Spruce and Peatland Responses Under Climatic and Environmental change

First Friday All Climate Change Talks
1 May 2015

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http://mnspruce.ornl.gov
SPRUCE

- An experiment to assess the response of northern-peatland, high-carbon ecosystems to whole-ecosystem increases in temperature and exposures to elevated atmospheric CO$_2$ concentrations.

- Funded by the Office of Biological and Environmental Research within the US Dept. of Energy’s Office of Science.

- A cooperative venture between ORNL and the USDA Forest Service with interested university cooperators.
Key Science Questions

• Will deep belowground warming in the future release 10,000 years of accumulated carbon from peatlands that store 1/3 of the earth’s terrestrial carbon? At what rate?

• Will releases of C be in the form of CO$_2$ or CH$_4$ with 30 times the warming potential?

• Are peatland ecosystems and organisms vulnerable to atmospheric and climatic change? What changes are likely?

• Will ecosystem services (e.g., regional water balance) be compromised or enhanced by atmospheric and climatic change?
WHY ARE NORTHERN PEATLANDS IMPORTANT?

• Culturally and aesthetically important.
• As habitat for fauna and unique flora.
• As sources of forest products, horticultural peat, and biofuels.
• As records of past environmental conditions,
• Storage of organic matter (i.e. carbon).
  – Regulate greenhouse gases in the atmosphere.
  – Have feedbacks on global climate.
Why study the response of a peatland to warming and elevated CO$_2$?

→ Conduct research on an **understudied ecosystem**
→ They systems has a potential to show **dramatic carbon cycle and organismal responses** under projected environmental and atmospheric change
→ An ecosystem located at the southern extent of the boreal forest considered **vulnerable** to climate change.
→ It is expected to generate important **greenhouse gas feedbacks** to the atmosphere (both CO$_2$ and CH$_4$)
→ Provide quantitative data to **enhance ecosystem and global circulation models** with a limited capacity to capture high-carbon wetland response
WHAT IS A HIGH-CARBON, VULNERABLE, ECOSYSTEM?

• Seasonal and annual air temperatures will be warmer and atmospheric greenhouse gas concentrations will be higher by the end of the century.

• **Temperature shifts will be greater at higher latitudes.**

• Peatlands along the northern- and southern-most fringes are expected to be most vulnerable to shifts in ecosystem regimes.

An 8 ha peatland at the Marcell Experimental Forest

11,200 ton of stored C = Amount of C emitted from 4100 Hummer H3’s in 1 year
Marcell Experimental Forest

Northern Research Station
MEF Long-Term Data Bases

- Streamflow (1960)
- Water Quality (1982)
- Water Table (1960)
- Climate (1960)
- Precipitation Quality (1977)
- Soil Temperature (1989)
- Soil Moisture (1960)
- Frost (1960)
- Snowpack (1960)
- Upland Runoff (1972)
- 40+ Thesis/Dissertations, 320+ papers

- http://nrs.fs.fed.us/ef/marcell/data/
MEF Research Program

- Peatland Hydrology and Soils
- Forest Management Effects on Water Quality and Quantity
- Biogeochemical Cycles
- Mercury
- Climate Change/Carbon Science
MEF Synthesis of 50 Years of Research

Project Setting – S1 Bog at the MEF
The SPRUCE *Picea-Sphagnum* Bog

PFTs:
- Trees (*Picea, Larix*)
- Shrubs (Spp)
  - *Sphagnum* (Spp)
- Aerobic Microbes
- Anaerobic Microbes

Soil: Histosol 2 to 3 m deep with seasonally variable water table.
S2-Bog Profile
Terrestrial vs. Peatland Ecosystem Carbon

Peatlands contain 15 times more C than occurs in a healthy regrowth forest of the Eastern US. Ecosystems.

Eastern Deciduous Forest C
WB = 15.9 kgC m⁻²
Dominated by Live Biomass

S1 Ombrotrophic Peatland C
245.1 kgC m⁻²
Dominated by Accumulated Peat
Experimental Goal: Whole-Ecosystem Warming

- A new warming approach that encompasses target ecosystem diversity, and enables decade-long observations and sampling
- An approach for long-lived and ‘tall’ stature vegetation able to produce plausible future conditions both above and belowground
- An approach to manipulate intact ecosystems (i.e., from the tops of the trees through deep soil microbial communities).
A method for whole-ecosystem warming

- 12-m diameter internal study area.
- +8-m tall aboveground chamber.
- Deep soil Heating to -2 to -3 meters within peat.
- Belowground environment enclosed in a subsurface chamber.
  (Hanson et al. 2011, Barbier et al. 2012)
Exterior Soil Heater

Interior Deep Soil Heater

Simulated Differential Soil Temperature Contours (°C)

Simulated Differential Air Warming Contours (°C)
PAST FOREST MANAGEMENT EXPERIMENT

1968

RR Bay photo

1969

RR Bay photo

1974

ES Verry photo
S1-Bog Infrastructure Development

October 2011 - Pre-SPRUCE

May 2012 - Roads and Bog Access

August 2012 - Boardwalks

November 2014 - Tank Farm Cleared

2013 - Electrical Systems added

2015 - Enclosures

April 16 – All above/below chamber structures built, glass has been installed, currently working on the duct/heater systems and runoff system.

Plan is to “flip the switch”, mid to late June – Open House Celebration August 26
Multiple levels of warming at ambient and elevated CO₂ levels:

- Soil and air temperature levels from +0 to +9 °C
  - +0, +2.25, +4.50, +6.75, and +9 °C
- Unchambered Controls
- Elevated CO₂ approaching 900 ppm which is over twice current levels, but consistent with end-of-century projections for atmospheric [CO₂].
Warming Treatment Assignments to a Regression Design (half will receive elevated CO₂)
Regression design with elevated CO$_2$ will be applied to characterize the shape of temperature response curves for a range of response variables.

10- Planned Experimental Units

Five temperature treatments with and without elevated carbon dioxide.
ENVIRONMENTAL MONITORING AND SCIENTIFIC MEASUREMENTS

Data will be archived for sharing with scientists, educators, and the public.

| Environmental monitoring: temperature, precipitation, wind speed/direction, solar radiation. |
| Tree, shrub, grass/sedge, and *Sphagnum* growth; respiration; mortality; community composition; primary productivity; root growth; litter fall; and seed dispersal. |
| Soil microbial community composition and function. |
| Phenology. |
| Plant tissue chemistry. |
| Foliar gas exchange. |
| Decomposition rates. |
| Trace gas (carbon dioxide, methane) and water vapor emissions. |
| Precipitation, runoff, and pore water chemistry for nutrients, organic matter, pH, alkalinity, ions, and trace metals. |
| Peat volume, chemistry, and physical properties. |
| Availability and cycling of carbon, nutrients, and mercury. |
| Surface runoff and water table levels. |
| High-resolution microtopography surveys. |
SPRUCE

“Hypothesized Responses”
Warming

**SPHAGNUM MOSSES**
- GPP
- NPP (Shading, desiccation)

**VASCULAR PLANTS**
+ Photosyn/Resp
+ NPP
+ Phenology
+ Mineralization enhanced “N”
? Mortality (benefits from nutrient release offset C loss)

**ECOSYSTEM FLUXES**
++ CO₂
++ CH₄
+ ET

**SPHAGNUM MOSSES**
+ GPP
+ NPP
- Nutrients (response modulated with nutrient cycle changes)

**VASCULAR PLANTS**
+ GPP
+ NPP
- Nutrients (response reduced from plant competition)

**ECOSYSTEM FLUXES**
+? CO₂
+? CH₄
- ET

**BIOGEOCHEMISTRY**
+++ Temperatures
--- WT level (Drier)
+++ Nutrient availability
++ CH₄ production and consumption

Some enhancement of nutrient availability expected from NPP derived carbon priming of the microbial systems from exudation of turnover of C pools.
Pretreatment Observations:

Setting the Stage for a Decade-Long Manipulation
Peat Profile Characterization – All Chambers

Bulk Density (g cm⁻³)

Ash %

[C] %

[N] %

CN Ratio

[P] ppm

[S] ppm

[K] ppm

[Mg] ppm

[Ca] ppm

[Si] ppm
• The mean net C accumulation rate throughout the 10,000-year peat development period was 21 g C m\(^{-2}\) y\(^{-1}\).
Modeling Wetland Processes

A Challenge for Global Circulation Models
Community Land Model (CLM) and SPRUCE

An improved land model for global wetlands (CLM-Wetlands) is being developed and tested with SPRUCE.
Water table height warming response

Multi-year declines in dry periods
CO$_2$ flux warming response

NEE (gC m$^{-2}$ day$^{-1}$)

GPP (gC m$^{-2}$ day$^{-1}$)

Hollow diff
Hummock diff
Methane warming response

- Currently uses CLM4Me model (Riley et al., 2011).
- More mechanistic treatment of microbes, methane production (Xu et al., in review) currently being calibrated with SPRUCE pre-treatment data.
- Large uncertainties

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**Hollow CH$_4$ production (gC m$^{-2}$ day$^{-1}$)**

**Hollow CH$_4$ surface flux (gC m$^{-2}$ day$^{-1}$)**

- Wet years

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**Year of experiment**

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**Year of experiment**
Nitrogen warming response

Net N mineralization (gN m⁻² day⁻¹)

- Strong increases in hollow N mineralization driven by combination of peat warming and expansion of aerobic layer.
- Less significant changes in hummock as drying occurs in deeper layer with less modeled available labile C.
- Drives significant vegetation growth in hollows, leaf area begins less than 50% of hummocks, catches up in 10 years.
- Suggestion of long term decline late in the period as litter quality declines.
Warming response of carbon stocks

- Significant increase of vegetation carbon in the hollows, slight decline in hummocks.
- More significant decline of soil organic matter carbon in hollows
- Hollows slight net sink, hummocks become moderate source
- Large model uncertainties: Sphagnum response, shading/canopy radiation changes, Changes in C allocation strategies, mortality.
Deep Peatland Heating

- Deep Peat Heating was initiated in 2014 to take advantage of installed infrastructure, get a head-start on the slow belowground warming process, and enable testing of the sensitivity of deep and old carbon stocks to warming.
- By September 9th the deep peat heating protocol had produced a wide range of temperatures by depth allowing for the assessment of a range of variable responses to deep peat heating (e.g., DOC, enzyme activity, microbial community composition, available nutrients).
Warming levels were achieved over a 25-day (+2.25 °C) to a 60-day (+9 °C) period in general agreement with an a priori energy balance model simulations.
• DPH which had limited impact on surface temperatures in the aerobic surface layers did not enhance dark CO$_2$ efflux rates.

• Following a couple of months of heating, ground-level net surface flux of CH$_4$ was correlated to deep soil temperature differences.
<table>
<thead>
<tr>
<th>Year</th>
<th>Design</th>
<th>Construction</th>
<th>Implementation</th>
<th>Completion</th>
</tr>
</thead>
<tbody>
<tr>
<td>2009</td>
<td>Research discussions begin</td>
<td>Field testing to develop sensors and protocols</td>
<td>NEPA assessment prepared, reviewed, released, &amp; approved</td>
<td>DOE funds the project through ORNL</td>
</tr>
<tr>
<td>2010</td>
<td>Field testing to develop sensors and protocols</td>
<td>NEPA assessment prepared, reviewed, released, &amp; approved</td>
<td>Collect data, analyze samples, post data, archive samples</td>
<td>Report and publish initial results</td>
</tr>
<tr>
<td>2014</td>
<td>Experiment begins</td>
<td>Collect data, analyze samples, post data, archive samples</td>
<td>Decommission and remove infrastructure</td>
<td>Report and publish final findings</td>
</tr>
<tr>
<td>2015</td>
<td>Research proposed, reviewed, &amp; approved</td>
<td>Collect data, analyze samples, post data, archive samples</td>
<td>Decommission and remove infrastructure</td>
<td>Report and publish final findings</td>
</tr>
<tr>
<td>2024</td>
<td>NEPA assessment prepared, reviewed, released, &amp; approved</td>
<td>Decommission and remove infrastructure</td>
<td>Revise global climate models to reflect results</td>
<td>Report and publish final findings</td>
</tr>
</tbody>
</table>

**TIMELINE**

- **Design**: Research discussions begin, Field testing to develop sensors and protocols, NEPA assessment prepared, reviewed, released, & approved, Design, prototype, initiate monitoring, prepare site, and construct.
- **Construction**: Experiment begins, Collect data, analyze samples, post data, archive samples.
- **Implementation**: Decommission and remove infrastructure.
- **Completion**: Report and publish initial results, Revise global climate models to reflect results.
SPRUCE
Independently-Funded Collaborators

1. The response of soil carbon storage and microbially mediated carbon turnover to simulated climatic disturbance in a northern peatland forest: revisiting the concept of soil organic matter recalcitrance. Principal Investigators: Joel E. Kostka, Georgia Institute of Technology & Jeff Chanton, Florida State University (2012-2013)

2. Toward a predictive understanding of the response of belowground microbial carbon turnover to climate change drivers in a boreal peatland. Principal Investigators: Joel E. Kostka Georgia Institute of Technology & Jeffrey P. Chanton, William T. Cooper Florida State University (2014 to present)

3. Understanding the mechanisms underlying heterotrophic CO₂ and CH₄ fluxes in a peatland with deep soil warming and atmospheric CO₂ enrichment. Principal Investigators: Scott D. Bridgham, University of Oregon & Jason Keller, Chapman University (2013 to present, with renewal pending)

4. Can microbial ecology inform ecosystem level C-N cycling response to climate change? Principal Investigators: Kirsten Hofmockel, Iowa State University & Erik Hobbie, University of New Hampshire (2014 to present)

5. Mercury and sulfur dynamics in the spruce experiment. Principal Investigators: Brandy Toner and Ed Nater, University of Minnesota & Randy Kolka and Steve Sebestyen, USDA Forest Service MN (2103 to present)

6. Improving models to predict phenological responses to global change. Principal Investigator: Andrew D. Richardson, Harvard University (2013 to present)

7. Lichen community responses to warming. Principal Investigators: Bruce McCune, Oregon State University, Sarah Jovan, USDA Forest Service OR (2013 to present)

8. Fungal, bacterial, and archaeal communities mediating C cycling and trace gas flux in peatland ecosystems subject to climate change. Principal Investigator: Erik Lilleskov, USDA Forest Service MI and Michigan Technological University with Joint Genome Institute Support (2013 to present)
9. **Effects of experimental warming & elevated CO$_2$ on trace gas emissions from a northern Minnesota black spruce peatland: measurement and modeling.** Principal Investigator: Adrian Finzi, Boston University (2014-present)


11. **Using microbial enzyme decomposition models to study the effects of peat warming and/or CO$_2$ enrichment on peatland decomposition.** Principal Investigator: Brian H. Hill and Colleen M. Elonen, Terri M. Jicha, Mary F. Moffett US Environmental Protection Agency (2014-present)

12. **Peatland Mercury Cycling in a Changing Climate: A Large-Scale Field Manipulation Study.** Carl Mitchell, University of Toronto Scarborough (2014-present)

13. **The role of the Sphagnum microbiome in carbon and nutrient cycling in peatlands - JGI's Community Science Program.** Joel E. Kostka and Gen Glass Georgia Institute of Technology, David Weston Oak Ridge National Laboratory, Erik Lilleskov USDA Forest Service – Houghton, MI, Jon Shaw Duke University, and Susannah Tringe at the Joint Genome Institute. (2015-present)

14. **Soil fauna biodiversity sampling at SPRUCE.** Zoë Lindo University of Western Ontario. (starting in 2015)

15. **Monitoring warming and elevated CO$_2$ induced changes in photosynthetic efficiency via canopy spectral reflectance.** Michael J. Falkowski University of Minnesota, Evan Kane Michigan Technological University, Brian Benscoter Florida Atlantic University, & Randy Kolka US Forest Service.

16. **Wood decomposition rates and functional types in a shifting climate.** Jonathan Schilling and Jason Oliver, University of Minnesota, Randy Kolka, United States Forest Service (starting in 2015)
## SPRUCE Effort Investment

<table>
<thead>
<tr>
<th>Institution - Job Category</th>
<th>Personnel Effort FTEs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oak Ridge National Laboratory</td>
<td></td>
</tr>
<tr>
<td>Science Staff</td>
<td>3.9 to 4.3</td>
</tr>
<tr>
<td>Technical Staff</td>
<td>3.4 to 3.9</td>
</tr>
<tr>
<td>USDA Forest Service (In-Kind Effort)</td>
<td></td>
</tr>
<tr>
<td>Science Staff</td>
<td>0.5</td>
</tr>
<tr>
<td>Technical Staff</td>
<td>0.75</td>
</tr>
<tr>
<td>SPRUCE Collaborators</td>
<td>14 Groups / 20 Institutions</td>
</tr>
<tr>
<td><strong>2010 through 2015 Site Development</strong></td>
<td><strong>Cost ($K)</strong></td>
</tr>
<tr>
<td>---------------------------------------</td>
<td>--------------</td>
</tr>
<tr>
<td><strong>ORNL In-House Costs</strong></td>
<td><strong>$1,254K</strong></td>
</tr>
<tr>
<td>[NEPA, Prototypes, MN Construction Managed through ORNL]</td>
<td></td>
</tr>
<tr>
<td><strong>Subcontracted Effort</strong></td>
<td><strong>$9,225K</strong></td>
</tr>
<tr>
<td>[e.g., boardwalks, electric, enclosures, etc.]</td>
<td></td>
</tr>
<tr>
<td><strong>Total Development $</strong></td>
<td><strong>$10,479K</strong></td>
</tr>
<tr>
<td><strong>Total Annual Operations Cost</strong></td>
<td><strong>$1,400K</strong></td>
</tr>
</tbody>
</table>
• Large-scale manipulations like SPRUCE provide a reality check for prediction models where analogs in the historical and observational record are not available for end-of-century warming and atmospheric CO$_2$ levels.

• Together, large-scale manipulations, landscape observations through time and model projections provide key inputs for National and IPCC Assessment activities.