Negative carbon emissions from wetlands through restoration and management

\[ \text{CO}_2 \]
\[ \text{CH}_4 = 25 \text{ CO}_2 \text{eq} \]
\[ \text{N}_2\text{O} = 310 \text{ CO}_2 \text{eq} \]

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Special thanks to:
Global Annual Methane Emissions

40% from wetlands
Global Wetland Distribution

Temperate and tropical are limited, but have strong GWP implications
Global Wetland Methane Flux (modeled at 3°x 3°)
Rising GHG fluxes: Effects of elevated CO$_2$

Global changes are not just $f$ (temperature and water)

% effect of elevated CO$_2$ (~630 ppm)

Effect expressed on the global scale.

Wetlands store a lot of carbon in a small area (IPCC 2000)

Table 1: Global carbon stocks in vegetation and soil carbon pools down to a depth of 1 m.

<table>
<thead>
<tr>
<th>Biome</th>
<th>Area (10^9 ha)</th>
<th>Vegetation</th>
<th>Soil</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tropical forests</td>
<td>1.76</td>
<td>212</td>
<td>216</td>
<td>428</td>
</tr>
<tr>
<td>Temperate forests</td>
<td>1.04</td>
<td>59</td>
<td>100</td>
<td>159</td>
</tr>
<tr>
<td>Boreal forests</td>
<td>1.37</td>
<td>88</td>
<td>471</td>
<td>559</td>
</tr>
<tr>
<td>Tropical savannas</td>
<td>2.25</td>
<td>66</td>
<td>264</td>
<td>330</td>
</tr>
<tr>
<td>Temperate grasslands</td>
<td>1.25</td>
<td>9</td>
<td>295</td>
<td>304</td>
</tr>
<tr>
<td>Deserts and semideserts</td>
<td>4.55</td>
<td>8</td>
<td>191</td>
<td>199</td>
</tr>
<tr>
<td>Tundra</td>
<td>0.85</td>
<td>6</td>
<td>121</td>
<td>127</td>
</tr>
<tr>
<td><strong>Wetlands</strong></td>
<td><strong>0.35</strong></td>
<td><strong>15</strong></td>
<td><strong>225</strong></td>
<td><strong>240</strong></td>
</tr>
<tr>
<td><strong>Croplands</strong></td>
<td><strong>1.60</strong></td>
<td><strong>2</strong></td>
<td><strong>128</strong></td>
<td><strong>131</strong></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>15.12</strong></td>
<td><strong>466</strong></td>
<td><strong>2,011</strong></td>
<td><strong>2,477</strong></td>
</tr>
</tbody>
</table>

Note: There is considerable uncertainty in the numbers given, because of ambiguity of definitions of biomes, but the table still provides an overview of the magnitude of carbon stocks in terrestrial systems.

...but sequestration potential is uncertain, considering GHGs.

CCSP (2007), SOCCR

Wetlands United States sequestration

0.02 Pg carbon (annual sequestration) ± >100 percent

Z. Zhu et al., USGS OpenFileReport 2010-1144
Wetland GHG flux is hard to model

Competing processes, variable landscapes, dynamic substrates

- 3 pathways for methane production (Oremland 1988)
- 2 pathways for methane oxidation (Oremland 2010)
- Landscape variability (Teh et al. 2011, Ecosystems)
- Salinity variability (Poffenbarger et al. 2011, Wetlands)
- Plant species variability (Couwenberg and Fritz 2012, MiresPeats)
- Lack of environmental steady-state conditions
  - Labile carbon turnover
  - Coupled oxic-anoxic processes
    - Humic electron acceptors (Keller et al. 2009)
- GHG production ≠ GHG emission

But models are necessary for monitoring and sound decision making.
Subsided Peatland in the Sacramento-San Joaquin Delta

~7000 year old peat soils have subsided over past 150 years

Current emissions are positive:
10-20 MT CO$_2$ ha$^{-1}$ y$^{-1}$

Today: (below sea level)
• 2.5 billion m$^3$ “bowl”
~50 Tg C

By 2100:
4.5 billion m$^3$ “bowl”
~90 Tg C

USGS, 2008
**Carbon Capture Wetland Farm Bio-Sequestration**

Stops peat oxidation and accretes “proto-peat” rapidly

- Continuously submerged about 1 ft
- Low oxygen conditions
- Balance between plant growth and reduced decomposition
- Average annual soil sequestration: 1 kg C m\(^{-2}\) yr\(^{-1}\) in soil
- Equivalent to Amazon Rainforest rates

![Graph showing land surface change and CO\(_2\) emissions](image)

37 MT CO\(_2\) ha\(^{-1}\) yr\(^{-1}\)
20 MT CO\(_2\) ha\(^{-1}\) yr\(^{-1}\)

Miller et al. 2008, SFEWS
Wetland reverses CO$_2$ flux, but what about GHG flux?

From a net CO$_2$eq source to a net CO$_2$eq sink?

\[ \Delta \text{GHG} = -\left( \text{ag CO}_2 \uparrow + \text{ag N}_2\text{O} \uparrow + \text{ag CH}_4 \uparrow \right) \\
+ \text{wet CO}_2 \downarrow + \text{wet CH}_4 \uparrow + \text{wet N}_2\text{O} \uparrow \]
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+ \text{wet} \text{CO}_2 \downarrow + \text{wet} \text{CH}_4 \uparrow + \text{wet} \text{N}_2\text{O} \uparrow

High Net Productivity → High Methane Flux

Whiting and Chanton, 1993
Vann and Megonigal, 2002

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Wetland reverses CO₂ flux, but what about GHG flux?

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\[ \Delta \text{GHG} = -(\text{ag CO}_2 \uparrow + \text{ag N}_2\text{O} \uparrow + \text{ag CH}_4 \uparrow ) + \text{wet CO}_2 \downarrow + \text{wet CH}_4 \uparrow + \text{wet N}_2\text{O} \uparrow \]

Modified from Megonigal and ETH Zurich

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U.S. Geological Survey

Methane oxidation:
\[ \text{CH}_4 + 2\text{O}_2 \rightarrow \text{CO}_2 + 2\text{H}_2\text{O} \]

Methanogenesis:
- Hydrogenotrophic: \( \text{CO}_2 + 4\text{H}_2 \rightarrow 2\text{H}_2\text{O} + \text{CH}_4 \)
- Acetotrophic: \( \text{CH}_3\text{COOH} \rightarrow \text{CO}_2 + \text{CH}_4 \)
Wetland reverses CO$_2$ flux, but what about GHG flux?

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$\Delta$GHG = $-\left( \text{ag CO}_2 \uparrow + \text{ag N}_2\text{O} \uparrow + \text{ag CH}_4 \uparrow \right) + \text{wet CO}_2 \downarrow + \text{wet CH}_4 \uparrow + \text{wet N}_2\text{O} \uparrow$

<table>
<thead>
<tr>
<th>Monthly Data on Peak Daily Chamber Flux</th>
<th>C Seq (MT CO$_2$ ha$^{-1}$ y$^{-1}$)</th>
<th>C Seq - CH$_4$ in CO$_2$e$\uparrow$ Worst case scenario (Max CH$_4$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shallow Wetland</td>
<td>-65±3</td>
<td>-23±4</td>
</tr>
<tr>
<td>Deep Wetland</td>
<td>-53±4</td>
<td>0±6</td>
</tr>
</tbody>
</table>

From Miller (2011) Wetlands
Monitoring GHG Fluxes

What are the net GHG fluxes? Can we find a way to optimize GHG flux?

Eddy Covariance  Static Chamber  Leaf Photosynthesis
Net CO$_2$ Fluxes (from Eddy Covariance 2010-2012)

Night Respiration is Low
Interannual Variability is High

2011 West Pond CO2 Flux

2011 East Pond CO2 Flux

2010 East Pond CO2 Flux
Net CH$_4$ Fluxes (from Eddy Covariance 2010-2012)

Daytime Maximum - Diurnal Pattern
Limited Interannual Variability

2011 West Pond CH4 Flux

2010 East Pond CH4 Flux

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Net GWP Fluxes (from Eddy Covariance April 2011-2012)

2011 EC-based GWP for land use conversion:
MT CO$_2$ eq ha$^{-1}$ yr$^{-1} = -10 + 6.5 + 0 - (25 + 2.5) = -31$

- CO$_2$
- CH$_4$
- N$_2$O
- CO$_2$
- N$_2$O

Annual Carbon Budget West Pond (2011 - 2012)

GWP Annual Total: -351 g CO$_2$/m$^2$/yr
-3.5 MT CO$_2$/ha/yr
Interannual variability in CO$_2$ flux

Map by S. DiTomasso

NDVI 2011
Carbon Capture: Wetland Farm - Spatial Variability

Some sites are GWP sinks, and some are sources

(August 2011)

\[
\begin{array}{ccc}
\text{g CO}_2 \text{ m}^{-2} \text{ d}^{-1} & \text{C} & \text{B} & \text{A} \\
-0.2 & -15 & -49 \\
0.7 & 0.5 & 0.4 \\
\text{g CH}_4 \text{ m}^{-2} \text{ d}^{-1} & \text{C} & \text{B} & \text{A} \\
+17 & -3 & -40 \\
\text{g CO}_2\text{eq m}^{-2} \text{ d}^{-1} & \text{C} & \text{B} & \text{A} \\
\end{array}
\]
High density data (1Hz): Chamber Effect

True CO$_2$ flux may be underestimated by incubations > 1 min.

Average CO$_2$ Flux (All 8 Minutes)

Initial CO$_2$ Flux (First Minute)

- A1: $y = 0.64x + 0.5$, $R^2 = 0.93$
- A2: $y = 0.69x + 0.2$, $R^2 = 0.90$
- B1: $y = 0.59x + 0.1$, $R^2 = 0.72$
- B2: $y = 0.49x + 0.4$, $R^2 = 0.51$
- C1: $y = 0.65x + 0.7$, $R^2 = 0.90$
- C2: $y = 0.60x + 0.5$, $R^2 = 0.81$
High density data (1Hz): CH$_4$ Ebullition

Diffusion and Ebullition have different patterns

In addition to diffusive flux:
A – 7%
B – 21%
C – 34%
High density data (1Hz) from chambers

N$_2$O uptake during daytime – plant uptake?

Mean Hourly N$_2$O Flux - Piers A, B and C

![Graph showing mean hourly N$_2$O flux for Piers A, B, and C.](image)
What drives spatial variability in GHG flux?

Biomass? Temperature? Depth?

<table>
<thead>
<tr>
<th></th>
<th>C</th>
<th>B</th>
<th>A</th>
</tr>
</thead>
<tbody>
<tr>
<td>g CO₂ m⁻² d⁻¹</td>
<td>-0.2</td>
<td>-15</td>
<td>-49</td>
</tr>
<tr>
<td>g CH₄ m⁻² d⁻¹</td>
<td>0.7</td>
<td>0.5</td>
<td>0.4</td>
</tr>
<tr>
<td>Spp/Stem</td>
<td>TYAN (79)</td>
<td>TYAN (41)</td>
<td>SCAC (226)</td>
</tr>
<tr>
<td>NPP</td>
<td>2.0</td>
<td>1.8</td>
<td>4.4</td>
</tr>
<tr>
<td>Depth</td>
<td>17cm</td>
<td>17cm</td>
<td>20cm</td>
</tr>
<tr>
<td>Temp</td>
<td>18/16</td>
<td>18/16</td>
<td>20/18</td>
</tr>
</tbody>
</table>
What drives spatial variability in GHG flux?

Hydrology? Electron Acceptors?

PW Fell
- <1 ppm
- 1-10 ppm
- 10-100 ppm
- >100 ppm

PW Sulfide
- <1 µM
- 1-10 µM
- 10-100 µM
- >100 µM

PW Acetate
- <1 µM
- 1-10 µM
- 10-100 µM
- >100 µM

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What drives spatial variability in GHG flux?

**Microbial Community?**

Heatmap of Odds Ratios

- Samples with more **methanogenesis genes** have less dissimilatory sulfate/nitrate reduction genes.
- **Methane oxidation** genes were most abundant in rhizomes.
- Difference between replicate cores can be large.

Susannah Tringe, unpublished data
What can we say about net and optimal GHG fluxes:

Findings from the Carbon Capture Wetland Farm

• Inlet site has low CH$_4$ flux, apparently due to low CH$_4$ production.
  – Patterns of CH$_4$ flux track methanogens and lab incubations.
  – High rates of ebullition were observed, perhaps high as 34% of total CH$_4$ flux.
• NPP is negatively correlated with CH$_4$ flux across sites.
• N$_2$O is consumed, rather than produced, at peak growing season.
• Carbon storage may be related to plant physiology.
  – High leaf area, vertical light penetration, and carbon use efficiency (~66%)
  – High allocation to belowground biomass
• Carbon storage may be climate-related.
  – Warm days/ cool nights
What can we say about net and optimal GHG fluxes:

Management is ESSENTIAL to maintain optimal CCWF GHG flux

High rates of NEP can be restored by:
  - Maintaining water depths
  - Lodging dead material

CH$_4$ release can be limited by:
  - Enhanced consumption
  - Aerobic or anaerobic?
  - Reduced production
  - Gypsum additions? Humic?

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Challenges:

- Accurate footprint
- Laminar flow
- Larger scale than corresponding environmental data for model
Global Organic Soils Distribution

Many peat wetlands are candidates for restoration, but
avoided C loss is most important (IPCC Wetlands Supplement 2015)
We manage wetlands for many reasons. We should be able to manage them for GHG’s simultaneously.

Thank you.

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