Biogeochemistry of C and nutrients in peatlands: 

**Applied aspects**

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- Biogeochemical processes wet / dry
- Decomposition and eutrophication
- Role of water & sediment quality
- Applied ecological issues: desiccation / restoration / wetland creation / water storage
Natural Development of Raised Bogs in Ireland

- **7000 BC**
  - Mesolithic fisherman.
  - Glacial Moraine
  - Hazel and pine forest.

- **1500 BC**
  - Oak, Ash, Elm and farmland.
  - Bronze Age "hoard"
  - Peat
  - Fen

- **500 BC**
  - Trees on bog during dry period.
  - Heather
  - Birchwood and farmland.
  - Peat

- **500 AD**
  - Trees engulfed by the peat.
  - Marshy fen

- **1900 AD**
  - Turf drying in the Sun.
  - Cutting turf for fuel.
  - Agricultural drainage scheme.
Peatlands

1. High efficiency for C storage: low pO$_2$, low pH (bogs), recalcitrant organic matter (e.g. phenolic compounds), high C refixation potential.

2. Drainage, combustion, eutrophication, and S-pollution; transition C sink to source.

2. Biogeochem. key processes, ecosystem-microbial level;
   - global change (T, CO$_2$, CH$_4$, H$_2$O, N, S)
   - flooding risks (peat settlement)
   - reversal C sink-source transition (peatland restoration)
decomposition - waterlogged

mmol m⁻² day⁻¹

PMW  ZW  WI  WO

bog  fen

CH₄  CO₂

Lamers et al. in prep
Temperature and CO₂ concentration in the atmosphere over the past 400,000 years (from the Vostok ice core)

**CO₂ concentration, ppmv**

**Temperature change from present, °C**

**Year before present (present = 1950)**
Without greenhouse effect most of the earth’s surface covered with ice: 33°C colder!
Atmospheric Carbon Dioxide
Measured at Mauna Loa, Hawaii

Annual Cycle

Carbon dioxide concentration (ppmv)
temperatuurverhoging: voorspellingen
Global Carbon Cycling

Increased C sources (loss)
- Combustion fossil organic C
- Clearing of (rain)forests
- Drainage and increased T peatlands: decomposition
- Increased T permafrost
- Increased T decomposition other ecosystem types

Increased C sinks (sequestration)
- Increased primary production terrestrial ecosystems
- Increased primary production oceans (?)
Additional effect increased CO$_2$

- Higher primary productivity leads to higher proportion of recently assimilated organic carbon
- Higher DOC losses

  *Freeman et al. Nature 2004*

- Changes in plant composition due to interspecific competition
• Increased primary production?

- C4 plants
- dry tropics

[C4 plants diagram]

- C3 temperate regions
- actual level

[C4 CO₂ assimilation graph]

- CO₂ assimilation (µmol CO₂ m⁻² s⁻¹)
- Ambient CO₂ concentrations, Cₐ (µbars)
Figure 1. The global carbon cycle. All pools are expressed in units of $10^{15}$ gC and all fluxes in units of $10^{15}$ gC yr, averaged for the 1980s. Modified from Schlesinger (1997).
Northern peatlands: 20-30% of the global soil C stock
Decomposition of drained peatlands to 800 million tonnes CO₂ a year

- South East Asia: 62%
- Rest of Asia (without Russia): 16%
- Europe (without Russia): 9%
- Americas: 8%
- Africa: 4%
- Russia: 1%
Vulnerable Carbon Pools

**LAND**

- Permafrost: 900 Gt C
- High-latitude peatlands: 400 Gt C
- Tropical peatlands: 100 Gt C
- Vegetation subject to fire and/or deforestation: 650 Gt C

**OCEAN**

- Methane Hydrates: 10,000 Gt C
- Solubility Pump: 2,700 Gt C
- Biological Pump: 3,300 Gt C
Melting permafrost peatlands at Noyabrsk, Western Siberia. Succow (IMCG)

Carbon from the Pleistocene era
Pristine peat swamp forest, Sumatra.

Kalimantan: Peatland forest on fire
- Peat landscape: lakes, marshes, bogs, meadows - gradients pH-O₂-nutrients
- High biodiversity: succession
- Deterioration: desiccation, eutrophication, Spp loss, C sink-source transition
C-loss & land subsidence

[Map showing areas of different land subsidence levels in the Netherlands]

TNO / NITG / RWS
Relative Biomass (%) vs. CO₂ concentration in water layer (µmol L⁻¹)

Paffen & Roelofs Aquat Bot 1991
$\frac{\text{C-efficiency}}{\text{13C-CH}_4 \text{ into Sphagnum sterols:}}$

10-15% of total C source
Peat extraction

Vincent van Gogh 1883
Airborne pollution

N concentration Sphagnum (mg g^-1)

total inorganic N-deposition (kg ha^-1 a^-1)

Sphagnum "H-filter" unsaturated

Maier Oikos 1988
Branzetti et al. PNAS 2004
Eutrophication
Nutrient limitation

- **P** o-phosphate
  
  *e.g.* marshes, fens

- **N** ammonium, nitrate
  
  *e.g.* fen vegetations, moorland pools, bogs
  
  *often: N+P limitation*

- **C** inorganic carbon
  
  *e.g.* moorland pools, lakes, bogs
  
  *(C+N limitation)*

- **K** some fen meadows

*(Eutrophication always related to kind of nutrient)*
External eutrophication:
Eutrophication by extra input of nutrients from outside the system

Internal eutrophication:
Eutrophication by increased mobilization of nutrients inside the system (particularly in peatlands)

PO$_4^{3-}$ \quad Fe^{3+}(O)(OH) \quad Ca (O)(OH) \\
\rightarrow \quad PO$_4^{3-}$ \sim Fe^{3+}(O)(OH) \quad PO$_4^{3-}$ \sim Fe^{2+} \\
Ca_{10}(PO$_4$)$_6$(OH)$_2$ \quad (CaHPO$_4$) \\
\rightarrow \quad Org-P
Decomposition:

Metabolic breakdown of organic matter (humus, peat) to simple organic and inorganic molecules, generating energy.

Mineralisation:

The transition of a nutrient or another substance from organically-bound form to water soluble inorganic form, as a result of biological or (inorganic) chemical processes.
Regulation of decomposition / mineralisation in peatlands

- **Nutrient concentrations**

- Concentration / degradability organic matter

- Alkalinity (ANC)

- Ion strength: Cl⁻

- Electron acceptor availability (microbial redox reaction):

  \[
  \text{O}_2, \text{NO}_3, \text{Fe, SO}_4^{2-} : \\
  \text{SO}_4^{2-} + 2 \text{CH}_2\text{O} \rightarrow \text{HS}^- + \text{HCO}_3^- + \text{CO}_2 + \text{H}_2\text{O} \\
  \text{mineralisation (N, P, K)} \\
  \text{sulphide} \\
  \text{P mobilisation (Fe ~ P)} \\
  \text{acid buffering}
  \]
(bicarbonate) alkalinity

Smolders Ph.D. Thesis 1995
Smolders et al. Chem. Ecol. 2006
electron acceptor availability

Sweet track – Somerset Levels – 3806 BC

Decomposition

S: low high

electron acceptor availability

oxygen

\[ \text{CO}_2 + \text{CH}_4 (\text{mmol m}^{-2} \text{d}^{-1}) \]

waterlogged
moist
dry

0 50 100 150 200
WI WO

Lamers et al. in prep.
Regulation of decomposition / mineralisation in peatlands

- **Phenolic compounds regulate hydrolase activity**
- **Drainage (O\(_2\) intrusion) stimulates phenol oxidase, lowering phenolics, stimulating decomposition**

*Freeman et al. Nature 2001*

**Table 1 Effects on enzyme activities**

<table>
<thead>
<tr>
<th>Effect of oxygen on enzyme activity</th>
<th>Control</th>
<th>Manipulated</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sulphatase</td>
<td>66 ± 2.3</td>
<td>35 ± 1.4</td>
</tr>
<tr>
<td>Phosphatase</td>
<td>571 ± 2.4</td>
<td>387 ± 7.9</td>
</tr>
<tr>
<td>β-Glucosidase</td>
<td>237 ± 2.3</td>
<td>17.7 ± 12</td>
</tr>
<tr>
<td>Phenol oxidase</td>
<td>615 ± 93</td>
<td>4,350 ± 27</td>
</tr>
</tbody>
</table>

**Effect of increasing phenol oxidase abundance**

| Phenolics (µg l\(^{-1}\)) | 1,985 ± 55.4 | 1,444 ± 9.9 |
| β-Glucosidase              | 10,677 ± 280  | 1,216 ± 180  |

**Effect of phenolic removal on hydrolase activity**

<table>
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<tr>
<th>Sulphatase</th>
<th>Control</th>
<th>Manipulated</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phosphatase</td>
<td>3,707 ± 25</td>
<td>4,369 ± 180</td>
</tr>
<tr>
<td>β-Glucosidase</td>
<td>2,163 ± 180</td>
<td>2,163 ± 180</td>
</tr>
<tr>
<td>Xylosidase</td>
<td>116 ± 2.5</td>
<td>134 ± 5</td>
</tr>
<tr>
<td>Chitinase</td>
<td>243 ± 14</td>
<td>296 ± 3.5</td>
</tr>
</tbody>
</table>

Phenol oxidase activity (nmol 2-carboxy-2,3-dihydroindole-5,6-quinone formation min\(^{-1}\) per g peat), hydrolase activities (nmol methylumbelliferyl core formation min\(^{-1}\) per g peat) and phenolic compound concentrations (µg l\(^{-1}\)) are reported as mean ± s.e.
nitrate

Under investigation
Total N loss: 10-15 kg N ha⁻¹ day⁻¹

Fluorescence in situ hybridization (FISH) analysis of β-proteobacterial Thiobacilli

Van der Weele et al. FEBS Microbiol. Lett. 2006
sulfate

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Lamers et al. ES&T 1998
sulfate

Lamers et al. Limnol Oceanogr 2002
Roelofs Aquat Bot 1991
Smolders & Roelofs Aquat Bot 1993
$P$-limitation

- **surface water**
  - sulfate

- **groundwater**
  - reduction
    - alkalinity, sulfide
  - iron

Connections:
- Atmosphere
- Iron
- Sulfate reduction
- Alkalinity, sulfide
N-limitation

eutrophication

HPO$_4^{2-}$

HS tox.

Fe defic.

mineralization

FeS$_x$ ~ Fe ~ P

alkalinity, sulfide

reduction
% damaged roots

C. disticha

J. acutiflorus

0 20 40 60 80 100

C 25 S 250 S
Carex disticha

Juncus acutiflorus
Stratiotes aloides

Smolders et al., 1996
Phragmites australis

- Armstrong et al., 1996
**Caltha palustris**

- Detoxifying toxicants

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**Van der Welle et al. Environ.Tox.Chem. 2006**

**Smolders & Roelofs New Phytol. 1996**
Wetland restoration ?!
Rewetting measures in carr woods oxbow lakes

**before**
**after**

Stagnating high water table during summer generates strong eutrophication!!
Intensification of agriculture resulted in lower groundwater tables and desiccation of fens.
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Rewetting by damming groundwater or inlet of allochthonous surface (river) water:
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Stagnant, NO₃ low

Flowing, NO₃ high

Dubbroek carr
Stagnant, NO₃ low (µmol L⁻¹)

Lucassen et al 2004
Flowing, NO$_3$ high (µmol L$^{-1}$)
Kaldenbroek fen: no temporary desiccation (first two years)
Dubbroek: temporary desiccation

Lucassen et al 2005
Natural water table fluctuation: proof from 1617!

Rubens & Brueghel: Pan & Syrinx in Arcadia (Hollandica)
Towards a more natural hydrological regime:

- **Now:**  
  - Winter *low:* drainage (agriculture)  
  - Summer *hoog:* supply (agriculture, nature)  

Artificial regime!

- **Future:**  
  - Winter *higher:* water storage  
  - Summer *lower:* modest desiccation

**Profits:**
- Less allochthonous water
- Less P-mobilisation, more P-binding
- Stimulation growth and germination helophytes (e.g. Reed)
- Stimulation germination aquatic macrophytes
- Detoxification (e.g. for sulphide)

**Drawbacks (??):**
- Desiccation and S mobilisation (??)
- Increased mineralisation (??)
- Problems for infrastructure, recreation, homes
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Shallow peat lake (Geerplas, the Netherlands)

13 µmol/L!

Michels et al. 2007
Shallow peat lake (Geerplas, the Netherlands)

- Dredging
- Inlet P-stripped water!

13 µmol/L!

45 µmol/L!
sulfate
Flooding and wetland creation / restoration: seasonal effect?

- Winter
- Spring
- Summer

Sulphide (µmol/l)
- Wet + sulphate
- Wet
- Dry (-12 cm)

Phosphate (µmol/l)
- (5°C - 8/16 - flo)
- (20°C - 12/12 - flo)
- (20°C - 16/8 - dry)
Water storage

- Winter: less harm

In existing wetlands

- Spring/summer: high eutrophication risk (especially with alkaline, S-rich water)
- \( \Rightarrow \) not in oligo-/mesotrophic wetlands

In combination with wetland creation?

- Low conc. mobilisable P: - ok
- High conc. mobilisable P: - either remove top layer and P
- - or hypertrophic wetland
### Measures?

1. Lower influx P N
2. Hydrological measures: decreased internal mobilization!

<table>
<thead>
<tr>
<th></th>
<th>Input '82-'92</th>
<th>Weerribben '98</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Water</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HCO$_3^-$</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>SO$_4^{2-}$</td>
<td>1.5</td>
<td>0.3</td>
</tr>
<tr>
<td>Cl$^-$</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>PO$_4^{3-}$</td>
<td>0.5 / 1.5</td>
<td>2</td>
</tr>
<tr>
<td><strong>Sediment</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PO$_4^{3-}$</td>
<td>25</td>
<td>3</td>
</tr>
<tr>
<td>Fe</td>
<td>3</td>
<td>30</td>
</tr>
</tbody>
</table>

Conclusions

- Global change effects complex: decomposition, primary production, changes vegetation
- Mineralization (partly) coupled to decomposition
- Internal eutrophication: pollutants from the past
- Water en soil quality
- Management (e.g. wetland restoration) should take account of these internal processes