When is a wetland a wetland?

Carbon and water cycles in north temperate fens and bogs

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Biogeo-what?

- **Land and ocean ecosystems** have biophysical and biogeochemical dependences on the atmosphere
  - **Biophysical** – Interactions of moisture, heat, solar radiation between ecosystems and atmosphere
  - **Biogeochemical** – Cycling of nutrients, especially carbon and nitrogen

- As the **atmosphere** changes, both of these are changing in ecosystems! Leading to:
SURPRISE!
**SURPRISE!**

- **Ecosystems** are generally evolutionarily adapted to regional climate and its short-term variability.

- **Expectations** of how these ecosystems respond to climate variation form the basis of ecosystem ecology and biogeochemistry.

- But: **Surprises** are likely given the complex interplay between ecosystems and climate.
Surprises are no fun for ecosystem management

But: It’s also how science progresses

And: We are likely entering an era where surprises will be more common.

Why?
Our Era

• From 1990-2005:
  – World **Population** increased 22% to ~6,500,000,000 people
  – Global **oil consumption** grew 25% to 85,000,000 barrels per day
  – Gross World Product (GWP) grew 40% to $59,380,000,000,000 US dollars

• Population **doubling** times have increased
  – 1850-1930, 80 years, 1-2 billion
  – 1930-1975, 45 years, 2-4 billion
  – 1975-2015, 40 years, 4-8 billion

Source: UCAR
Why? CO$_2$!

Source: Lüthi et al (2008), CDIAC, & Wikimedia Commons
Since 1990

- Global annual CO₂ emissions grew 25% to 27,000,000,000 tons of CO₂

- CO₂ in the atmosphere grew 10% to 385 ppm

- At current rates, CO₂ is likely to exceed 500-950 ppm sometime this century

- But: Rate of atmospheric CO₂ increase is about half the rate of emissions increase. Why?
Where Is The Carbon Going?

Houghton et al. (2007)
What's The Big Deal?

### Radiative Forcing Components

<table>
<thead>
<tr>
<th>RF Terms</th>
<th>RF values (W m(^{-2}))</th>
<th>Spatial scale</th>
<th>LOSU</th>
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</thead>
<tbody>
<tr>
<td><strong>Long-lived greenhouse gases</strong></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>CO(_2)</td>
<td><strong>1.66 [1.49 to 1.83]</strong></td>
<td>Global</td>
<td>High</td>
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<tr>
<td>N(_2)O</td>
<td><strong>0.48 [0.43 to 0.53]</strong></td>
<td>Global</td>
<td>High</td>
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<tr>
<td>CH(_4)</td>
<td><strong>0.16 [0.14 to 0.18]</strong></td>
<td>Global</td>
<td>High</td>
</tr>
<tr>
<td>Halocarbons</td>
<td><strong>0.34 [0.31 to 0.37]</strong></td>
<td>Global</td>
<td>High</td>
</tr>
<tr>
<td><strong>Ozone</strong></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Stratospheric</td>
<td><strong>-0.05 [-0.15 to 0.05]</strong></td>
<td>Continental to global</td>
<td>Med</td>
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<tr>
<td>Tropospheric</td>
<td><strong>0.35 [0.25 to 0.65]</strong></td>
<td>Continental to global</td>
<td>Med</td>
</tr>
<tr>
<td><strong>Anthropogenic</strong></td>
<td></td>
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<tr>
<td>Stratospheric water vapour from CH(_4)</td>
<td><strong>0.07 [0.02 to 0.12]</strong></td>
<td>Global</td>
<td>Low</td>
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<tr>
<td>Surface albedo</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Land use</td>
<td><strong>-0.2 [-0.4 to 0.0]</strong></td>
<td>Local to continental</td>
<td>Med - Low</td>
</tr>
<tr>
<td>Black carbon on snow</td>
<td><strong>0.1 [0.0 to 0.2]</strong></td>
<td>Local to continental</td>
<td>Med - Low</td>
</tr>
<tr>
<td><strong>Total Aerosol</strong></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Direct effect</td>
<td><strong>-0.5 [-0.9 to -0.1]</strong></td>
<td>Continental to global</td>
<td>Med - Low</td>
</tr>
<tr>
<td>Cloud albedo effect</td>
<td><strong>-0.7 [-1.8 to -0.3]</strong></td>
<td>Continental to global</td>
<td>Low</td>
</tr>
<tr>
<td>Linear contrails</td>
<td><strong>0.01 [0.003 to 0.03]</strong></td>
<td>Continental</td>
<td>Low</td>
</tr>
<tr>
<td><strong>Natural</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Solar irradiance</td>
<td><strong>0.12 [0.06 to 0.30]</strong></td>
<td>Global</td>
<td>Low</td>
</tr>
<tr>
<td><strong>Total net anthropogenic</strong></td>
<td><strong>1.6 [0.6 to 2.4]</strong></td>
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</table>

IPCC, 4\(^{\text{th}}\) AR, (2007)
The Big Deal

Observations, Northern Hemisphere, proxy data

Global instrumental observations

Projections

SRES Scenarios

Highest historical temperature level for the last 400,000 years (A)

Proposed temperature threshold for dangerous climate change (B)

Bars show the range in year 2100 produced by several models

Scenarios
- A1B
- A1T
- A1FI
- A2
- B1
- B2

IPCC AR4 (2007)
A Small Problem

Friedlingstein et al. (2005)
Carbon Cycle

Houghton et al. (2007)
No Surprises Here

• The better we can reduce **uncertainty** of how ecosystem carbon/water/energy cycling responds to climate, the better we can model future climate change and impacts.

• I will present a **story** to illustrate surprises of ecosystem responses to a changing climate based on research conducted by my lab and collaborators.
A Wetland Story

• Expectation:
  – Wetlands store carbon under wet conditions

• Therefore:
  – Restoration of north temperate wetlands should lead to increased carbon sequestration
Boreal and subarctic wetlands contain an estimated 455 Pg soil carbon.

This is up to 1/3 of total global soil carbon pool (Gorham, 1991)

Biogeochemical Interactions

Underwater (anoxic; anaerobic bacteria)

Above water (oxygenated; aerobic bacteria)

$\text{CH}_4$ $\text{CO}_2$ $\text{CH}_4$ $\text{CO}_2$
Case 1: High water table
- High latent heat loss
- Low sensible heat loss

Case 2: Low water table
- High sensible heat loss
- Low latent heat loss
Northern Highlands

Buffam et al. (2010) GCB
Buffam et al. (2010) GCB
A Tower
A Useful Tower

Flux of $C$ across this plane

+ Rate of accumulation of $C$ below the flux sensor

Net sideways transport $= 0$

Net Ecosystem Atmosphere Exchange (NEE) of $C$
Many Useful Towers
A Useful Tower With Data

Lost Creek filled NEE

Year

NEE (g·m⁻²·day⁻¹)
Methods

- Multi-year flux tower **Net Ecosystem Exchange (NEE)** observed, quality controlled, gap-filled (Desai et al., 2005)

- Rates of photosynthesis – **Gross Primary Production (GPP)** and **Ecosystem Respiration (ER)** derived from moving window regression of NEE to environmental variables; NEE = ER-GPP (Desai et al., 2008)

- Results compared to seasonal **water table depth** observations at each site (Sulman et al., submitted)

- Six state-of-the-art **ecosystem models** parameterized and run at three sites with same meteorological forcing and biometric info (Shroeder et al., in prep)
Wetland Carbon Fluxes

Lost Creek ER, GEP, and NEE

Carbon flux (μmol m⁻² s⁻¹)

Year

2001 2002 2003 2004 2005 2006 2007
Seasonal Variability

Lost Creek cumulative NEE

Cumulative NEE (g/m²)

Day of year

Interannual Variability

Lost Creek yearly NEE

Date

NEE (gC·m⁻²·day⁻¹)
Natural Experiment

Lost Creek water table level

Date

Water table level (cm)
Declining Water Table

Lost Creek water table level

- Yearly
- Summer

Water table level (cm)

Year

2000 2001 2002 2003 2004 2005 2006 2007 2008 2009

-60 -50 -40 -30 -20 -10 0
Trend?

Sulman et al. (2009) Biogeosci.
Lakes Levels Are Dropping

Stow et al. (2008)
Regional Climate Trends

- Statistically-interpolated station data 1950-2006

Change in Summer Average Precipitation (inches) from 1950 to 2006

Change in Summer Average Temperature (°F) from 1950 to 2006

Source: Center for Climatic Research & Center for Sustainability and the Global Environment, Nelson Institute, University of Wisconsin-Madison

WICCI (2009)
What Drives Water Table?

- Water table elevation is driven by precipitation and evaporation

Sulman et al. (2009) Biogeosci.
Evapotranspiration

Lost Creek daily latent heat flux

Evapotranspiration (mm/day)

Year

2001 2002 2003 2004 2005 2006 2007 2008
Lost Creek summer and yearly evapotranspiration

Evapotranspiration (mm/day)

Year

- Summer
- Yearly
Case 1: High water table
- High latent heat loss
- Low sensible heat loss

Case 2: Low water table
- Low latent heat loss
- High sensible heat loss
• Net radiation increased due to increasing incoming radiation and decrease in albedo

• Sensible heat flux increased relative to latent heat flux

• If these changes occur on a large scale, they can have significant effects on regional climate (Sampaio et al. 2007, Foley et al. 2003)
A Wet Place
Some Wet Places

• 27 site-years of data

Sulman et al. (2010) GRL
Mer Bleue

Western Peatland
Western Peatland summer and yearly evapotranspiration

Evapotranspiration (mm/day)

-ET

Western Peatland yearly and summer NEE

NEE->

Year
Sandhill Fen (Sask)
Sulman et al. (2010) GRL
Sulman et al. (2010) GRL
Sulman et al. (2010) GRL
A Ha!

- Productivity and decomposition have consistent, similar relationships to water table elevation in north temperate wetlands
- But: Fens and bogs respond in opposite fashion
  - relationship stronger in fens
- The net effect is limited response of NEE to water table in both fens and bogs
- Interannual and long-term may respond differently
Do Models Get This?

- Six model, three site intercomparison
  - Residuals = Modeled flux – Observed flux

a) ER residuals
b) GPP residuals

Courtesy of N. Shroeder, UW
Discrepancies

Lost Creek GPP
Lost Creek NEE
Lost Creek ER

Western Peatland GPP
Western Peatland NEE
Western Peatland ER

Mer Bleue GPP
Mer Bleue NEE
Mer Bleue ER

TECO
SiBCASA
SiB
ORCHIDEE
LPJ
What’s Driving This?

- Adaptation of plants to drying conditions leads to increases in water use efficiency, especially for fens, maybe?
Morals For Wetlands

• Wetland carbon cycling is not a monotonic function of water table
  – Fens may be more resilient to climate change than bogs

• Plants adapt to change, but the timescale depends on the kind of ecosystem
From Sites to Regions

- The fundamentals of ecology and micrometeorology have been mostly studied at the **plot** scale.

- The fundamentals of surface-atmosphere interaction influence on the climate systems have been mostly studied **globally**.

- **Regions** (landscapes, watersheds, continents) are where climate-ecosystem interactions are least understood and likely to hold the most surprises.
  - It’s also the relevant scale for ecosystem management.
And Of The Region?

• Northern Wisconsin is a mix of upland forest (70%) and wetland (30%)
  – Should regional CO$_2$ fluxes respond to hydrologic setting?

• We can estimate regional fluxes using
  – top-down by inverse or boundary layer budget approaches, or
  – bottom-up from forest inventory or flux-tower optimized ecosystem modeling.
Methods

• Bottom-up (scaling)
  – IFUSE – Interannual Flux-Tower Upscaling Experiment
    • 12 regional flux towers categorized by land cover and age are used to parameterize simple regional model using MCMC approach (Desai et al., 2008; in prep)
  – ED – Ecosystem Demography Model v1.5
    • Height-and-age cohort succession model tuned to Forest Inventory and Analysis (FIA) data (Desai et al., 2007)

• Top-down (atmospheric budgets)
  – EBL – Equilibrium Boundary Layer
    • 1-D boundary layer budget inferred from WLEF 447-m tall tower CO$_2$ profile, NOAA marine CO$_2$ flask network, and NARR reanalysis subsidence rates (Helliker et al., 2004)
  – CT – CarbonTracker v2009
    • Global, nested-grid inverse model based on CASA surface model, global surface continuous and flask CO$_2$ network, and Ensemble Kalman Filter tracer-transport assimilation with TM5 winds (Peters et al., 2007)
Regional Flux

- Magnitudes vary, but variability is similar

Desai et al (2010) JGR-G
Regions and Water

- Prior year water table strongly influences anomalies in regional NEE.
Morals: Nothing Is Simple

- Carbon and water cycling linkages require close examination in ecosystem models
  - Moisture stress covaries with temperature and precipitation

- Complex interactions between the physical environment and all biological systems (e.g., insects, microbes) should not be underestimated – it’s where the surprises often hide
  - Lag effects, and positive/negative feedbacks can be complex
  - Models that incorporate, test, and verify these interactions can help us anticipate surprises

- Slow, steady rates of change allow us to anticipate and react to surprises; rapid climate surprises are likely to exacerbate ecosystem surprises
  - Policies that slow climate change or destabilization are wise with respect to minimizing ecosystem disruption
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