Impact of experimental drying, rewetting and flooding on belowground biogeochemistry in a northern fen: a synthesis

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Carbon biogeochemistry in peatlands

Processes

\[ \text{Gibbs free energy} \]

\[ \Delta G_r = \Delta G_r^0 \cdot R \cdot T \cdot \ln \frac{p(CH_4)}{p(H_2)^4 \cdot p(CO_2)} \]

\( k_h, D_w \)

\( \text{Gas filled porosity} \)

\( p(O_2, CO_2, CH_4) \)

\( CH_4, CO_2 \)

\( \text{electron acceptors} \)

\( CO_2, CH_4, <CH_2O>, <DOC> \)

\( ER, GEP \)

\( \text{heterotrophic respiration} \)

\( \text{autotrophic respiration} \)

\( \text{intrinsic decomposability} (k_i) \)

\( \text{peat}, \text{peat-plants} \)

\( k_h, D_w \)

\( \text{temperature} \)

\( CH_4, CO_2 \)

\( \text{volatile fatty acids} \)

\( \text{acetate} \)

\( \text{NO}_3, \text{SO}_4, \text{CO}_2, \text{H}_2 \text{S} \)

\( \text{N}_2 \text{O}, \text{N}_2, \text{Fe(II)}, \text{Fe(III)} \)

\( \text{Humics}, \text{Humic-H}_2 \)

\( \text{Methanogenesis} \)

\( \text{Homo-acetogenesis} \)

\( \text{Hydrolysis Fermentation} \)

\( \text{organic polymers} \)

\( \text{controls} \)
Hypotheses

- Biogeochemical processes represent a continuum of opposing and competing processes that is shifted by soil moisture levels.
- Event intensity and soil physical properties control biogeochemical process dynamics during drying-rewetting.
- Intensive experimental drought suppresses post-rewetting methane production on an annual scale due to electron acceptor buildup.
- Intensive drought-rewetting has little impact on CO$_2$ fluxes because of small contribution of deeper peat layers to C fluxes.
Experimental Approach

Field

Laboratory
Experimental Approach

- **Mass balancing**
  \[
  R_N = \frac{\Delta S_A}{\Delta t} + \left[ D_A \frac{\Delta C_{A,upper}}{\Delta x}\right]_{\text{upper}} - \left[ D_A \frac{\Delta C_{A,lower}}{\Delta x}\right]_{\text{lower}}
  \]
  - $R_N$: net production in layer N; $D_A$: diffusion coefficient; $S$: storage; $C$: concentration; $X$: depth

- **Electron flow budgeting**
  \[
  \Delta e = \sum R_N \text{ (DIC)} - \sum R_N \text{ (electron acceptors)}
  \]
  - Oxidation state of organic matter: 0; reduction of nitrate to $N_2$; methane production from acetate
• Simulation of strong summer drought
• Development of unsaturated conditions in the shallow peat
Redox Dynamics – Mesocosm Experiments

- Reoxidation during drought
- Sequential reduction of electron acceptors
- Suppression of methane production
- Production of methane in near-surface microenvironments
**Redox Dynamics – Ecosystem Experiments**

- Intensity of drying events critical for type of response
- Only large events lead to
  - nitrate-sulfate renewal
  - CH$_4$ suppression
- Uppermost peat layer is reduced above water table
- -> „smearing“ of redox zonation

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Depth (cm)</th>
<th>Day of year 2008</th>
<th>Day of year 2009</th>
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<td>Acetate</td>
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<td>H$_2$</td>
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<tr>
<td>CH$_4$</td>
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<tr>
<td>pH</td>
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</table>
**Redox Dynamics – Ecosystem Experiments**

**Experimental drying**
- Strong release of sulfate
- Uppermost peat layer is reduced above water table
- CH$_4$ suppression on annual time scale

**Flooding**
- Build-up of fermentation products
- Acidification-neutralization dynamics
CO$_2$ – Ecosystem Experiments – Soil Controls
Oxygen

Flooding Controls Drying-Rewetting

Seasonal drying Rewet. Post-rewetting Pre-drying Seasonal drying Rewet.

C1 Depth (cm)
-C10 -20 -30
C2 Depth (cm)
-C10 -20 -30
C3 Depth (cm)
-D10 -20 -30

Reinforced drying Rewet. Post-rewetting Pre-flooding Flooding initial Flooding final

D1 Depth (cm)
-D5 -15 -25
D2 Depth (cm)
-D10 -20 -30
D3 Depth (cm)
-D10 -20 -30

DOY 2008 180 200 220 240 260 280 300 320 DOY 2009 100 120 140 160 180 200 220 240 260 280 300 320

Bulk density (g cm⁻³)

DO (µmol L⁻¹) 0 40 80 120 160 200 240 280 320 360 400

Estop, Blodau, Biogeosciences, submitted (2012)
Water table and AFP – Controls on $O_2$

± 20 cm window of decoupling

10 % AFP
Oxygen – Controls and modelling

Logistic regression

\[ \pi = \frac{e^{-1.602 + 0.2RWT - 0.053ASH}}{1 + e^{-1.602 + 0.2RWT - 0.053ASH}} \]

CH$_4$

Controls

Drying-Retwetting

Air Temp. (°C) 15.0 13.1 6.4 2.9
Peat Temp. (°C) 13.3 12.2 7.8 5.1

Dissolved CH$_4$ (μmol L$^{-1}$)

Dissolved CH$_4$ (μmol L$^{-1}$)

Bulk density (g cm$^{-3}$)

Flooding
$\text{CH}_4$ – Effect of Drying Intensity and Duration

Estop & Blodau, Soil Biology and Biochemistry (2012)

5 – 25 % AFP
10 – 30 days
11 – 20°C
Electron flow budgets – Missing Methane

- Strong continued CO₂ production with no net electron acceptor consumption
  ⇒ oxygen in rhizosphere of sedges and in capillary fringe
- Drought generated electron acceptors to drive CO₂ production for 50-100 days
- Suppression of methane due to unknown electron acceptors likely

\[
\begin{align*}
\text{oxidation:} & \\
& 2383 \,(s) \\
& 342 \,(aq)
\end{align*}
\]

Knoor, K.H., Blodau C., Soil Biology and Biochemistry (2009)
Electron flow budgets – Missing Methane

Estimated pool of produced DIC (mmol m$^{-2}$)

Flooding initial
DOY 140-202

Flooding final
DOY 202-327

- nitrate
- sulfate
- iron
- oxygen
- methane
- acetate
- other processes

Plot - Period

D1  D2  D3  D1  D2  D3

Estop, Blodau, Biogeosciences, submitted (2012)
Strong redox dynamics with impact on methane production on the scale of weeks to months in mesocosm experiments.

Little impact of drying and rewetting on C-fluxes in mesocosm experiments with Wt between 10 and 50 cm.
**CO$_2$ Fluxes – Field experiments**

- Soil respiration flux in agreement with mesocosm results
- Little impact with drying/rewetting with WT between 20-80 cm below surface
- Soil respiration rather driven by soil temperature

Chamber flux data from Muhr, Höhle, Otieno, Borken (2010)
CO₂ Fluxes – Incubations – Soil Controls

Incubation experiments

- CO₂ rates (mmol g OM⁻¹ d⁻¹)
  - 5 cm
  - 10 cm
  - 15 cm
  - 20 cm
  - 25 cm
  - 30 cm
  - 40 cm
  - 50 cm

- AFP range (%)
  - Anaerobic
  - 3-7
  - 13-17
  - 23-29
  - 32-39
  - 44-50

Flux simulation - measurement

- “modelled” vs. “field measured”
- Water table range field

Surface layer dominates production

Estop & Blodau, Soil Biology and Biochemistry (2012)
Conclusions

• Enhanced summer drought leads to effective oxidation of reduced inorganic pools and suppression of methanogenesis in a minerotrophic fen on an annual scale
• The response is modulated by organic matter reactivity, bulk density, AFP -> entirely different response is possible
• TEAPs and methanogenesis coexist at and above water table when fluctuations small
• Effect of soil moisture and water table on C fluxes is small as there is a „short-circuit of carbon“ near the peatland surface
Thank you for your attention!

Marieke Osterwoud, Silke Hammer, Karin Söllner, Gunnar Lischeid
German Science Foundation (DFG)
Research Unit FOR 562 Soil Processes
under extreme meteorological conditions
Experimental Approach

Drying
- June 2008

Artificial rewetting
- August 2008

Post-rewetting
- November 2008

Flooding
- July 2009
Experimental Approach