Hydrology & Aquatic Carbon: Detecting Signals of Permafrost Thaw

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Rivers as Integrators of Terrestrial and Aquatic C Cycling

- Groundwater (DOC, DIC)
- Permafrost
- Surface runoff (DOC, DIC, POC, PIC)
- Sedimentation & Resuspension
- Decomposition of POC, DOC
- Photosynthesis
- Soil water (DOC, DIC)
- Bank erosion (POC, PIC, DOC, DIC)
- Weathering
- Respiration
- DIC + CaCO₃
- Decomposition of POC, DOC
- Sedimentation & Resuspension
- Glacial runoff (PIC)

CO₂, CH₄
Inland Waters as Reactors of Terrestrial Carbon

~2.9 Gt C yr\(^{-1}\) enters inland waters from terrestrial sources:
- 30% is discharged to oceans,
- 20% is sequestered in sediments,
- 50% is emitted to the atmosphere.

Active Aquatic Ecosystem Model
(Cole & others 2007; Tranvik & others 2009, SOCCR2)

Terrestrial Ecosystems
(NEP 1.6 – 4.2 Gt)

2.9- (6.4?)

CO\(_2\) & CH\(_4\) evasion
1.4 – (5?)

0.6
Sediments

Inland Waters

0.9
Ocean
WHAT IS AQUATIC CARBON?

- Carbon Gases ($\text{CO}_2$ & $\text{CH}_4$)
- Dissolved Inorganic Carbon (DIC)
- Dissolved Organic Carbon (DOC)
- Particulate Organic Carbon (POC)
- Particulate Inorganic Carbon (PIC)

Exact amounts of C emission and transport are not well quantified for inland waters in high latitudes… but they are known to be changing…..
Permafrost Thaw & Lateral C Exports

**Warming Scenario I**
- Active Layer (Increased Depth & duration)
- Soil DOC
- Respiration
- INCREASED DOC export to river
- DIC export to river

**Warming Scenario II**
- Active Layer (Increased Depth & duration)
- Soil DOC
- Respiration
- INCREASED CO₂
- INCREASED DIC export to river
- NO CHANGE or DECREASED DOC export to river

*Striegl et al., GRL, 2005*
Permafrost Degradation is *Inferred* by Changes in Hydrology, Mineral Weathering Products & C Exports

• **BASIN SCALE**
  • Decadal shifts in DOC & DIC exports *(Striegl et al. 2005; Frey & McClelland, 2009; Tank et al. 2016)*
  • Decadal increases in infiltration and baseflow *(Walvoord & Striegl 2007)*
  • Changing lake hydrology *(Wellman et al. 2013)*
  • Increased regional groundwater flow *(Walvoord et al., 2012)*
  • Increased weathering product exports *(Tank et al. 2012; 2016)*

• **INTERMEDIATE SCALE**
  • Inter-annual switching in DOC & DIC export *(Dornblaser & Striegl 2015)*

*But what about an aged $^{14}$C signal from permafrost thaw?*
Aiken et al., 2014, GBC; Raymond et al., 2007, GBC; Neff et al., 2006, GRL
Seasonal Shifts in $\Delta^{14}C$ Reflect Changes in Flowpath and Water Source

O’Donnell et al., JGR-B, 2014
Seasonal Shifts in Dominant Stream Source

**Surface Runoff**
- Dominant in Spring
- High [DOM]
- Short flow path
- Modern DOC

**Groundwater**
- Dominant in Winter
- Low [DOM]
- Long flow path
- Aged DOC

What are the chemical character and biodegradability of direct runoff from permafrost thaw?
Vonk et al. 2013, GRL; Wickland unpublished data
Recent focus: DOC from Pleistocene loess (yedoma) in the Yukon and Kolyma basins.

Vonk et al., 2013; Mann et al. 2015; Spencer et al., 2015; Drake et al., 2015

What’s different about the hydrology and composition of permafrost DOC?
HETEROGENEOUS SYSTEMS
(Not all Yedoma)

Large variability in:

I. Carbon source strength

II. Carbon & water flow path & residence time

III. Carbon chemistry & degradability

Map: Torre Jorgenson
Through cross-scale investigations, we aim to coalesce process-based understanding and large-scale observations -- ultimately advancing prediction capability.
I. Carbon source strength

Wide Range in Permafrost Soil C-Content & Leachability

- Holocene Active Layer
- Holocene Permafrost
- Pleistocene Permafrost (non-Yedoma)
- Yedoma

\[ R^2 = 0.76 \]

\[ R^2 = 0.63 \]
I. Carbon source strength

DOC Release from Active-Layer & Near-surface (<1m) Permafrost Soils

For a given soil C content or radiocarbon age, near-surface permafrost soils yield more DOC upon thaw than active-layer soils immediately above the permafrost boundary.

Histels and Turbels, the most spatially abundant permafrost soils, have the greatest potential for increased DOC release with near-surface permafrost thaw.

Wickland et al., submitted to ERL special issue
II. Carbon and water flow path & residence time

> Thaw > Infiltration > Residence Time & GW Contribution to Flow

- **95% Permafrost coverage**
  - Recharge = 28 mm/yr
  - (6% basin ppt)

- **89% Permafrost coverage**
  - Recharge = 55 mm/yr
  - (11% basin ppt)

- **67% Permafrost coverage**
  - Recharge = 146 mm/yr
  - (30% basin ppt)

Walvoord et al., 2012, WRR
II. Carbon and water flow path & residence time

Subsurface conditions are locally variable and transient =
Wide range in hydraulic connectivity & water residence time

Repeat survey in 2015

Figure: Burke Minsley
III. Carbon chemistry & degradability

General Trend Across the Arctic:

Biodegradability (BDOC) decreases from continuous to non-permafrost landscapes.

*Vonk et al., Biogeosciences 2015*
III. Carbon chemistry & degradability

RECENT ADVANCES:

• Kolyma: Yedoma DOC runoff preferentially degraded relative to modern DOC (Mann et al, Nature Comm, 2015)

• Kolyma: Rapid biodegradation of aliphatics in DOC from headwater streams (Spencer et al, GRL, 2015)

• Yukon: Large amounts of low molecular weight (LMW) organic acids (acetate) in yedoma permafrost DOM (Ewing et al, GRL, 2015)

• Yukon: Very rapid biodegradation of LMW organic acids (acetate & butyrate) & CO$_2$ production in yedoma leachates (Drake et al, PNAS, 2015)

• Yukon - ABoVE: Accumulation of LMW DOC in near-surface permafrost soils (Wickland et al, submitted ERL)
I., II., III. Carbon source, residence time & degradability

Water Residence Time (Days)

DOC Biodegradability (Per Day)

Drake et al. 2015; Spencer et al. 2015; Vachon 2015
I., II., III. Carbon source, residence time & degradability

<table>
<thead>
<tr>
<th>I. C Source</th>
<th>II. Residence time in flowpath</th>
<th>III. Degradability</th>
<th>Potential for</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pleistocene loess (yedoma)</td>
<td></td>
<td></td>
<td>Downstream Export</td>
</tr>
<tr>
<td>High source</td>
<td>Long RT</td>
<td>High deg.</td>
<td>Small export</td>
</tr>
</tbody>
</table>

| Colluvium | | | Moderate export | Mod. CO₂ / CH₄ |
|-----------|-------------------|-------------------|-----------------|
| Low source | Short RT | Moderate deg. | = | = |
Needs & Continued Research:

**Subsurface geophysics** – Characterization of permafrost extent & soil physics in undisturbed & disturbed locations.

**Hydrology** – Improved understanding of the partitioning & routing of surface & subsurface flow with varying permafrost.

**Carbon Biogeochemistry** – Amount, degradability, age, and chemical composition of permafrost carbon along aquatic flow paths.

**Models** - Develop field-verified reaction, chemical character & transport models of permafrost DOC, DIC, nutrients.
Thanks!