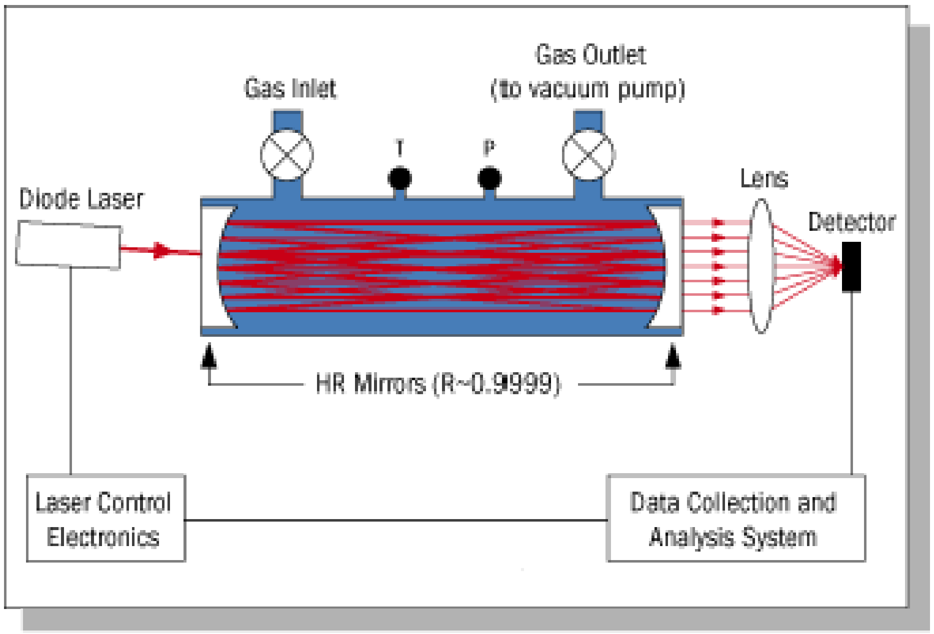
- Direct Measure of the Trace Gas Flux Density between the atmosphere and biosphere, mole m^{-2} s^{-1}
- *In situ*
- Quasi-continuous
- Integrative of a Broad Area, 100s m^2
- Introduces No artifacts, like chambers



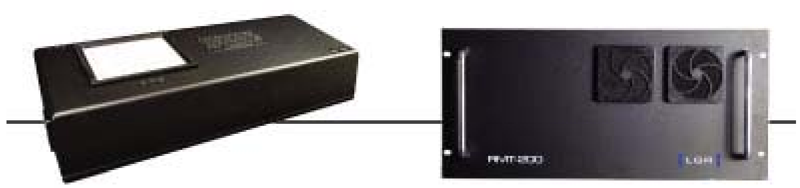
Eddy Covariance Tower
Sonic Anemometer, CO2/H2O IRGA,
inlet for CH4 Tunable diode laser spectrometer &
Meteorological Sensors
Drained Peatland Pasture, vegetated with Pepperweed, an invasive weed, 2007-present



Measuring Methane with Off-Axis Infrared Laser Spectrometer

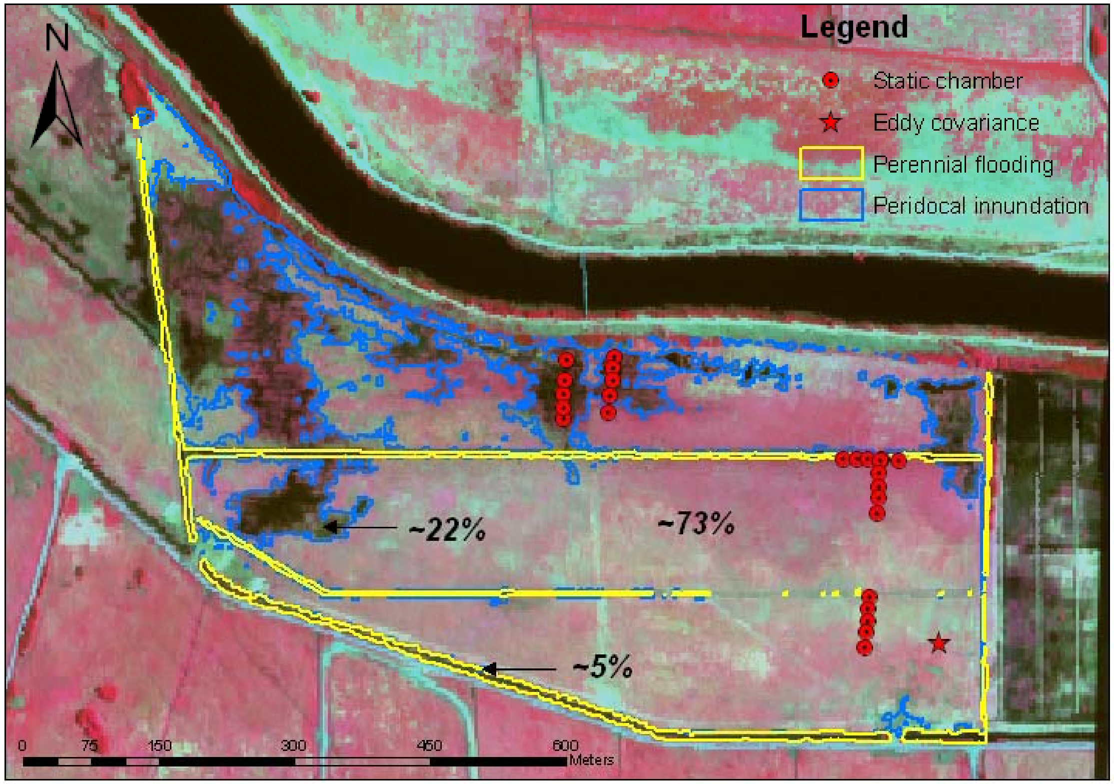


Closed path
Moderate Cell Volume, 400 cc
Long path length, kilometers
High power Use:
Sensor, 80 W
Pump, 1000 W; 30-50 lpm
Low noise: 1 ppb at 1 Hz
Stable Calibration



Los Gatos Research

Complex Greenhouse Gas Site with Lots of Spatial Heterogeneity of Sources

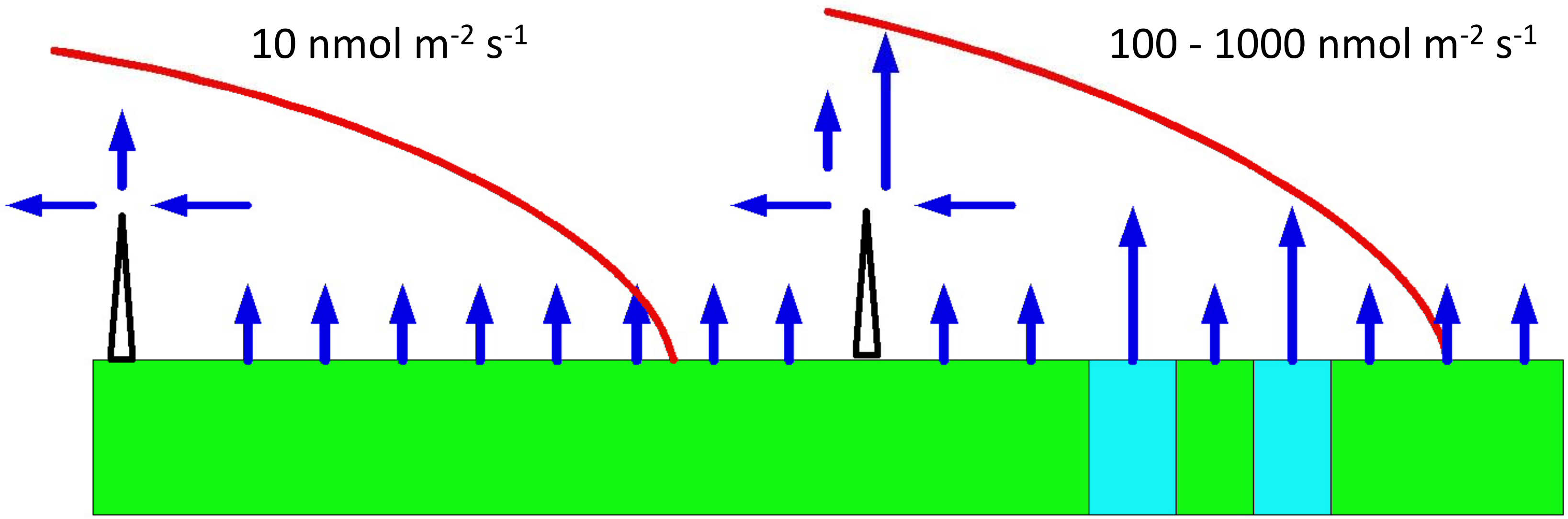


Teh et al, Ecosystems, 2011

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

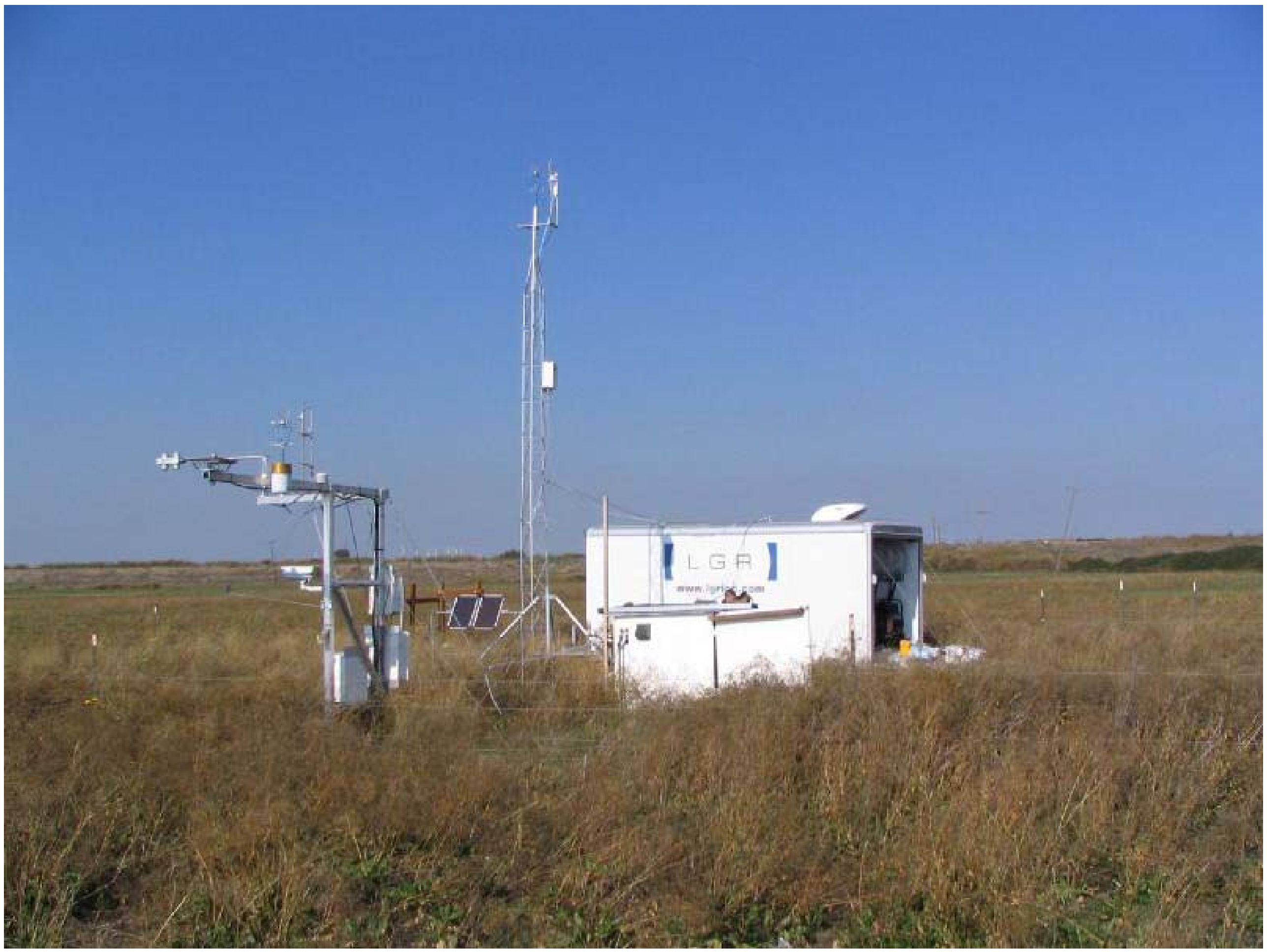
Even Over Perfect Flat Sites with Extensive Fetch
Advection can/does Occur with Methane:

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

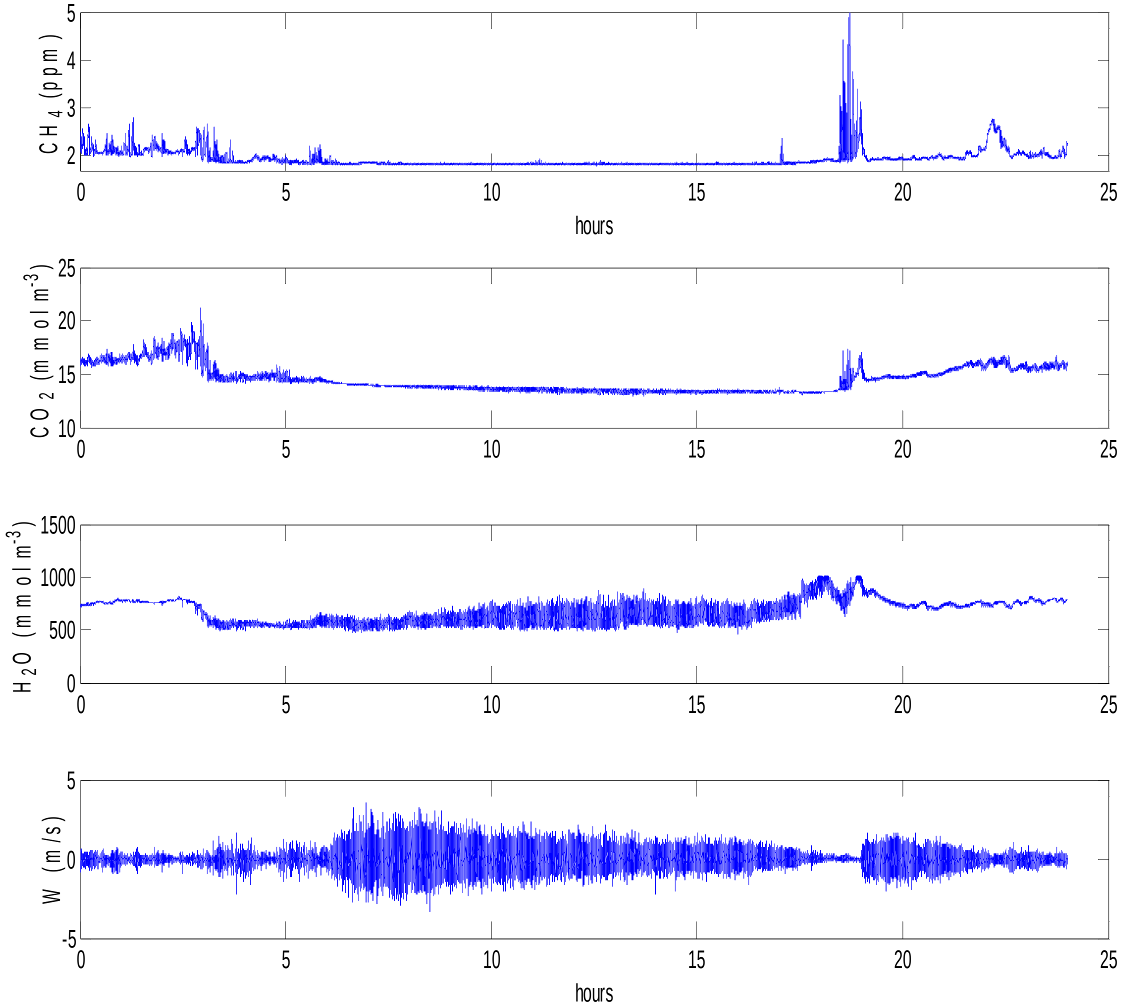


Such Advection is Less Pronounced for Water Vapor and CO_2 Fluxes Because Flux Differences Emanating from the Different LandForms are Smaller

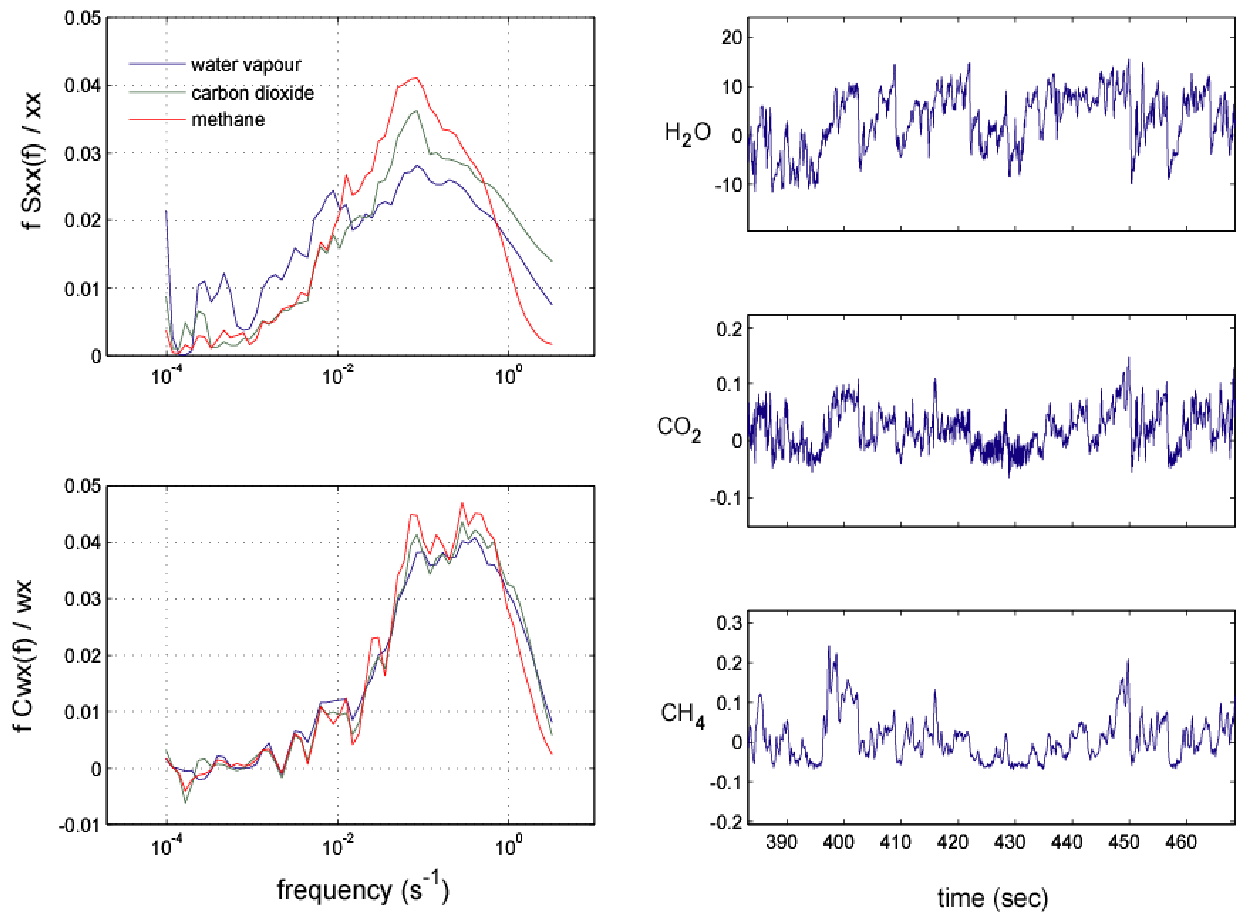
Results



Time Series at 10 Hz and 24 Hours



Spectral Performance of Gas Sensors

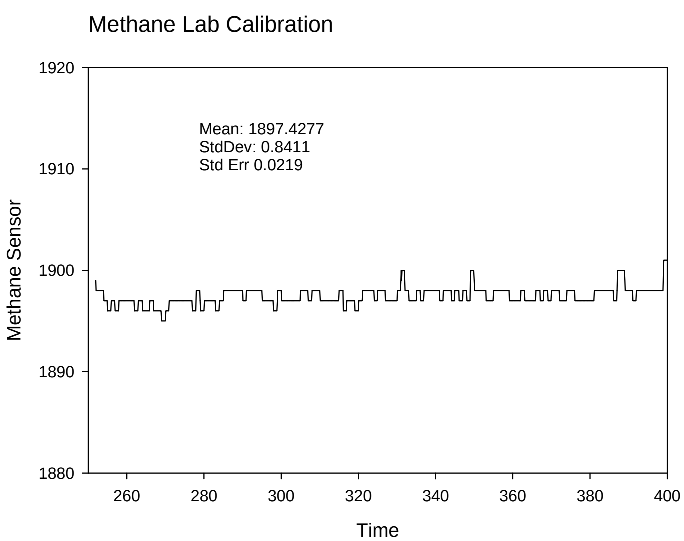


Detto et al., AgForestMet, submitted

Zero-Flux Detection Limit, Detecting Signal from Noise

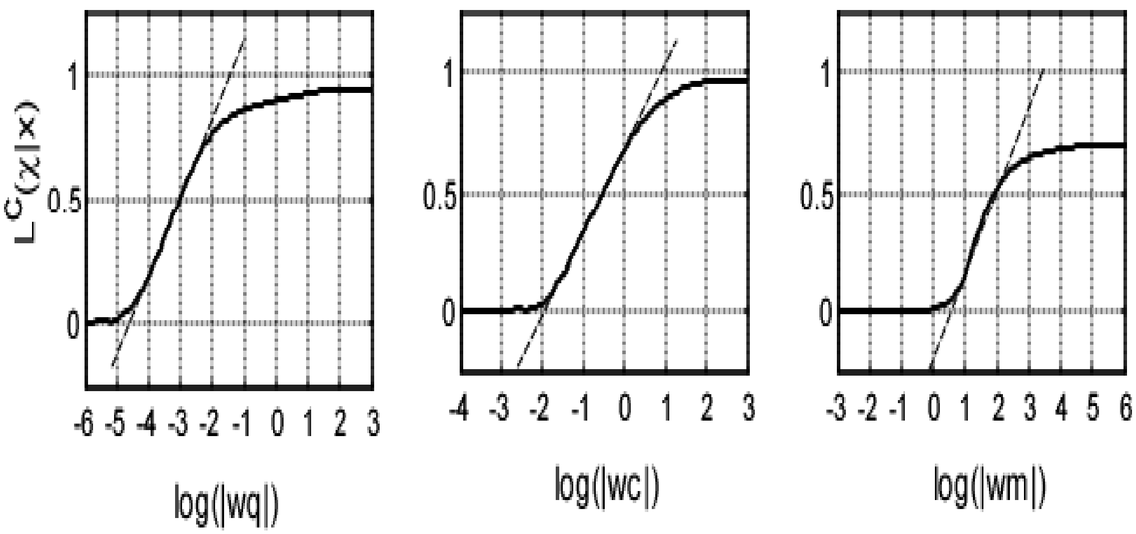
$$F = \overline{w'c'} \approx r_{wc}\sigma_w\sigma_c$$

r_{wc} ~ 0.5
σ_{ch4} ~ 0.84 ppb @ 1 Hz sampling rate
σ_{co2} ~ 0.11 ppm



U* m/s	σ_w m/s	$F_{min,}$ CH_4 nmol m^{-2} s^{-1}	$F_{min,}$ CO_2 μmol m^{-2} s^{-1}
0.1	0.125	2.1	0.275
0.2	0.25	4.2	0.55
0.3	0.375	6.3	0.825
0.4	0.5	8.4	1.1
0.5	0.625	10.5	1.375

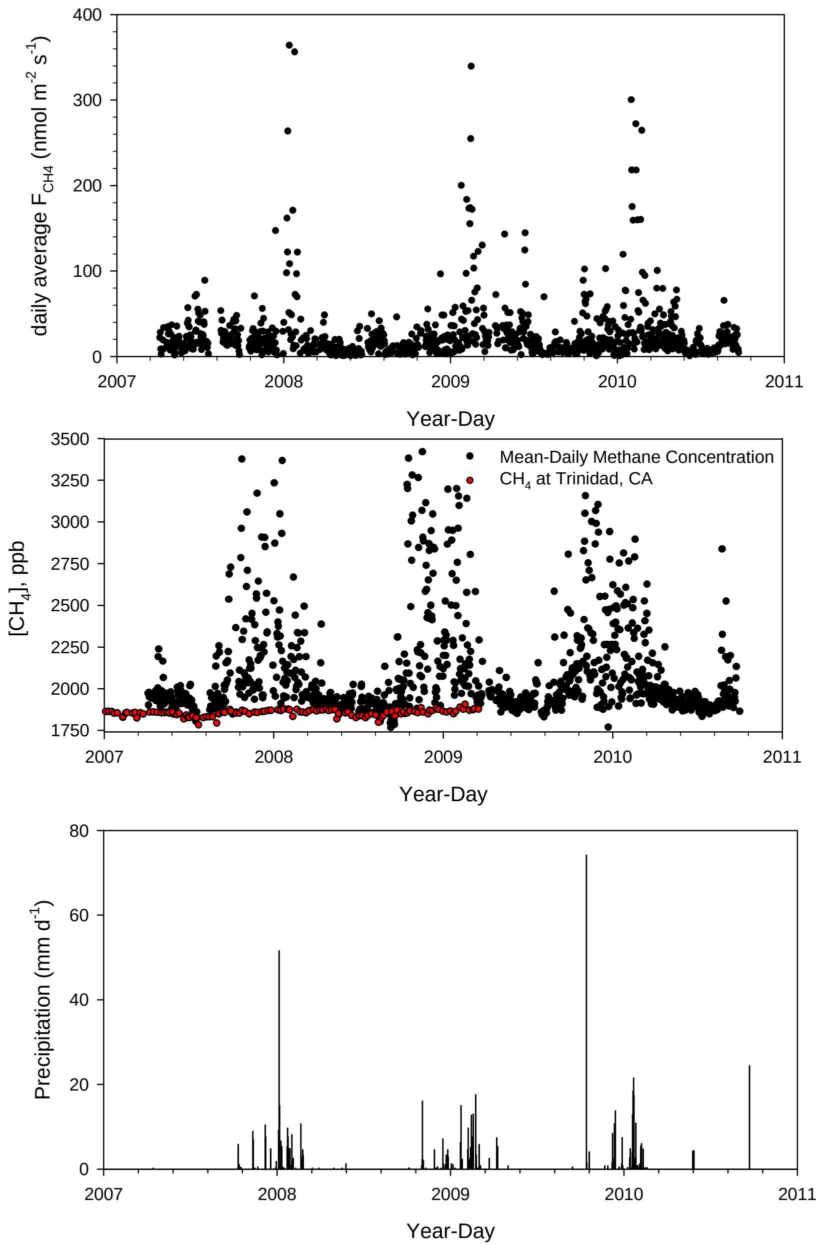
Flux Detection Limit, based on 95% CI that correlation between W and C that is non-zero



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,

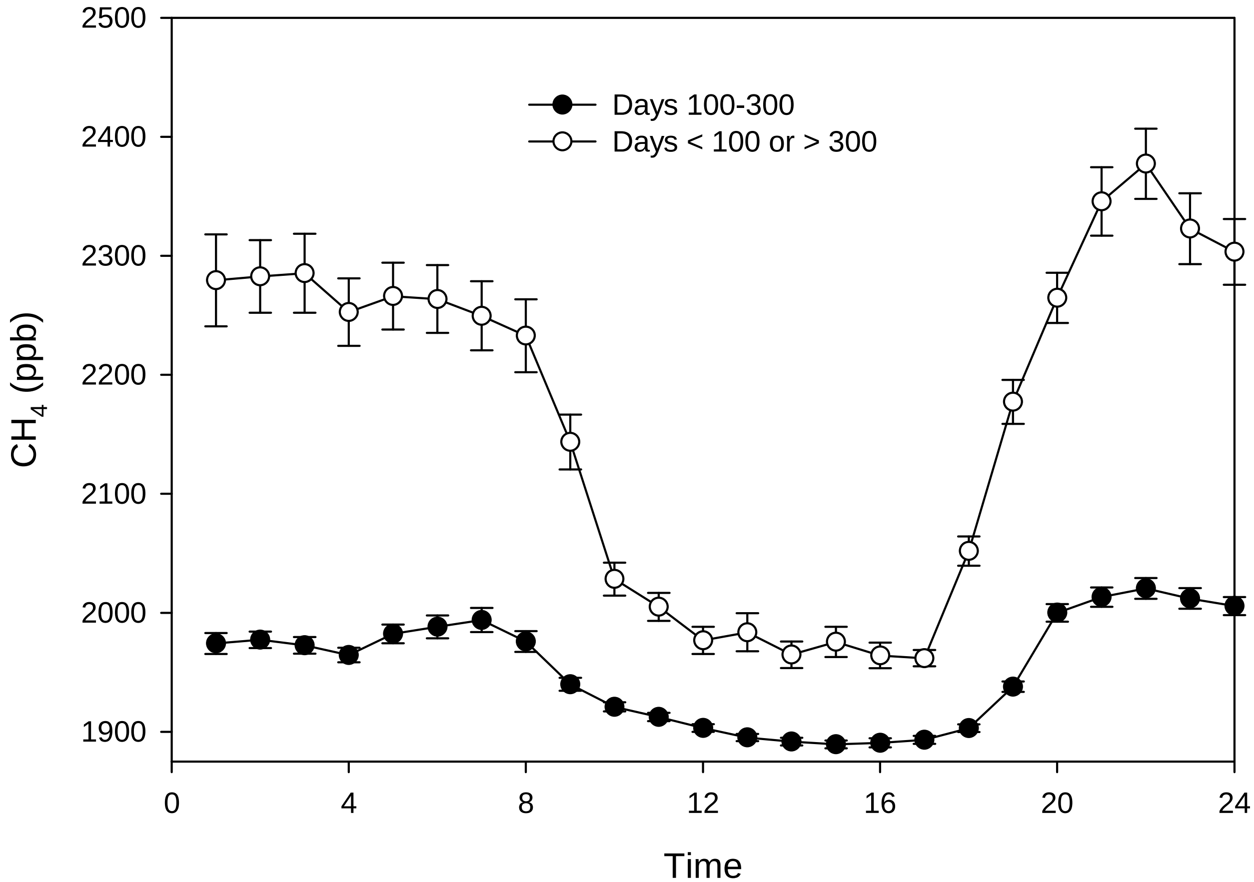
Detto et al, AgForestMet, submitted

3 Years of Methane Flux Data from Sherman Island



Baldocchi et al AgForMet, in press

Methane Concentrations Experience Nocturnal Maximum

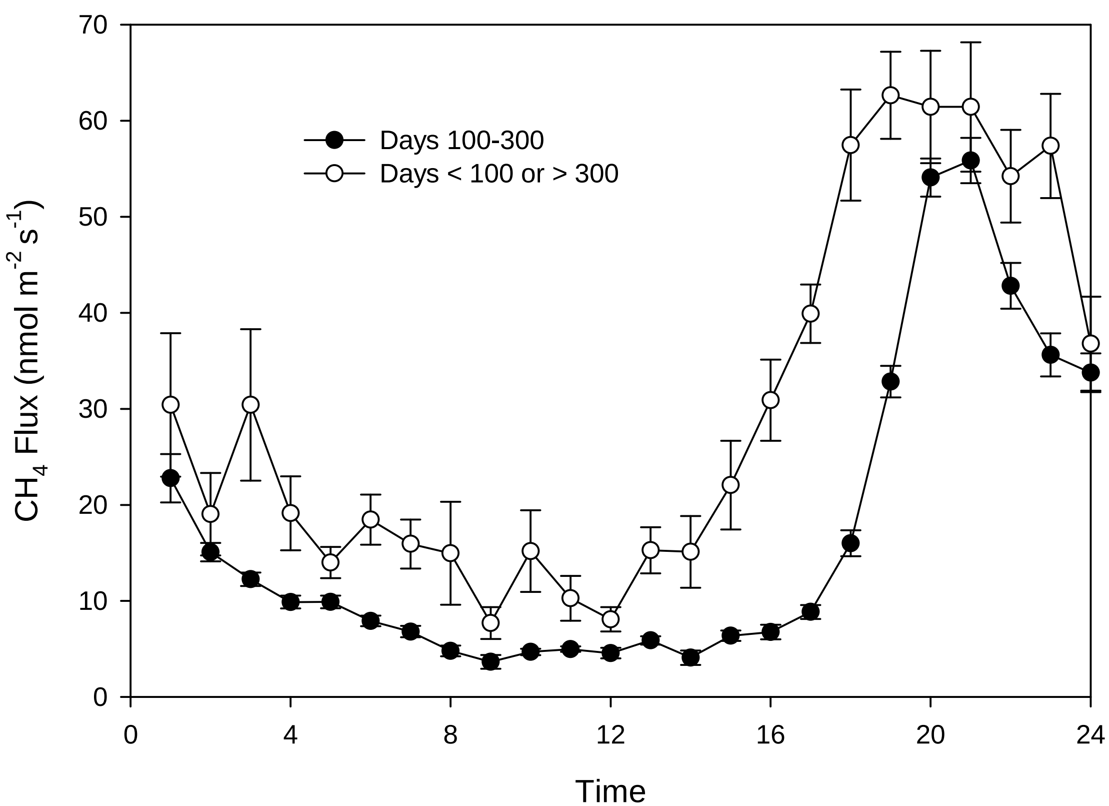


Boundary Layer Rectifier Effect ?

Baldocchi et al AgForMet, in press

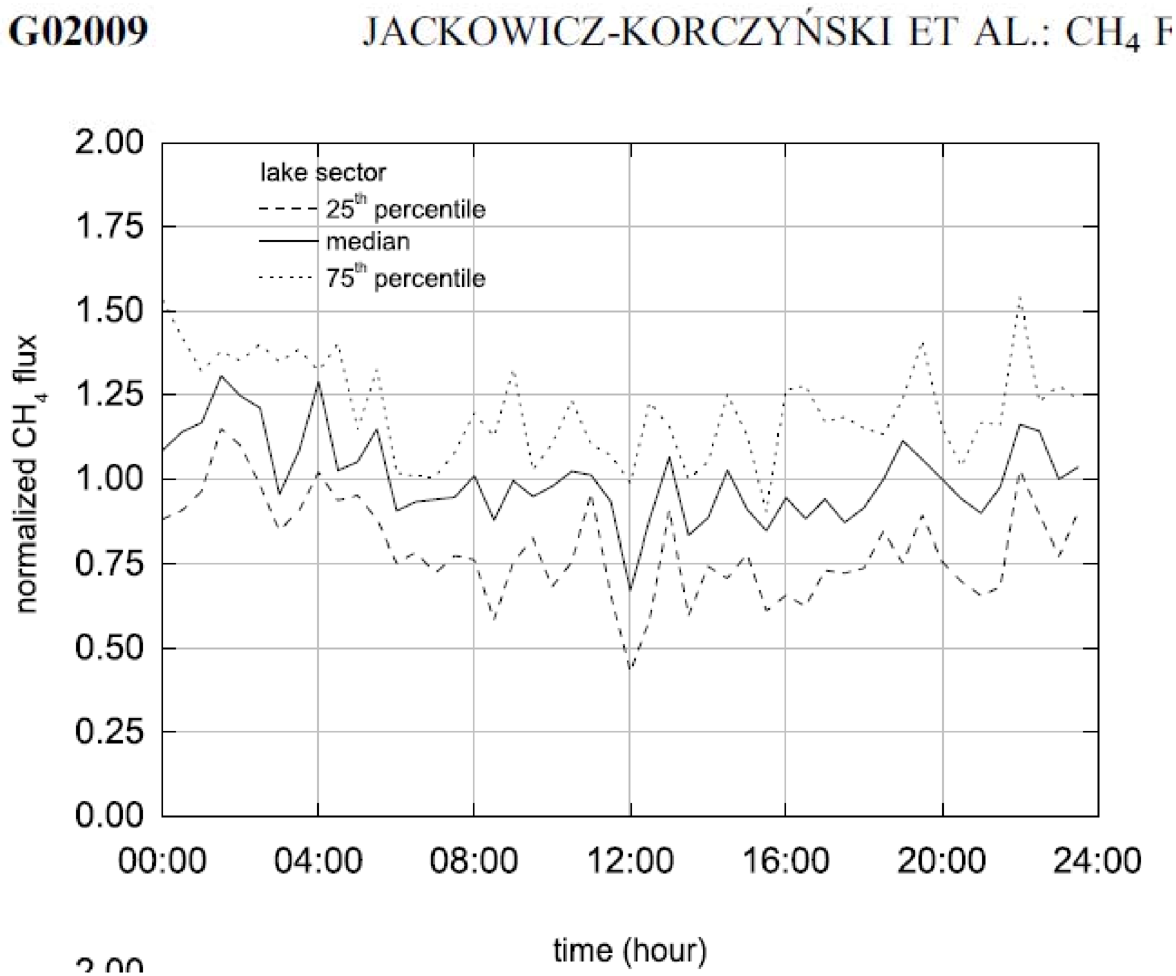
Emerging Mystery:

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



JGR-Biogeoscience, 2010

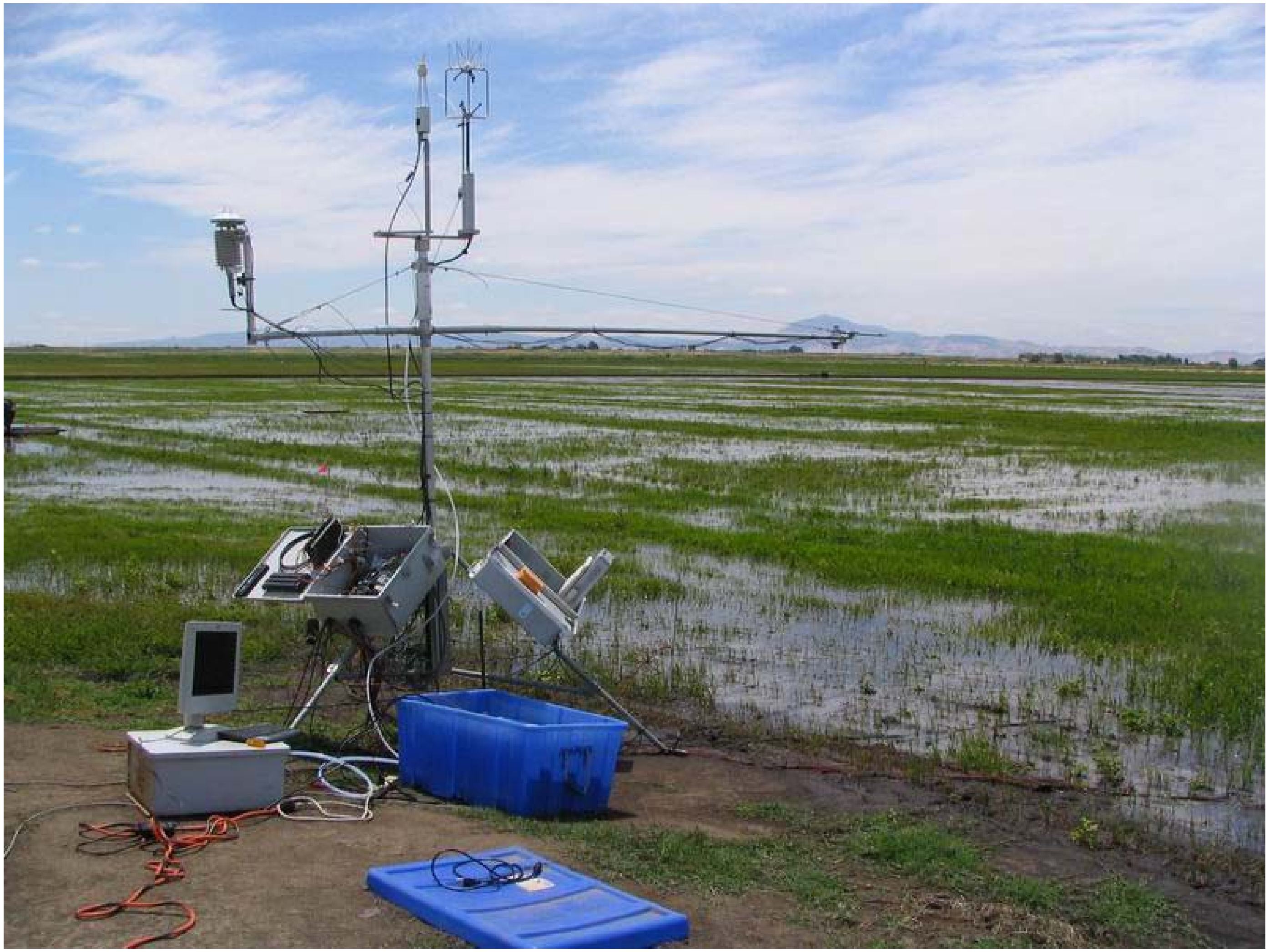
Why are Large Methane Concentrations and Fluxes Observed at Night?

- 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?

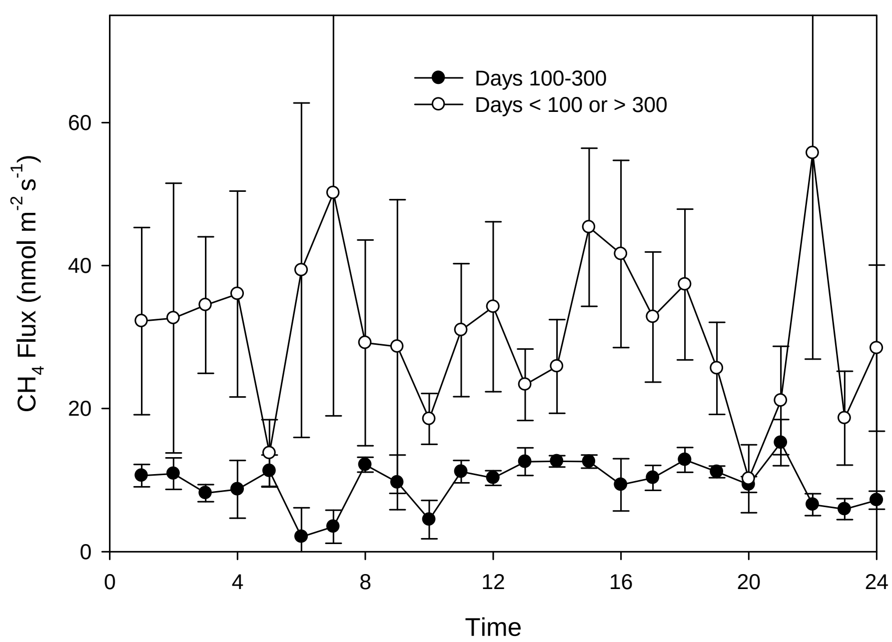
- Measure Methane Flux over Rice, a known, uniform methane source, downwind 10 km
- Bound Problem and Check Advection with
  - PBL Box Model and Flux Footprint Model
  - Flux Divergence Studies
- Commando Field Campaigns to Measure Methane Effluxes from the Marshlands upwind of the Site
- Measure Methane Fluxes of Tidal Marshland Upwind on the Levee
  - Site not secure, power limited, 2nd methane sensor not available
- Use Web Cam and Watch and Count Cows

Eddy Flux System at Rice

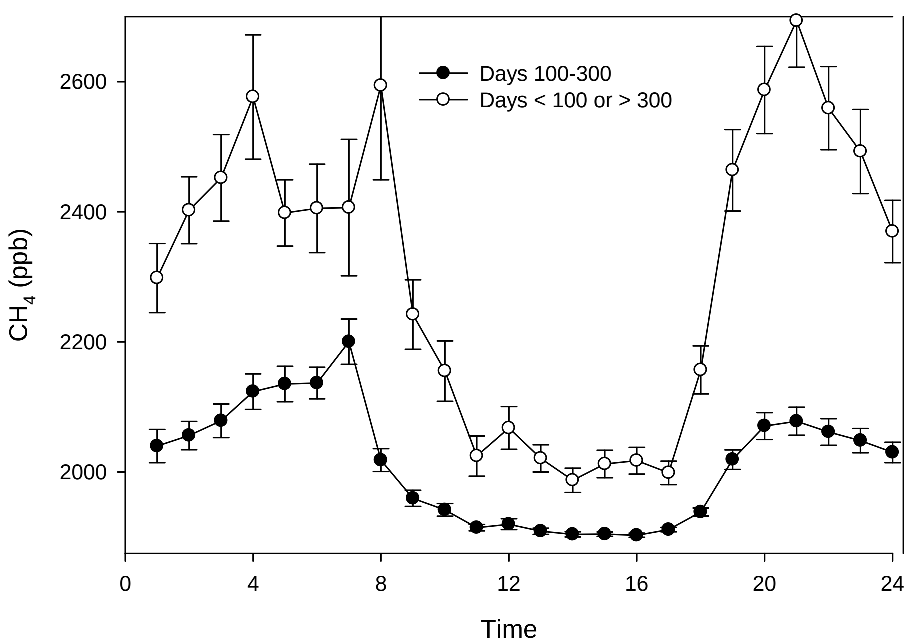


Companion Study over Rice on Twitchell Island, 2009

Twitchell Island, Rice, 2009-2010, Westerly Winds



Rice Does Not Exhibit Diurnal Pattern in Methane Efflux;
Fetch is Uniform and Extensive



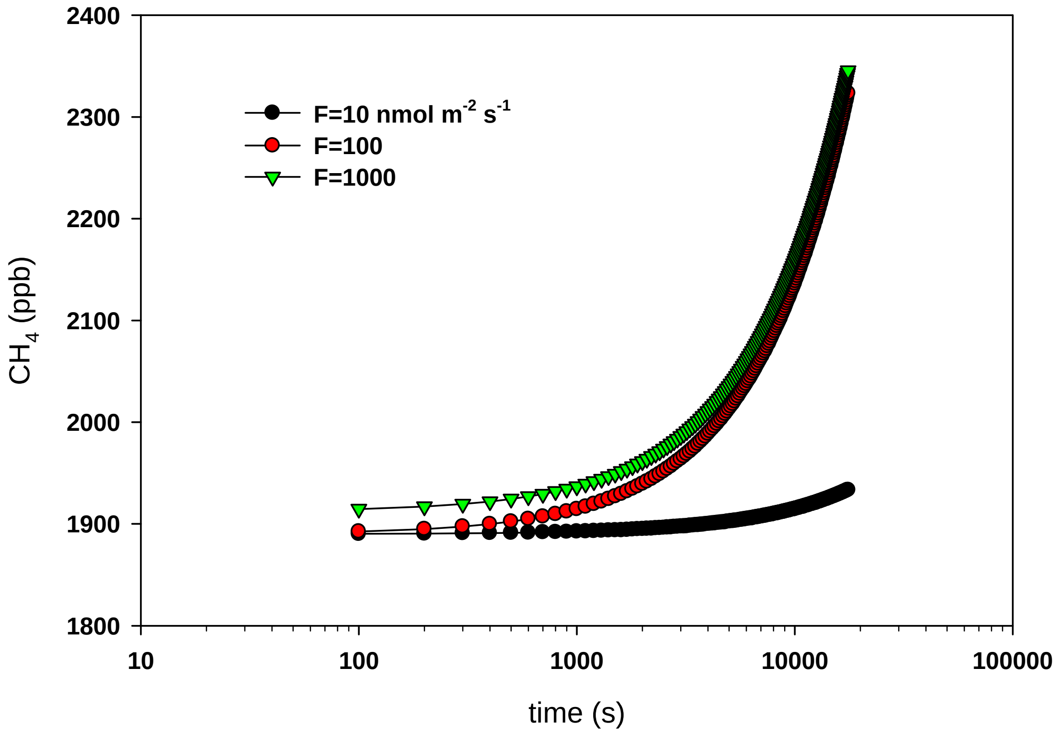
Rice Experiences Strong diurnal Pattern in Methane Concentration

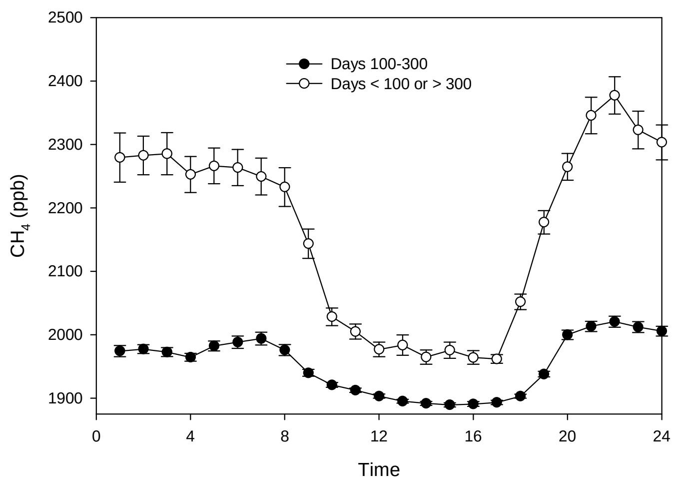
Baldocchi et al AgForMet, in press

Is the Tule Wetland, Upwind of Sherman Island, a Large CH_4 source?

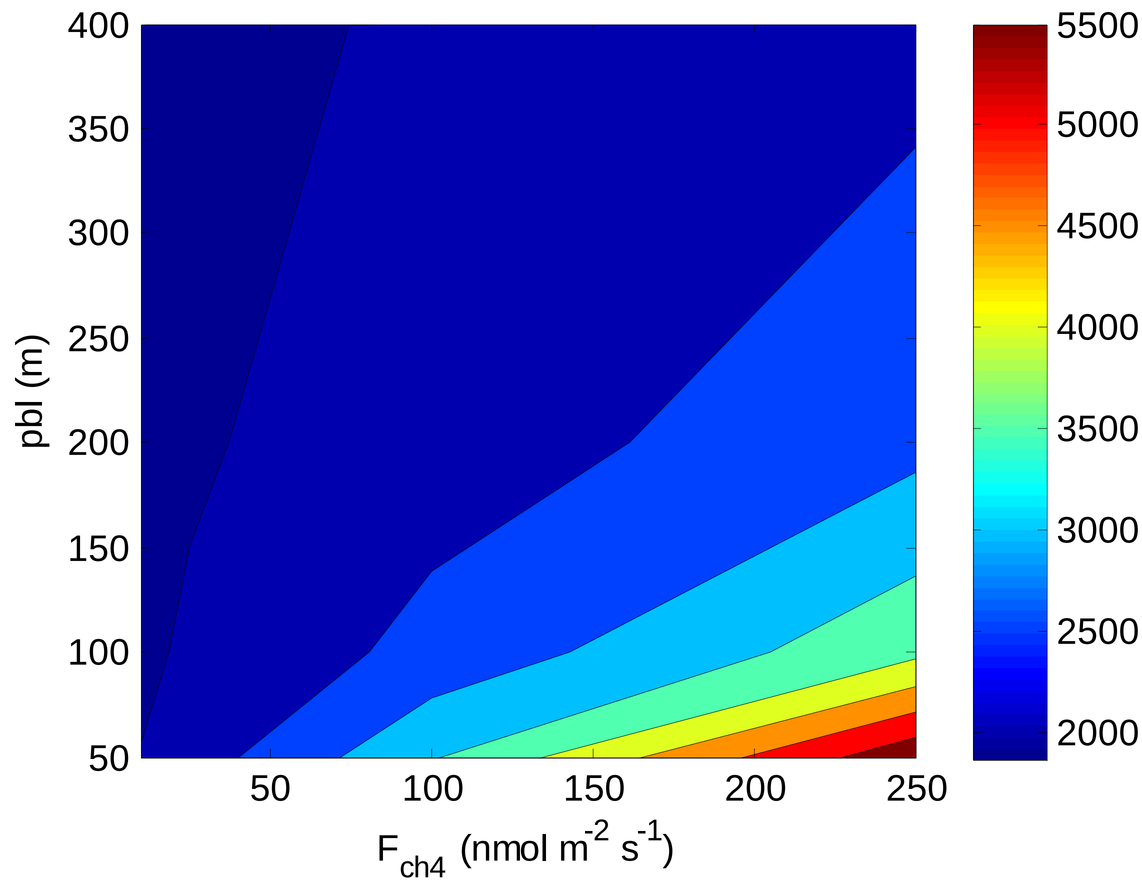
Observed increase in [CH4] after Sunset is too Fast to be Explained by the PBL Box, which infers a complex source due to wetlands, wet fields and ditches

pbl height = 100 m





Elevated [CH4] (> 2500 ppb) corresponds with Low Boundary Layers (< 200 m) and High Effluxes (50 to 250 nmol m-2 s-1)



$$\rho_a \frac{\Delta c}{\Delta t} = -\frac{F_0}{z_i}$$

$$c(t) = c(t_0) + \frac{F_0}{\rho_a z_i}(t - t_0)$$

Figure 5 Computation of CH_4 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.

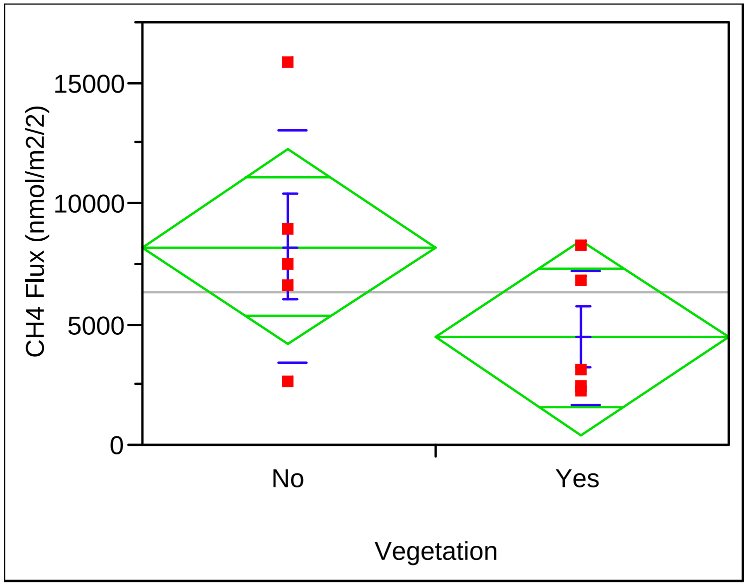
Commando Raids into the Tules with Methane Flux Chambers!

Pilot Study on Sherman Lake

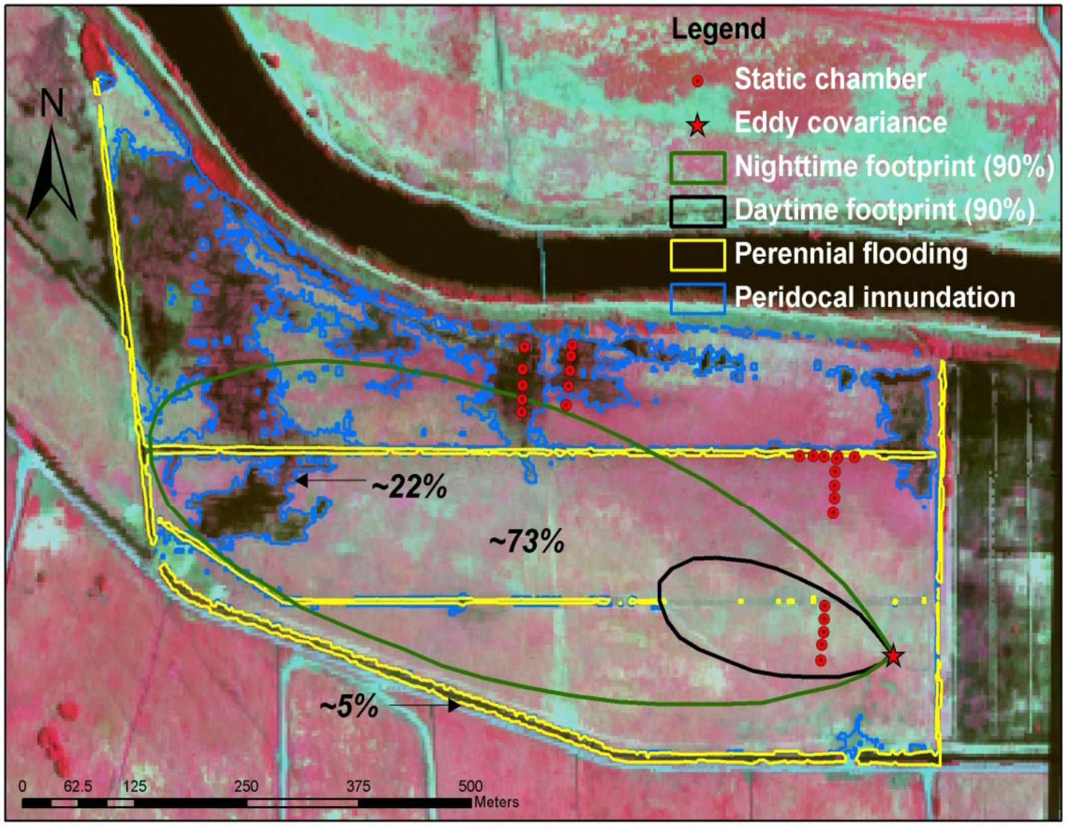
- Average CH_4 fluxes for the flooded site were 6381 nmol m^{-2} s^{-1} and peak rates exceeded 13000 nmol m^{-2} s^{-1}

- 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



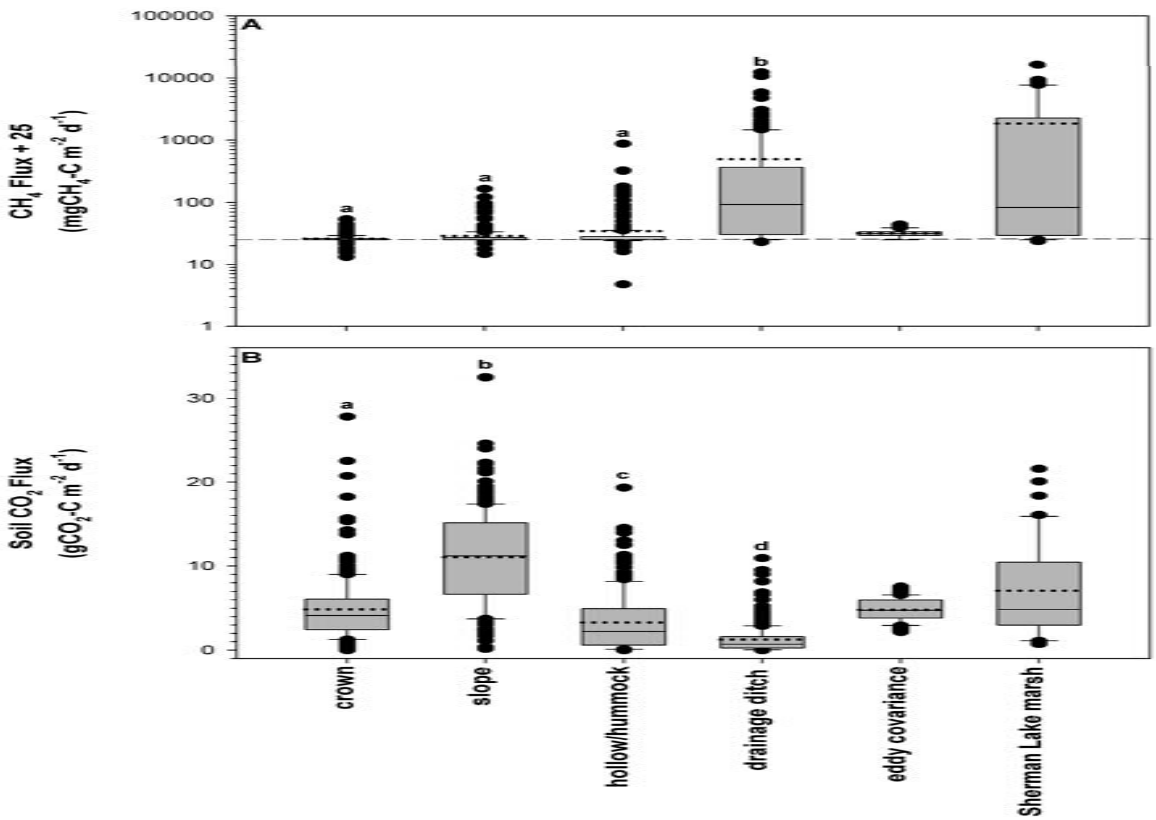
Daytime Footprint, drained ditches and paddock
Night Footprint, wetter fields and ditches



Night-time Flux Footprint Does Not Extend to the Wetlands

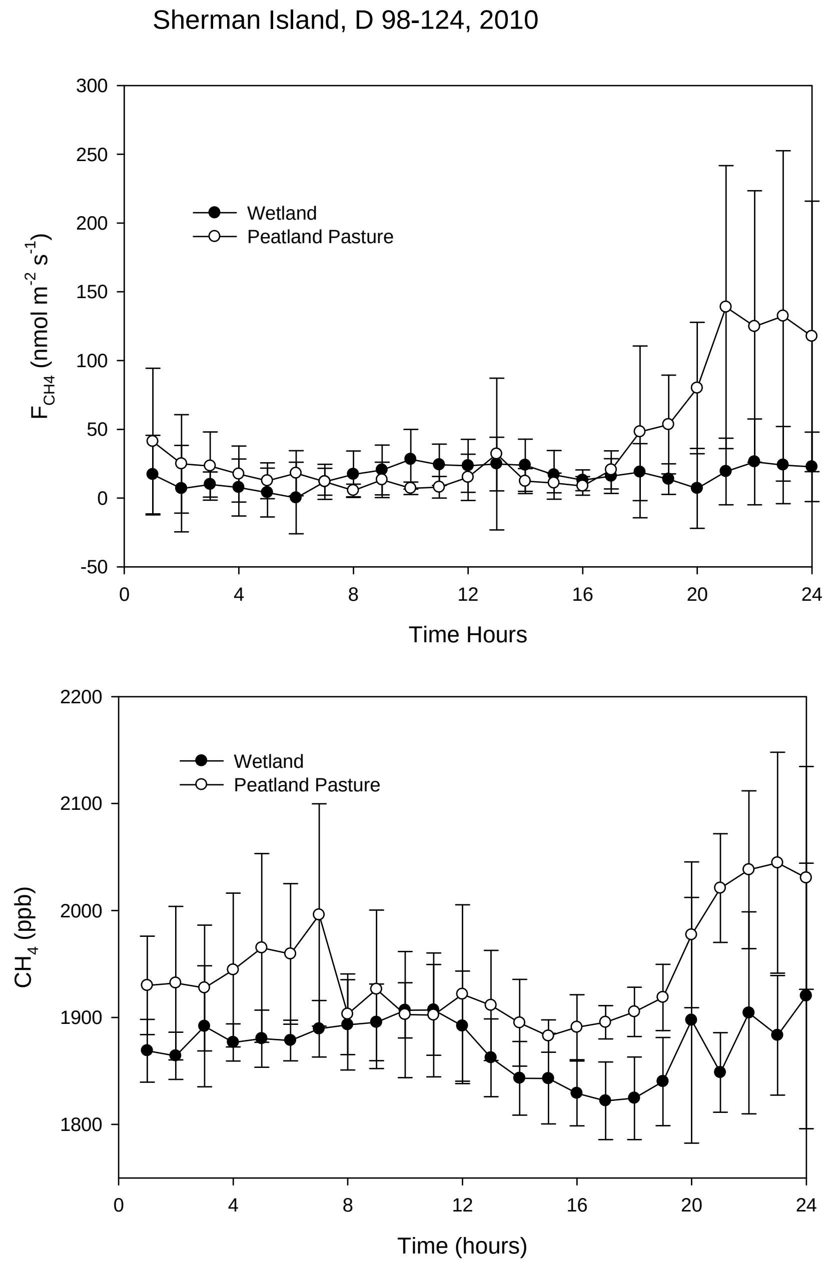
Chamber Fluxes Across Landscape Features
Ditches, upland hummocks, wet areas

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

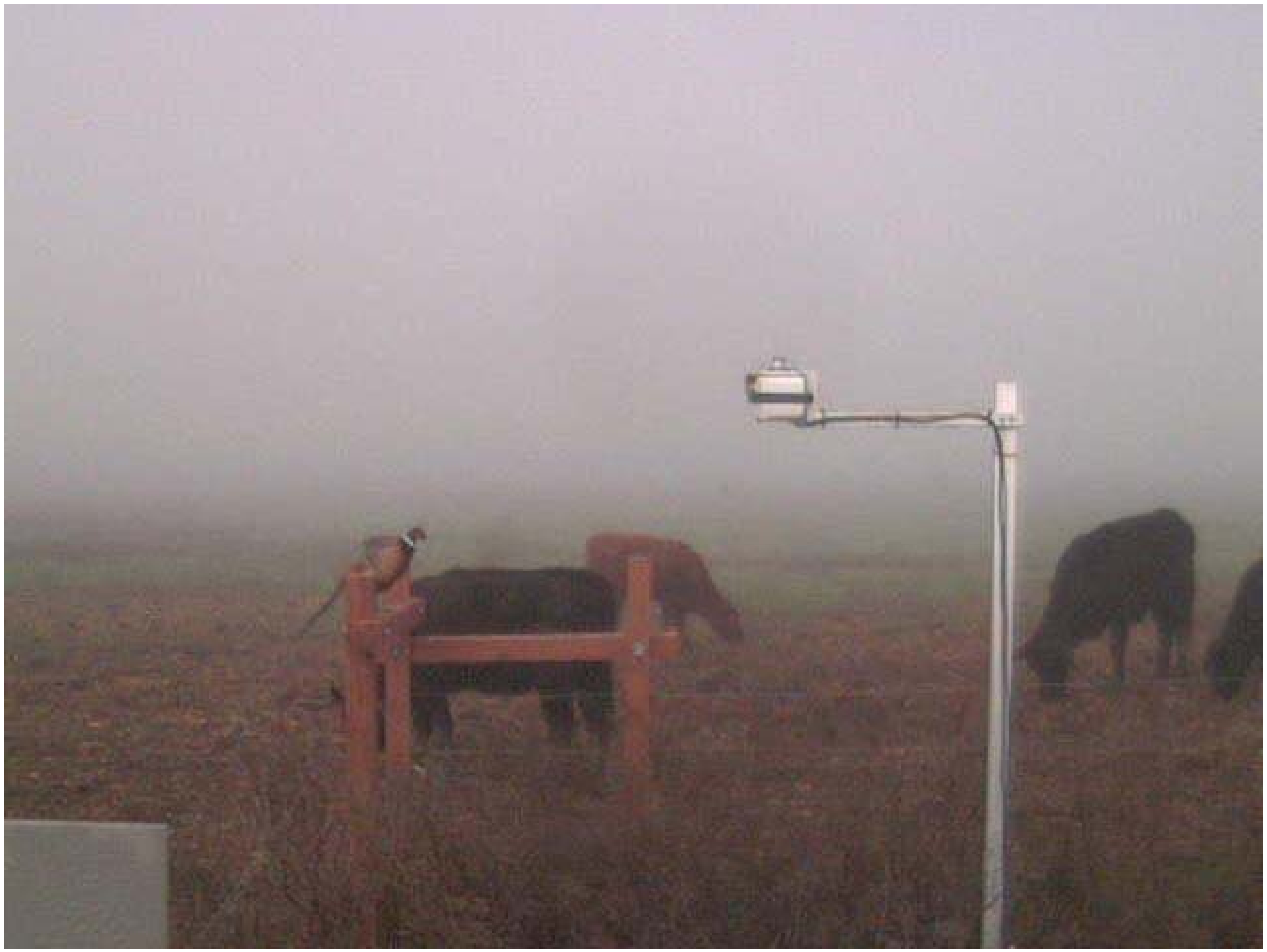


Natural Tule Wetland, upwind of Paddock, Does NOT experience diurnal pattern in methane Efflux

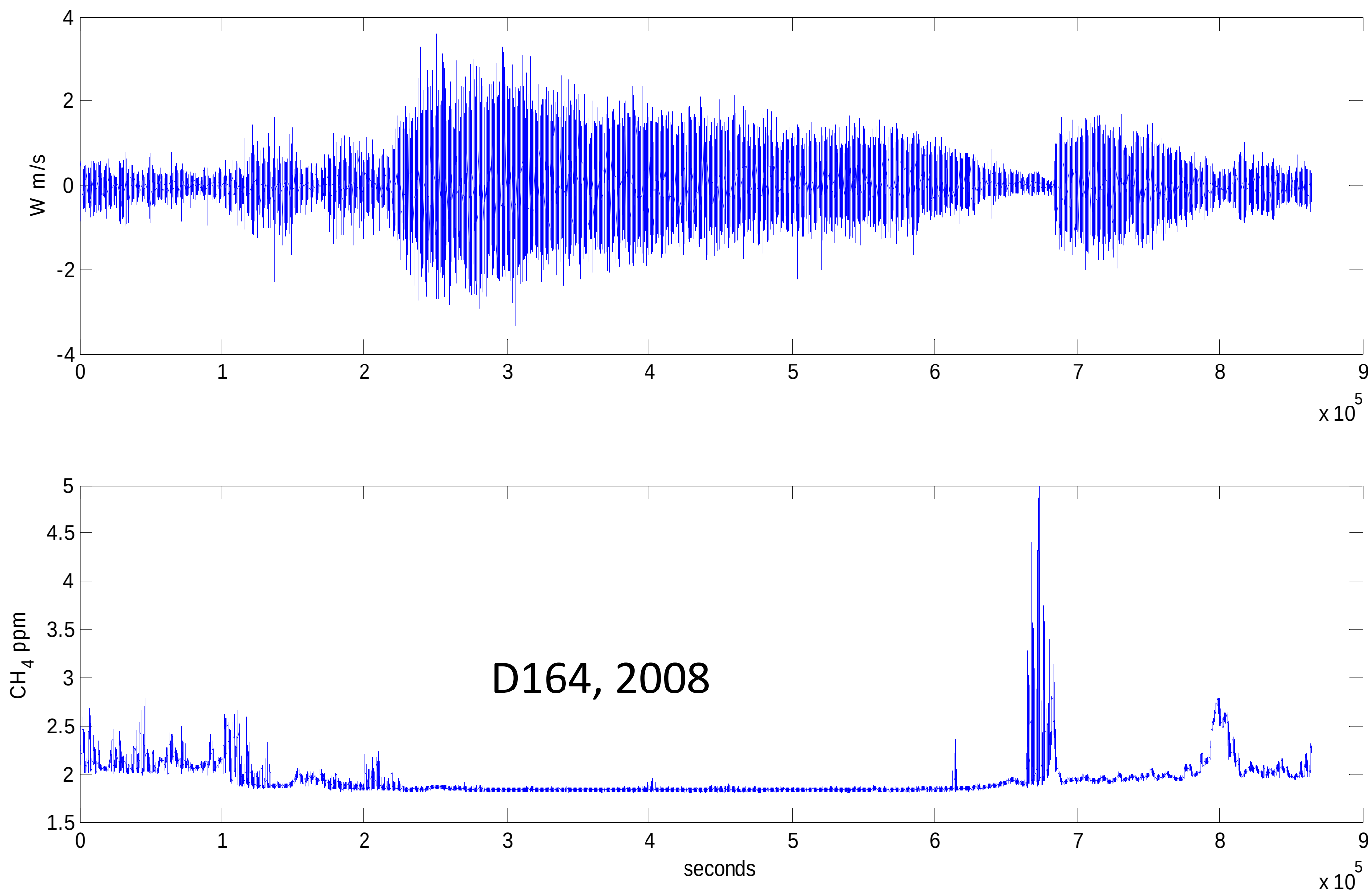
Natural Tule Wetland, upwind of Paddock,
Experiences lower methane concentrations than grazed paddock, downwind, and No Diurnal Variation

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

Cow efflux calculations!!

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 * 100/(380000*24 *60*60) = 30 nmol m^{-2} s^{-1}
30 * 100/(380000*24 *60*60) = 90 nmol m^{-2} s^{-1}

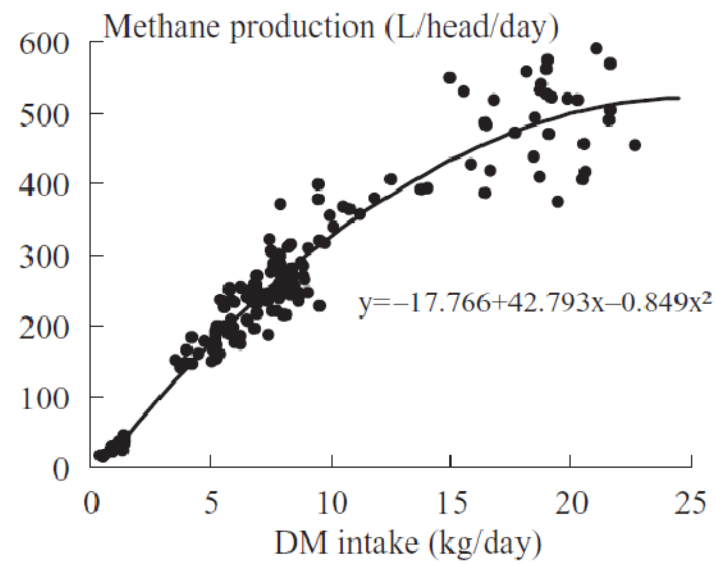
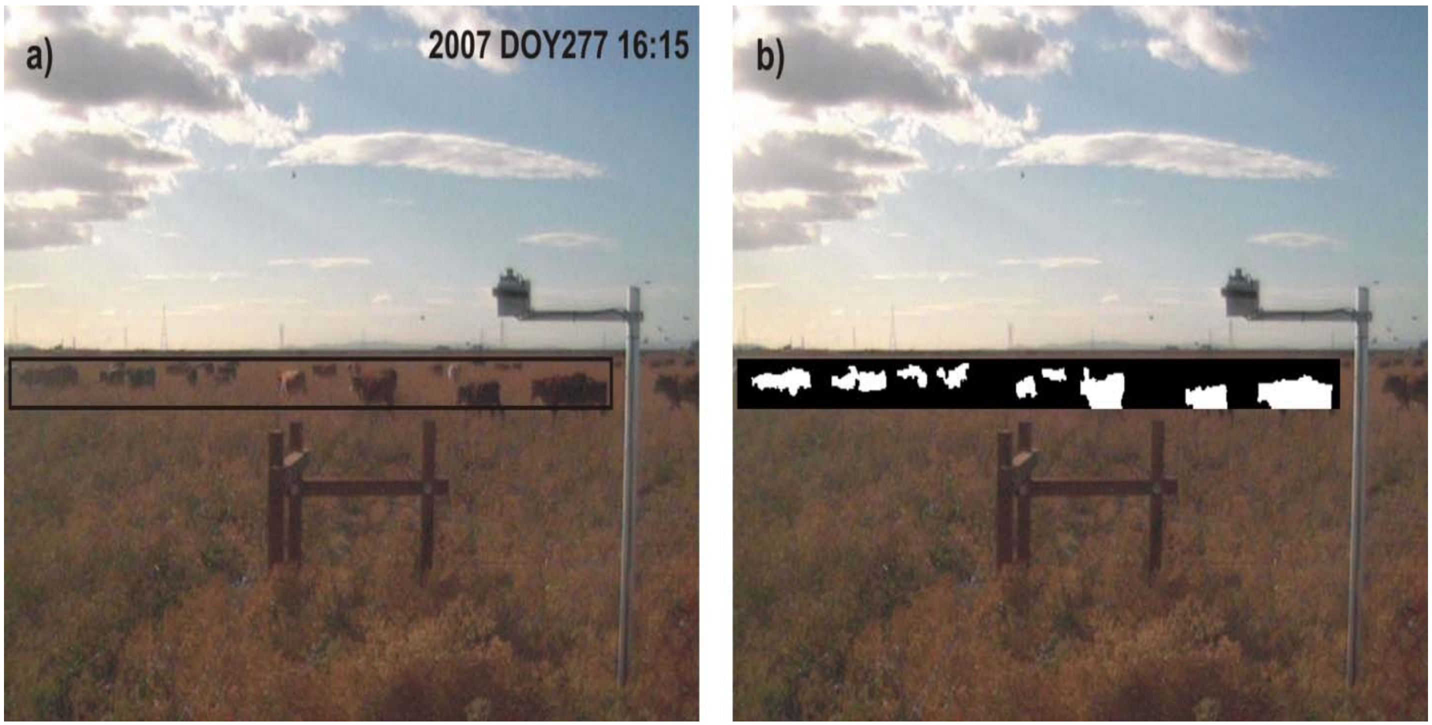


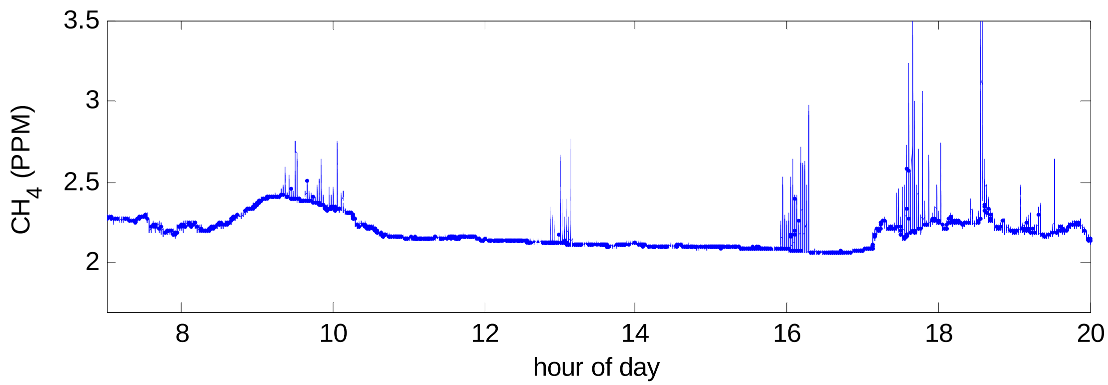
Figure 1 Relationship between dry matter (DM) intake (kg/day) and methane production (L/head/day). Data from Shibata *et al.* (1993).

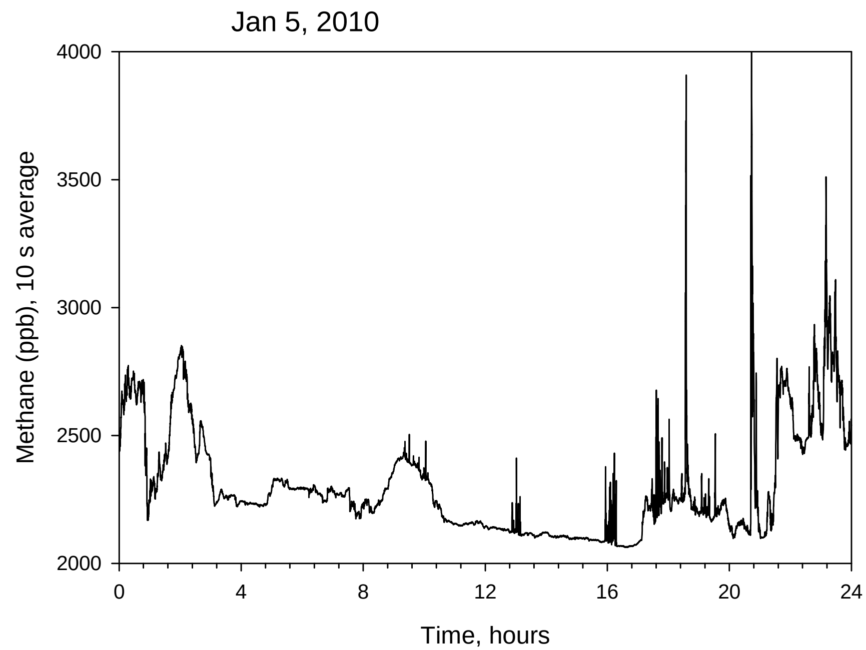
Cow Cam



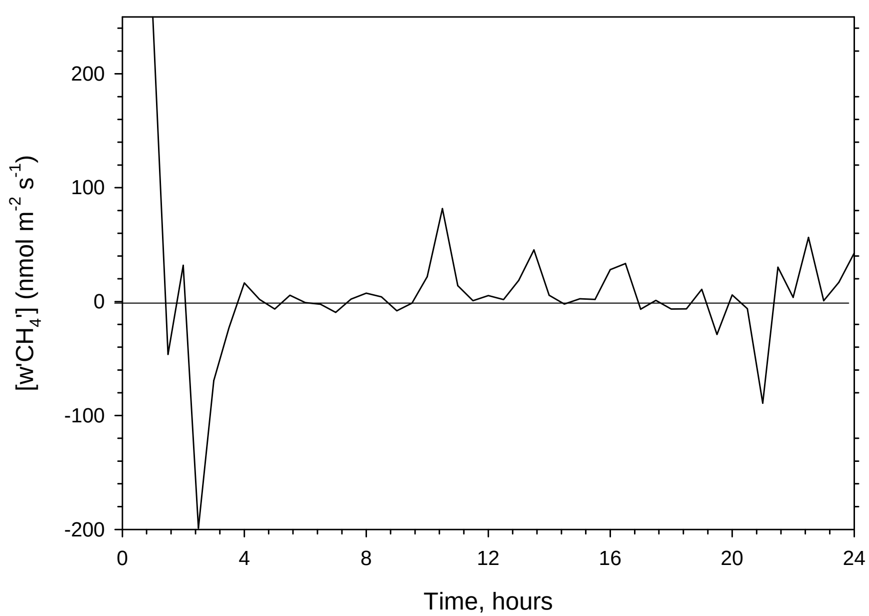
Oliver Sonnentag, analyst

The Wonders of MatLab and Inspecting Raw Data
Cows, Near-Field Diffusion and CH_4 Spikes



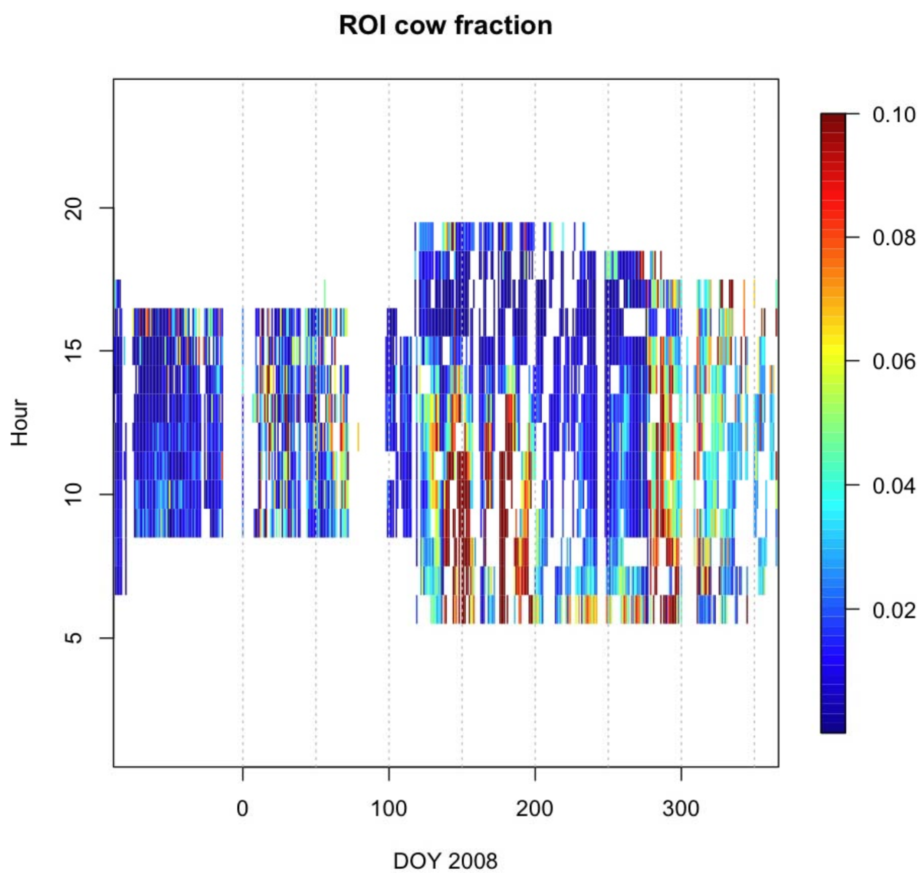


Jan 5, 2010
Methane (ppb), 10 s average
4000
3500
3000
2500
2000
0
4
8
12
16
20
24
Time, hours



[wCH4'] (nmol m-2 s-1)
200
100
0
-100
-200
0
4
8
12
16
20
24
Time, hours

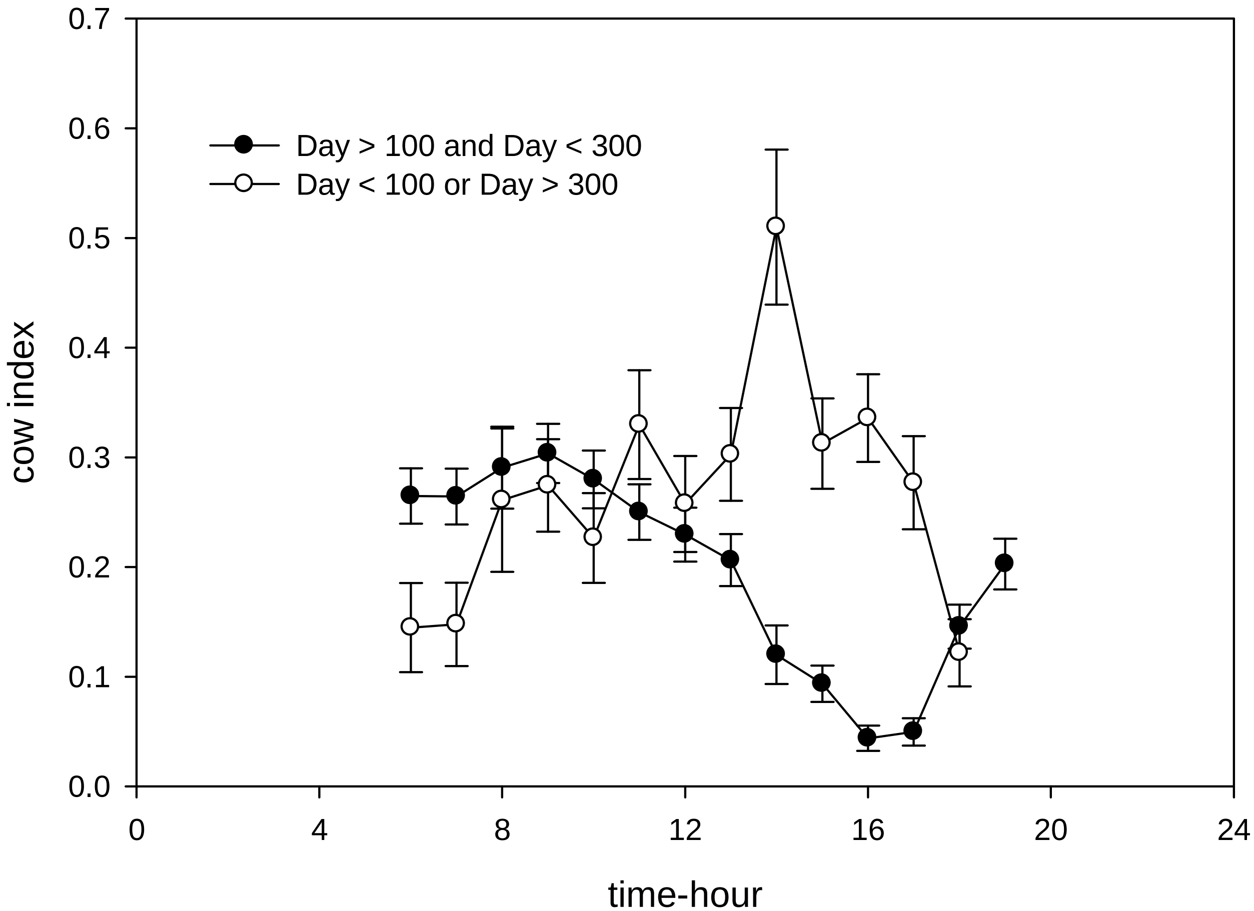
Cow-Cam Climatology



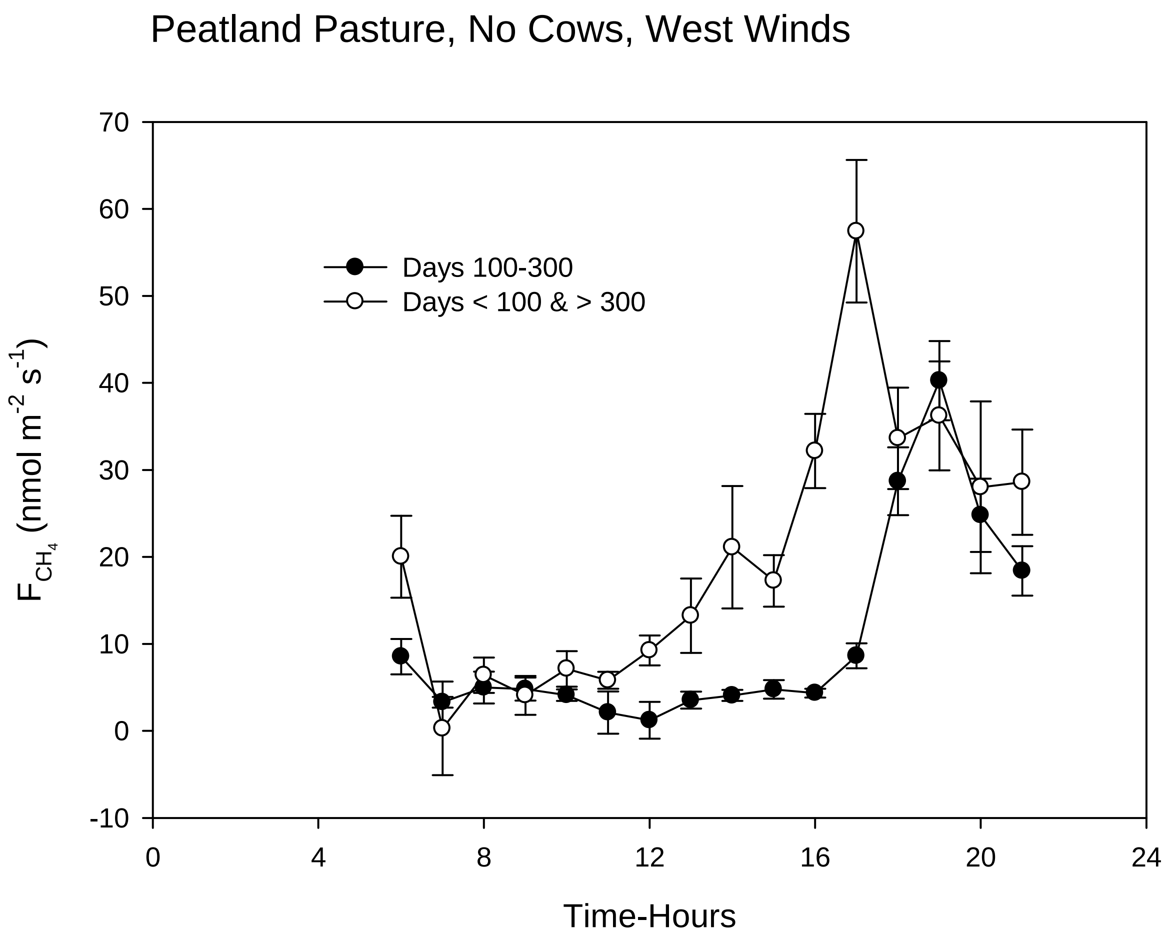
Oliver Sonnentag, analyst

Diurnal Variation in Cow-Cam Index

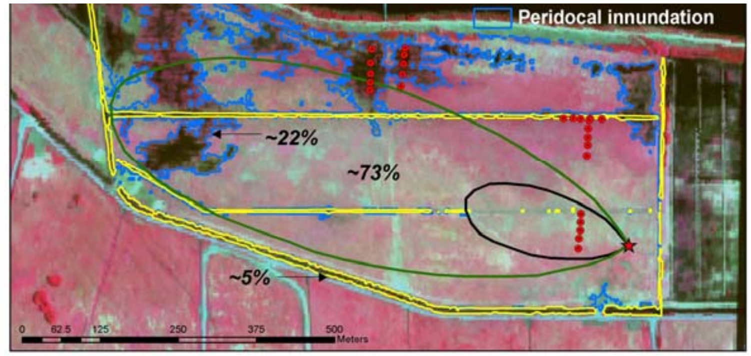
Sherman Island, Westerly Winds



Night-time Maximum in CH4 Flux Persists with No Cows in Fetch



Annual Budgets of Methane Efflux

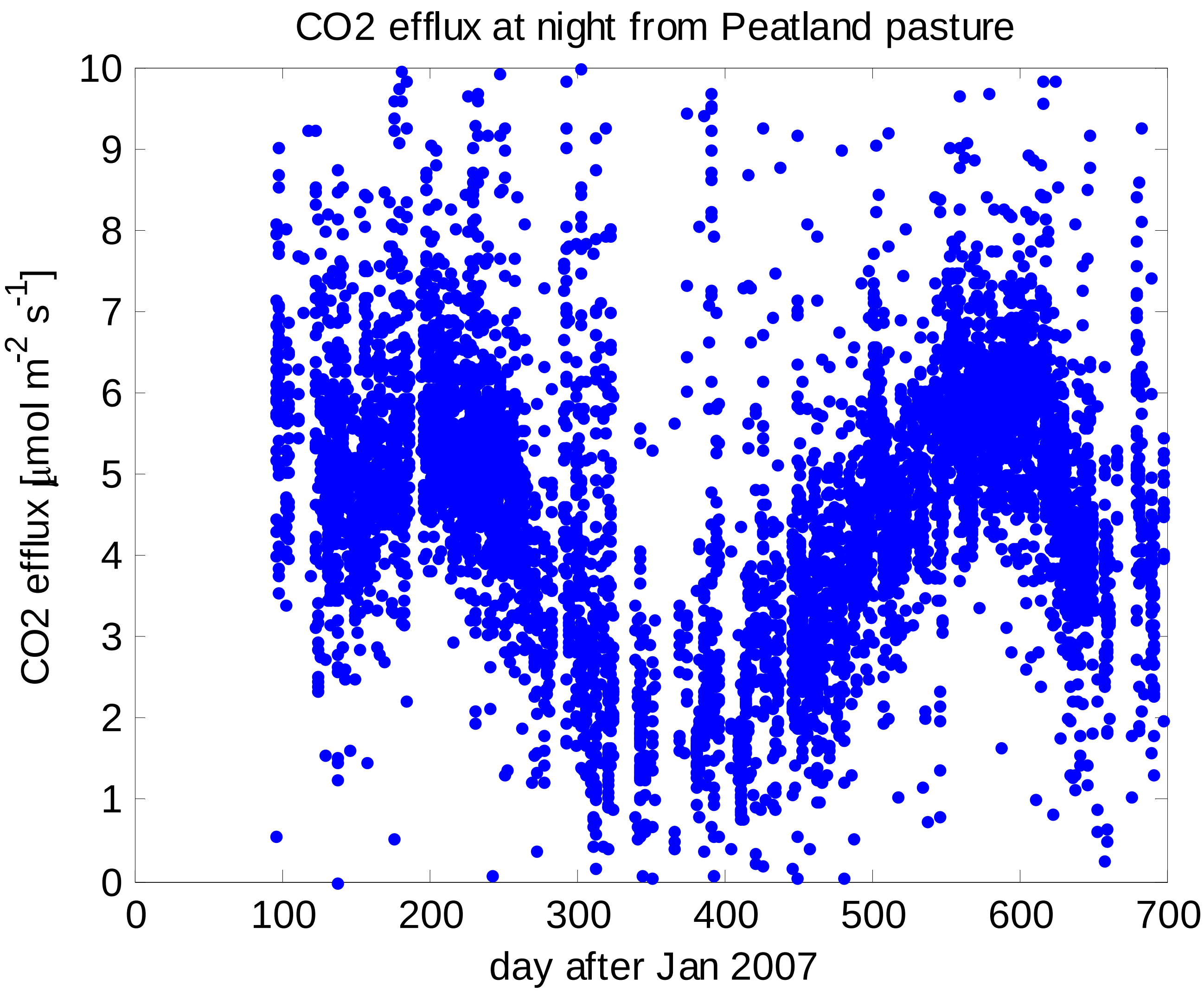


	Variable footprint	Small footprint	Large footprint	Large-small footprint: flooded-portion of the field	Small footprint: Dry portion of the field
	Day and Night, with cows	Day only, with cows	Night only, with cows	Night-Day, with cows	Day only, without cows
gC m^{-2} y^{-1}	8.66+/- 6.65	4.2 +/- 1.93	13.1 +/- 6.67	8.77	2.68 +/- 1.42
mol m^{-2} y^{-1}	0.721 +/- 0.554	0.353 +/- 0.161	1.08 +/- 0.556	0.73	0.223 +/- 0.119

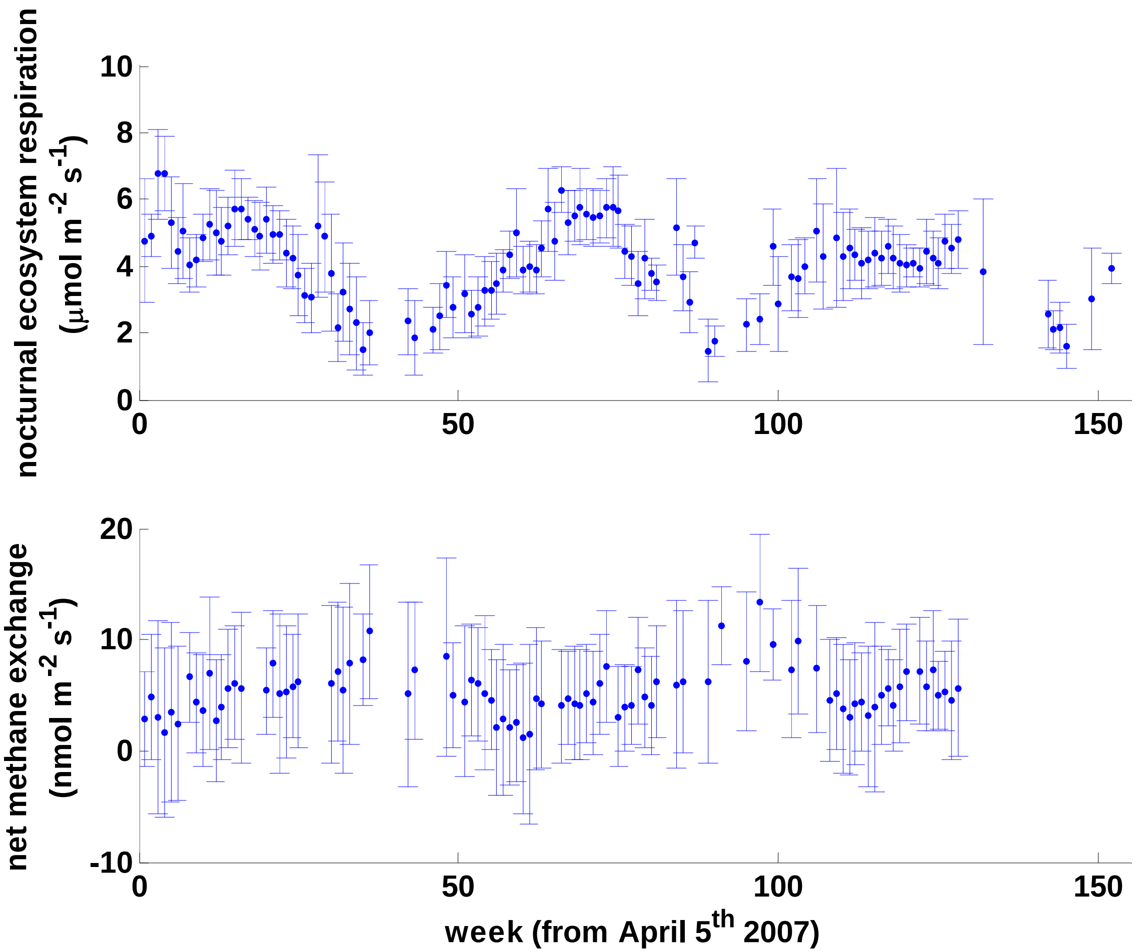
Interim Summary

- 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 s are Huge Sources of CO2 as they continue to Subside



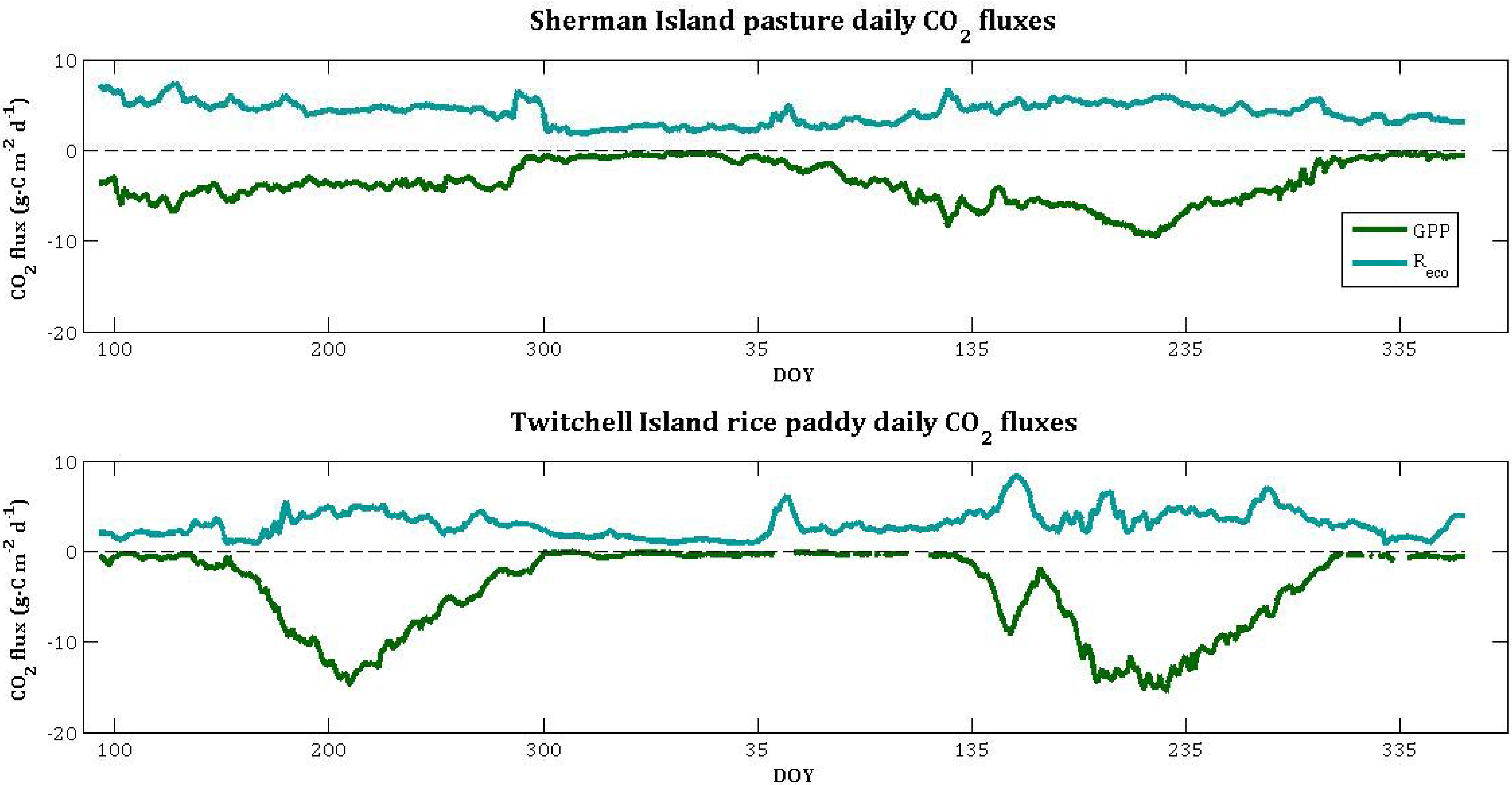
Analysis with Cow Artifacts Removed



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

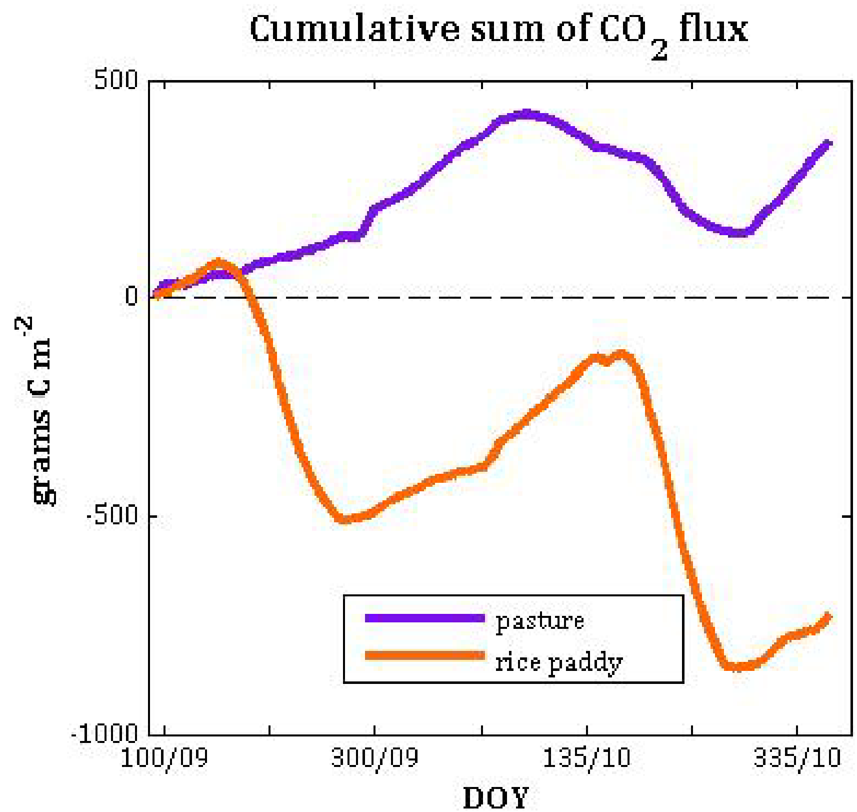
Twitchell Island Rice

CO_2: Pasture vs Rice



Hatala, Baldocchi, Detto and Verfaillie, unpublished

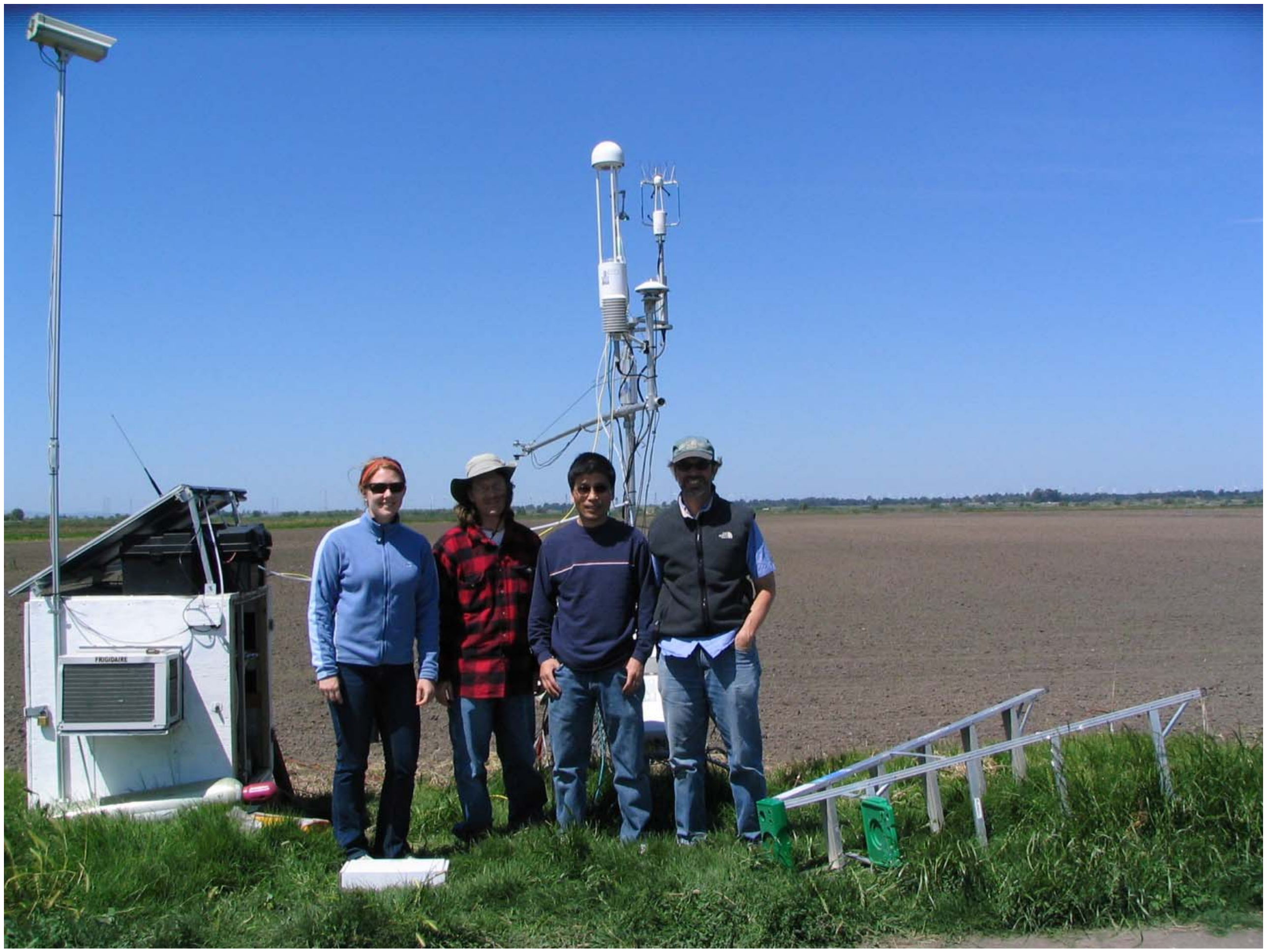
CO_2: Annual budgets



Hatala and Baldocchi

	2009	2010
Pasture	+308 g-C m^{-2}	+50 g-C m^{-2}
Rice paddy	-412 g-C m^{-2}	-316 g-C m^{-2}

New Licor 7700 Open Path Methane Spectrometer:
Low Power, NO PUMPS



New Studies, Off the Grid!

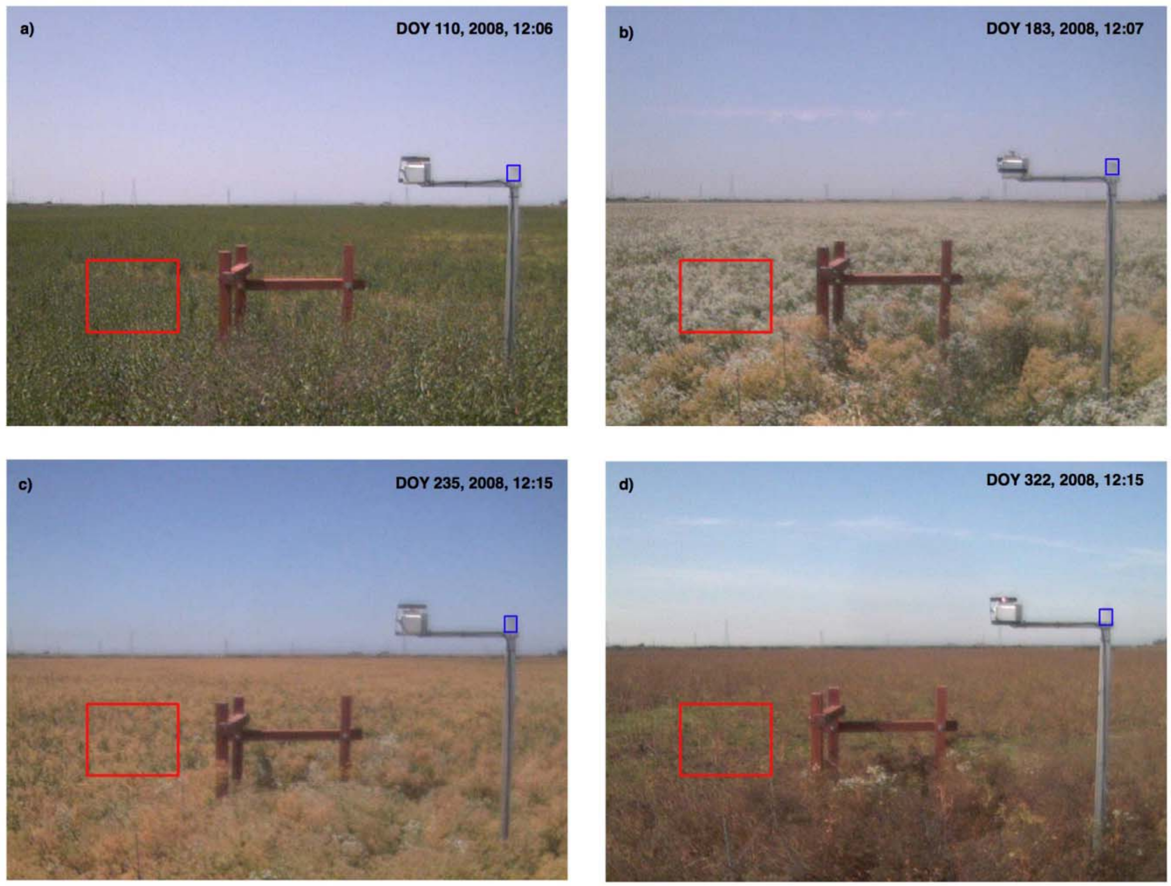
Restored Wetland, Mayberry Ranch on Sherman Island

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



Vegetation

Flowering

Seeding

Senescent

Sonnentag et al, AgForestMet, submitted

Fluxes: daily averaged