Water Table Dynamics & CO_2 Fluxes

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Journal of Hydrology

Volume 509, 13 February 2014, Pages 245-256

Water table fluctuations and soil biogeochemistry: An experimental approach using an automated soil column system

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Soil & Climate

Climate: One of the most important factor on **Soil Processes**

Climate governs the **rate and type of soil processes** and is also the main determinant of **vegetation distribution**.

Climate has two major components:

1) **Moisture**
2) **Temperature**

The factors that determine the **Soil Temperature**:

- air temperature, snow, rain, evaporation rate, type of vegetation

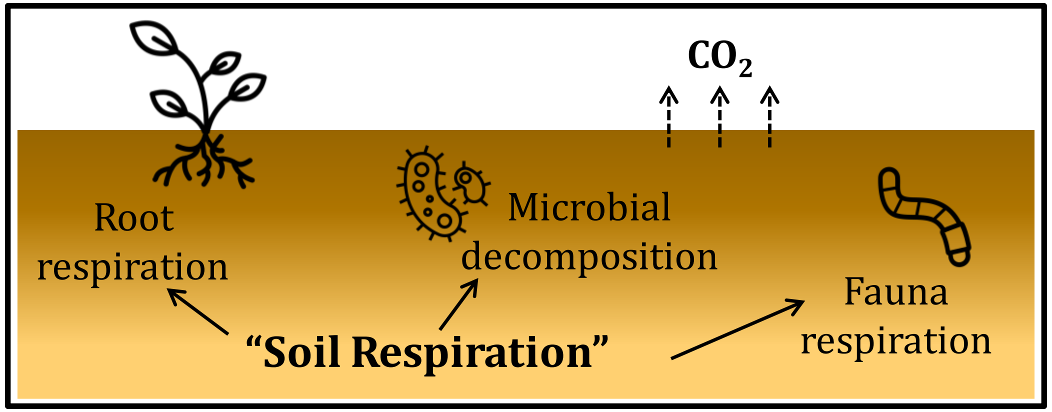
The factors that determine the amount of **Soil Moisture**:

- snow, rain, irrigation; water storage capacity of soil; evaporation rate; height of water table; amount and type of vegetation

Climate and Soil Biological Properties: Soil Respiration

- Soils are the largest carbon pool in terrestrial ecosystems
- **Microbial activity**, measured in terms of biomass and respiration, reflects the flux of carbon

Soil respiration refers to the production of CO_2 when soil organisms respire.



- **Major pathways:**

Respiration: soil organic C + O_2 → atmospheric **CO_2**

*under anaerobic conditions the electron acceptors change (*e.g.*, NO_3-, SO_4^{2-}, methanogenesis)

Fermentation: soil organic C → atmospheric **CO_2**

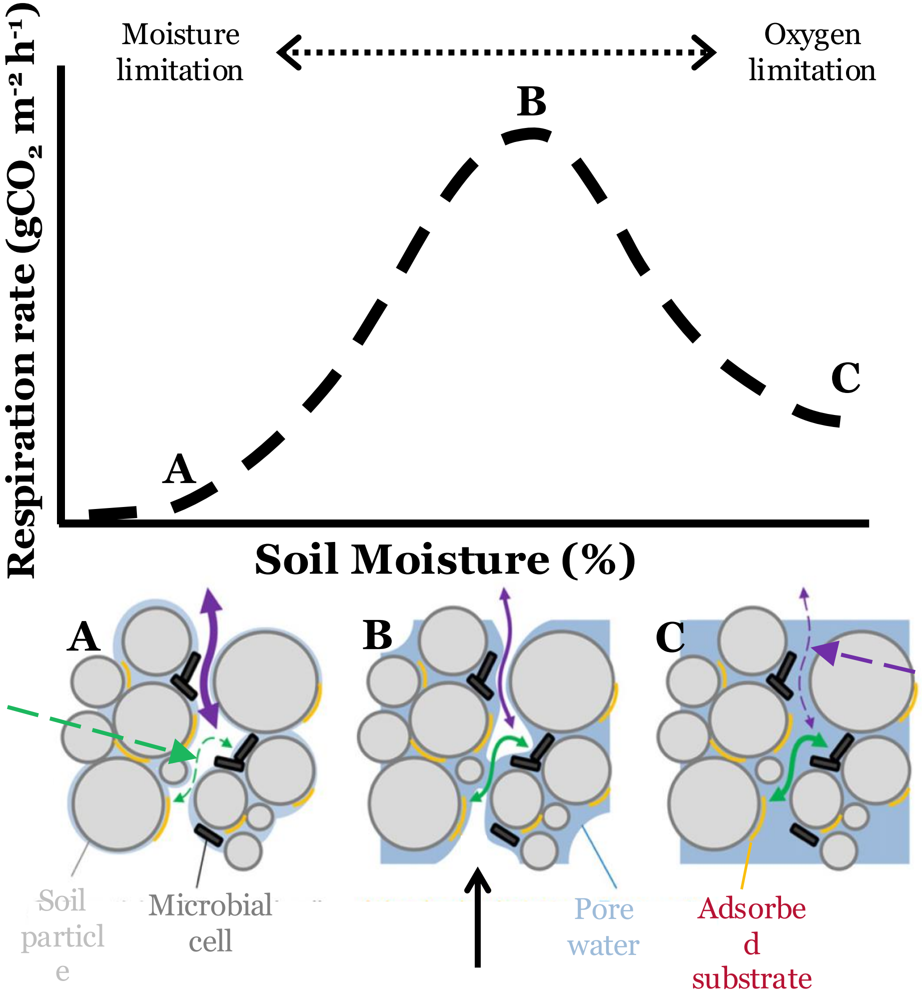
Soil Respiration influenced by:

Physical factors (**soil water**, **temperature**, structure and etc.)

Chemical factors (pH, **oxygen**, cation exchange capacity, salinity and etc.)

Biological factors (soil fauna, organism interactions and etc.)

Soil Respiration & Soil Moisture



Low soil moisture

Low connectivity of

H_2O-filled pores

↓

Limited diffusion of dissolved substrates (*e.g.*, organic carbon)

High soil moisture

Low connectivity of

air-filled pores

↓

Limited diffusion of oxygen

Figure modified from Moyano et al. 2013; Linden Fairbairn

- **Soil moisture**
  - As moisture increases, respiration rates increase until the pores are overly saturated, resulting in lower oxygen content and lower soil organism respiration
  - ~60% pore space saturation (field capacity) is ideal for respiration
  - Dry soils have low respiration rates because of less support for biological activities

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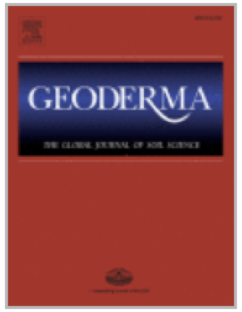
Geoderma

Volume 434, June 2023, 116493



Relationship between soil CO_2 fluxes and soil moisture: Anaerobic sources explain fluxes at high water content

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$$DOC_{av} = D_l[DOC]\theta^n \tag{4}$$

$$O_{2,liq} = 0.209D_g(\phi - \theta)^{4/3} \tag{5}$$

where $[DOC]$ is the DOC concentration of the porewater, n is an empirical (adjustable) parameter, θ is the volumetric water content, and 0.209 is the volumetric fraction of O_2 in air ($L\ L^{-1}$); the dimensionless D_l and D_g coefficients account for transport rates in the aqueous phase and across the gas–water interface, respectively. The volumetric water content, θ, is given by:

$$\theta = \theta_s\phi + \theta_r(1 - \theta_s) \tag{6}$$

where θ_s is the water saturation (WFPS) and θ_r is the residual water content. In our experiment, θ_r values were much smaller than θ_s and, therefore, we assumed that $\theta = \theta_s\phi$. Air-filled porosity is calculated as ($\phi - \theta$).

Our extended model also considers CO_2 fluxes not derived directly from aerobic mineralization of DOC. For simplicity, all the "anaerobic" CO_2 sources are combined into one term (R_{An}):

$$R_{An} = V_{max,An}\frac{DOC_{av}}{k_{c,An} + DOC_{av}}\frac{k_{in}}{k_{in} + O_{2,liq}} \tag{7}$$

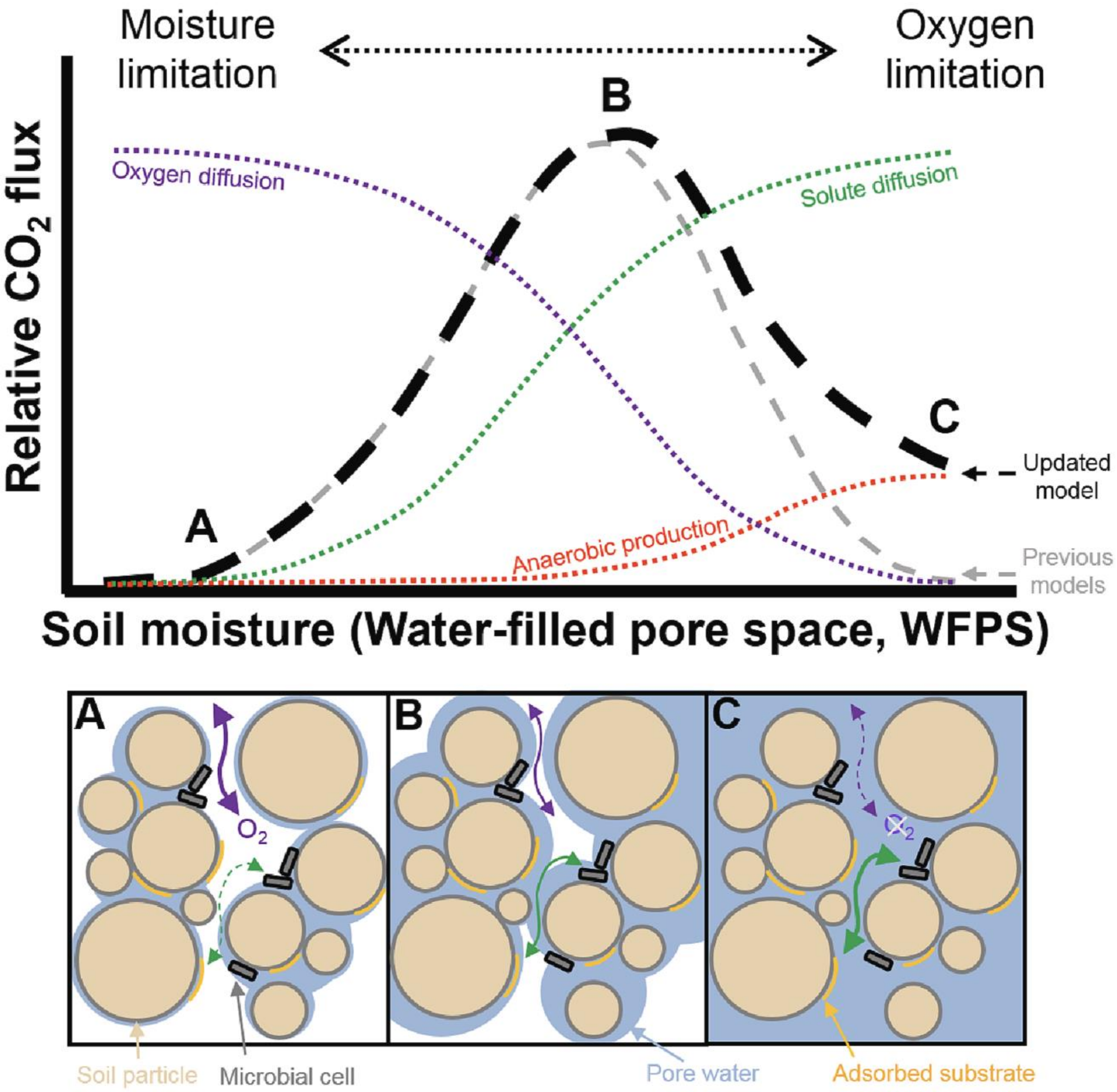
where $V_{max,An}$ is the maximum rate of anaerobic CO_2 production (nmol cm^{-3} hr^{-1}) and $k_{c,An}$ is the corresponding half-saturation constant of DOC. The last term on the RHS of Eqn. (7) accounts for the inhibition of anaerobic CO_2 production by O_2 using an inhibition coefficient k_{in} (Van Cappellen and Gaillard, 2018). The amalgamation of all CO_2 production processes other than aerobic respiration into one term is further discussed in the Discussion section.

In the oxic incubations, CO_2 fluxes result from both the aerobic and anaerobic production terms that, in turn, both depend on the soil moisture content. Substituting Eqns. (3), (4), (5), and (7) into Eqn. (2) gives the following equation for the CO_2 fluxes in the oxic incubations:

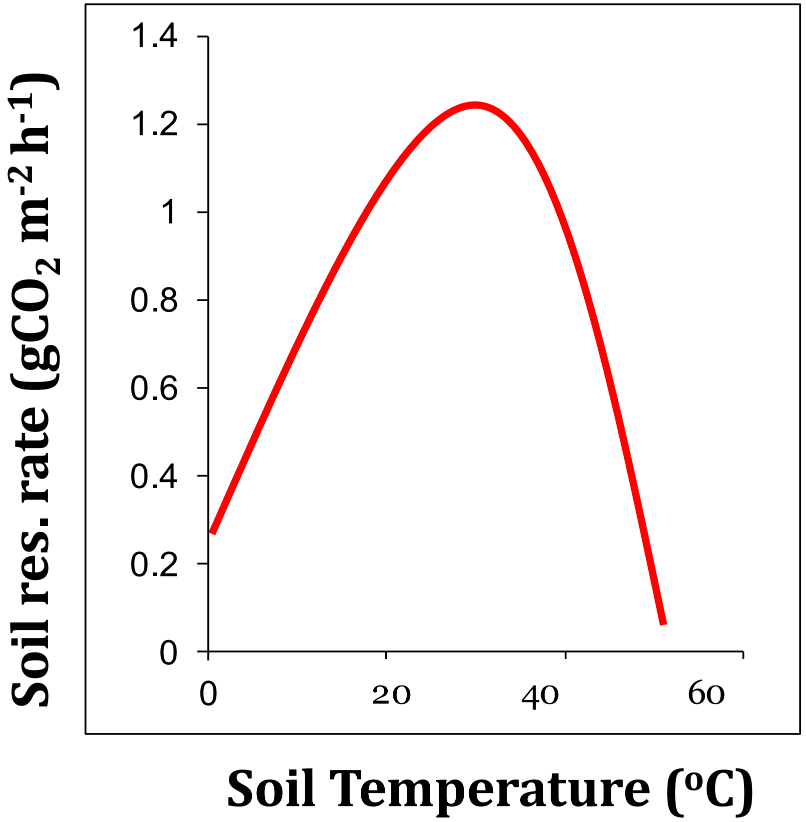
$$\begin{aligned}(R_{CO_2})_{Ox} = {} & V_{max,Ox}\frac{D_l[DOC]_{Ox}\theta^{n_{Ox}}}{k_{c,Ox} + D_l[DOC]_{Ox}\theta^{n_{Ox}}}\frac{0.209D_g(\phi-\theta)^{4/3}}{k_o + 0.209D_g(\phi-\theta)^{4/3}} \\ & + V_{max,An}\frac{D_l[DOC]_{Ox}\theta^{n_{Ox}}}{k_{c,An} + D_l[DOC]_{Ox}\theta^{n_{Ox}}}\frac{k_{in}}{k_{in} + 0.209D_g(\phi-\theta)^{4/3}}\end{aligned} \tag{8}$$

In the anoxic incubations, however, only R_{An} contributes to the observed CO_2 fluxes. Because the inhibition term on the RHS of Eqn. (7) now equals 1, R_{An} is given by:

$$(R_{CO_2})_{An} = V_{max,An}\frac{D_l[DOC]_{An}\theta^{n_{An}}}{k_{c,An} + D_l[DOC]_{An}\theta^{n_{An}}} \tag{9}$$



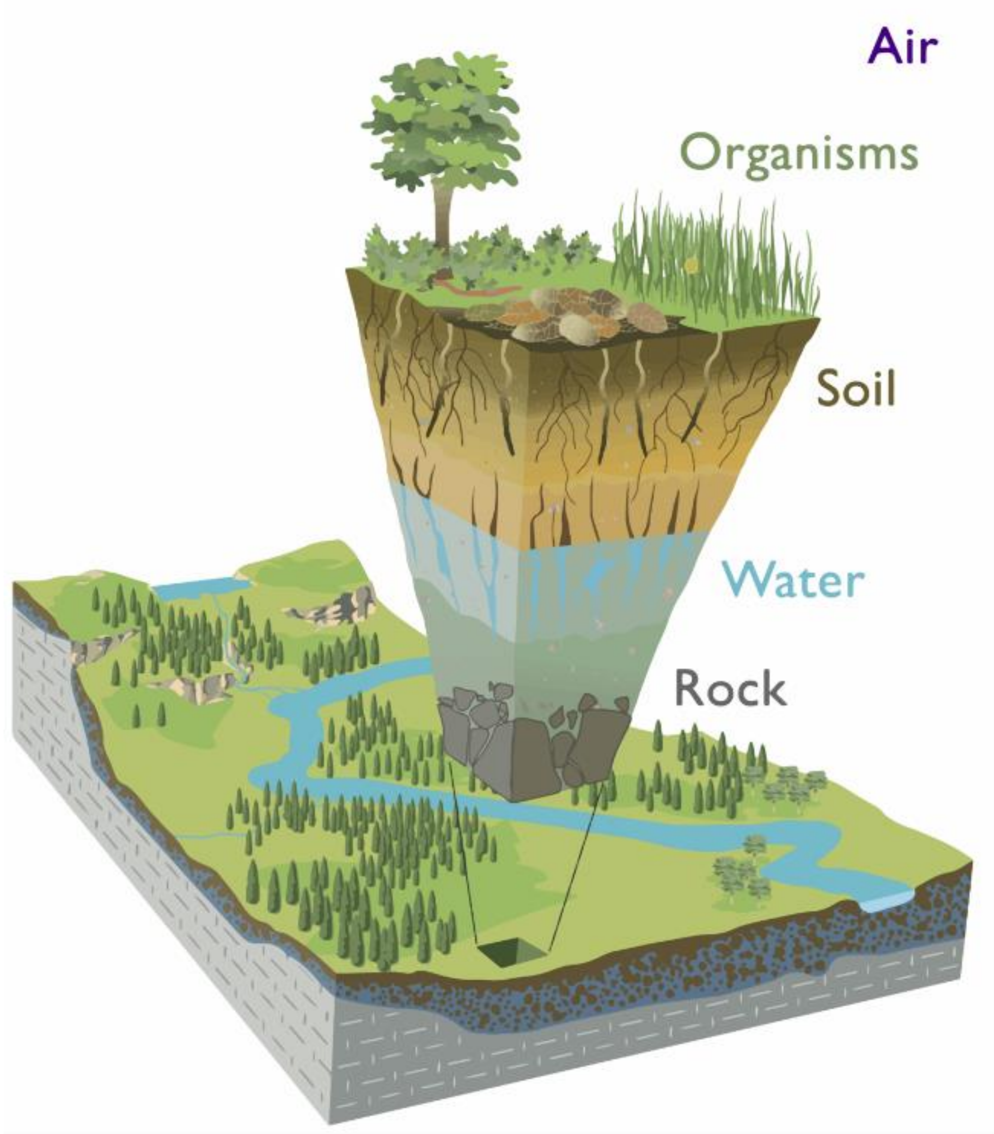
Soil Respiration & Soil Temperature



Soil temperature

- As temperature increases, respiration rates increase up to a threshold of ~30-35°C, above which respiration rates decrease with increased temperature

- Colder soils have low respiration rates due to lower biological activity



Chorover *et al.* (2007)
(Artwork by R. Kindlimann)

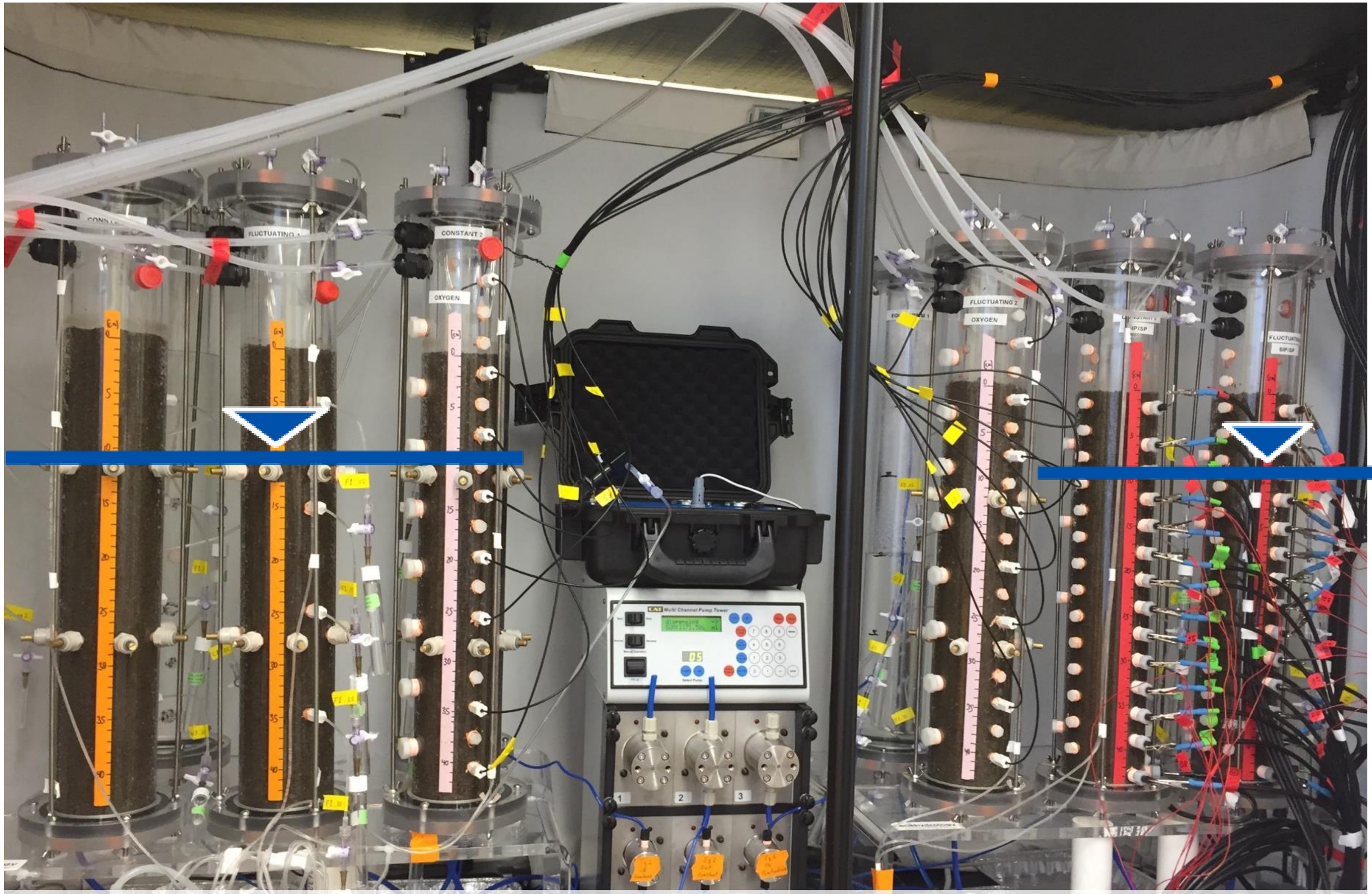
Dynamic Hydrological and Climatic conditions:

- **Wet-dry cycles**
- Flooding events
- Groundwater extraction
- **Freezing and thawing cycle**
- Land use

Biogeochemical Processes:

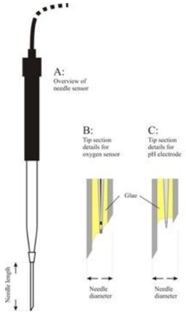
- Turnover of carbon, nutrients and redox-active elements
- Emissions of greenhouse gases

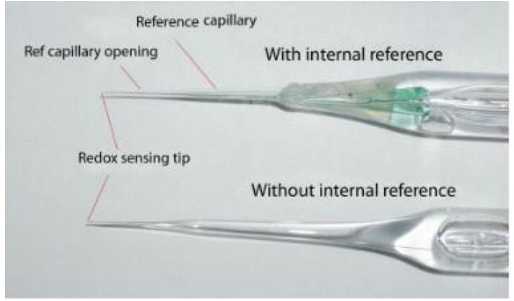
Automated Water Table-Soil Column System

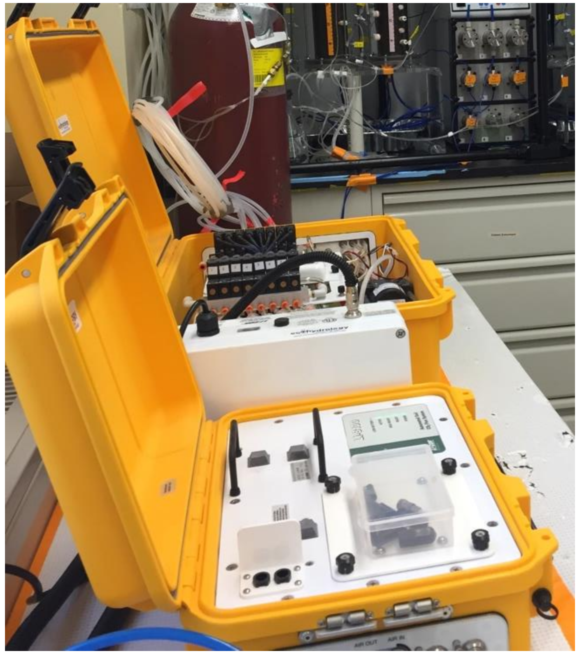


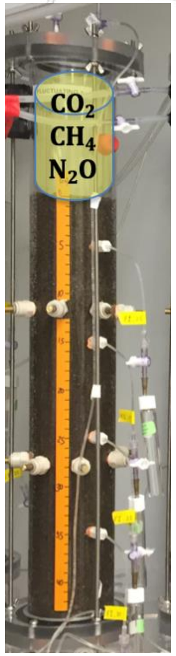
The role of "**Water Table Oscillations**" in the
"**Biogeochemical Functioning of Soils**"

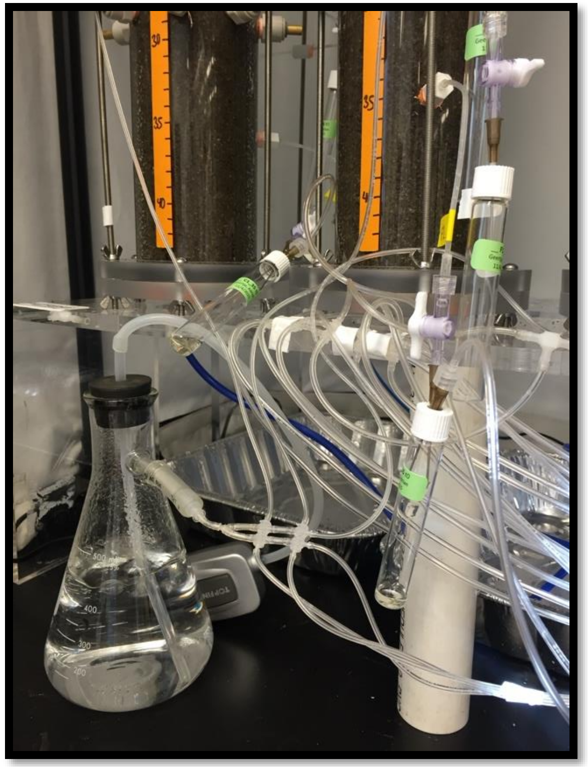
Column Instrumentation

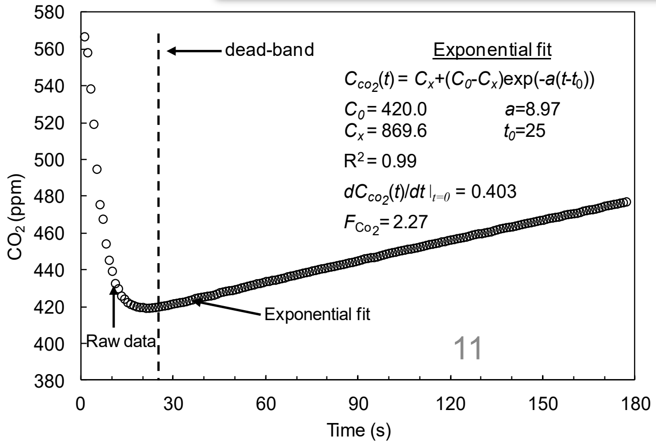




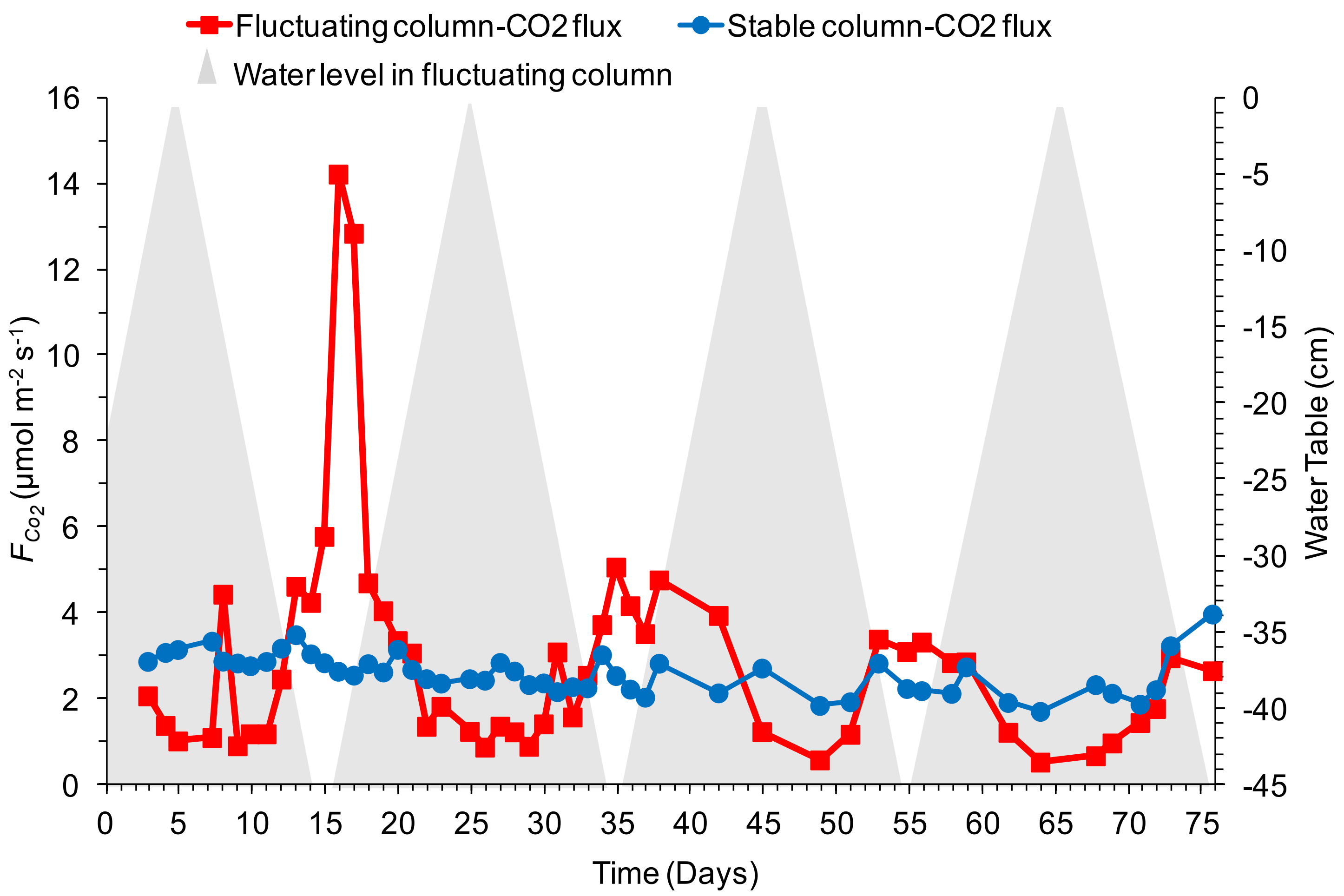








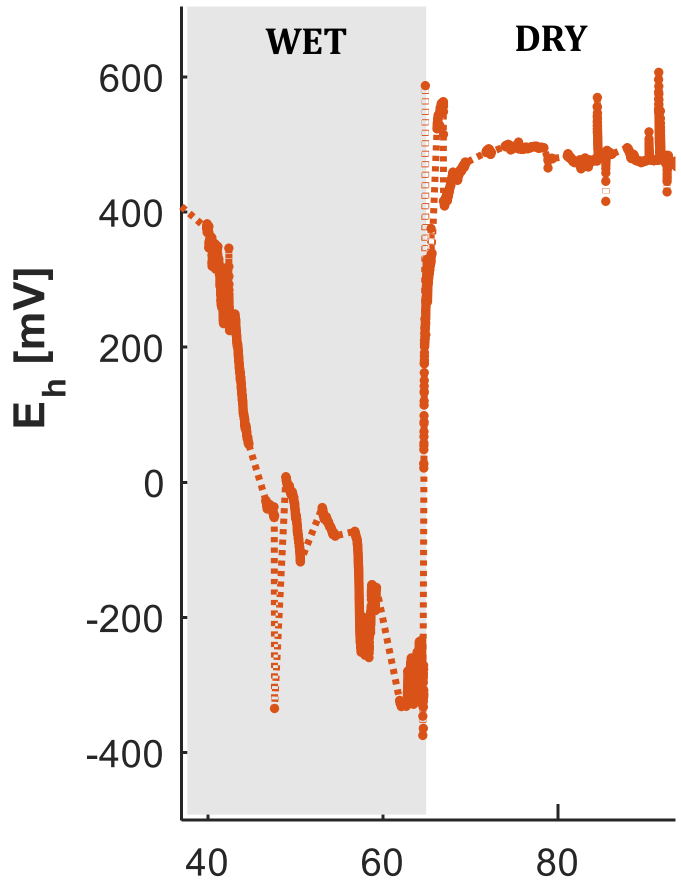
Water Table Fluctuation & CO_2 Flux

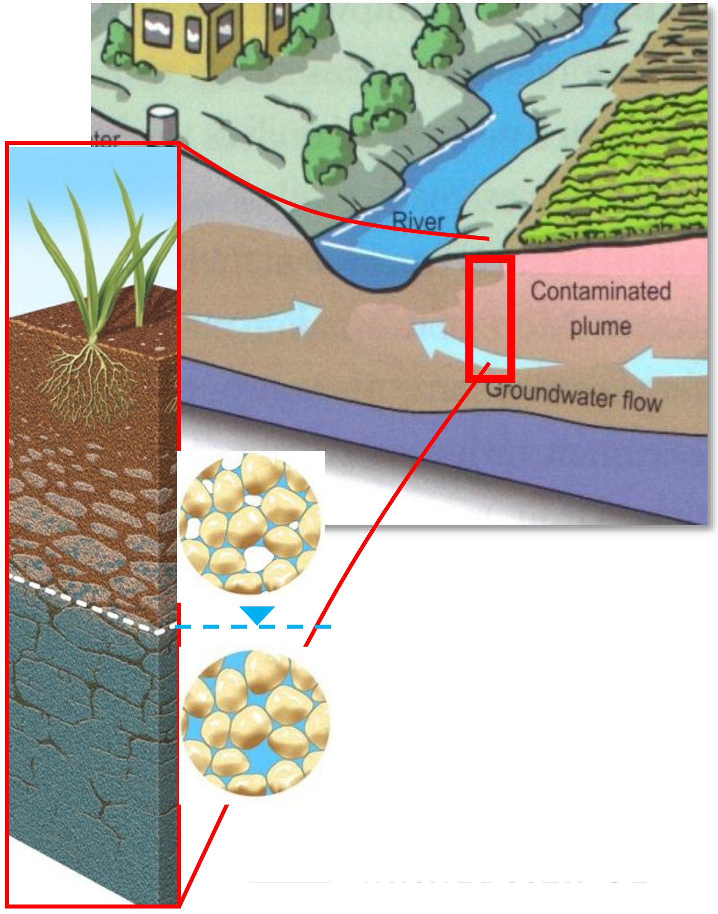


Water table fluctuations resulted in significant variations in CO_2 emissions, not seen in the stable water table system.

✓ Sensitivity of soil carbon degradation and nutrient dynamics to climate change through water-table fluctuation

Water table fluctuations in **transition zone** result in development of important zone of strong and variable **redox gradients**.

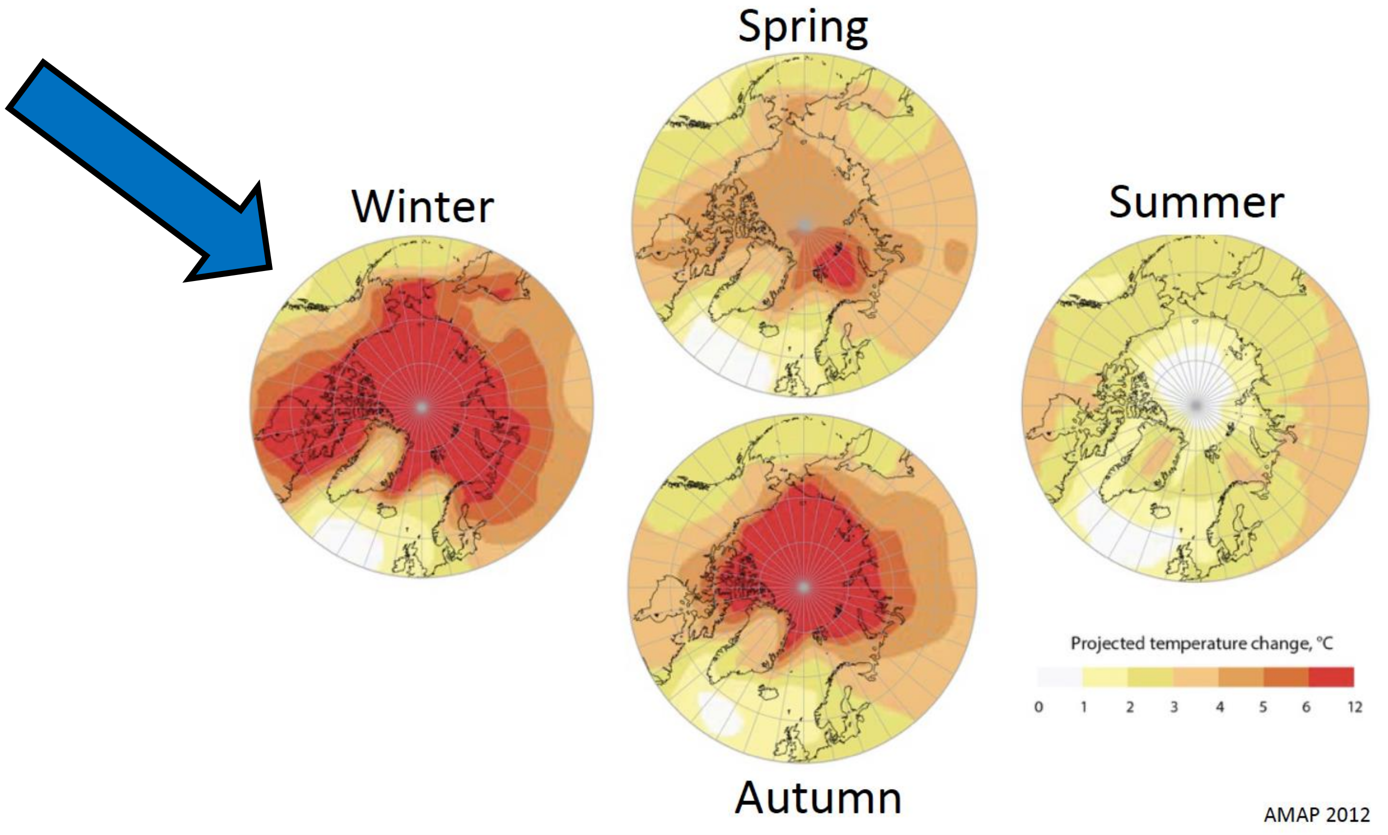




Winter Climate Warming

High Latitude Cold Regions are warming more than twice as fast as the rest of the planet, with the

Greatest Warming Occurring During the Winter.



Colder Soils in a Warming World?

Winter Climate Warming:

- ✓ Air temperature is rising
- ✓ Less extreme cold days (-30°C or colder)
- ✓ Rain is increasing

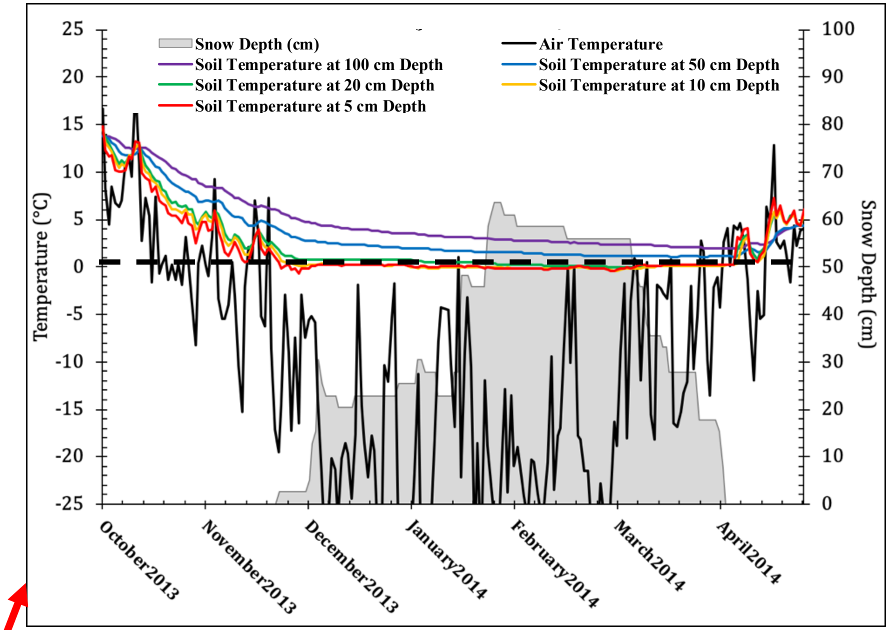
Winter Warming expose soils to:

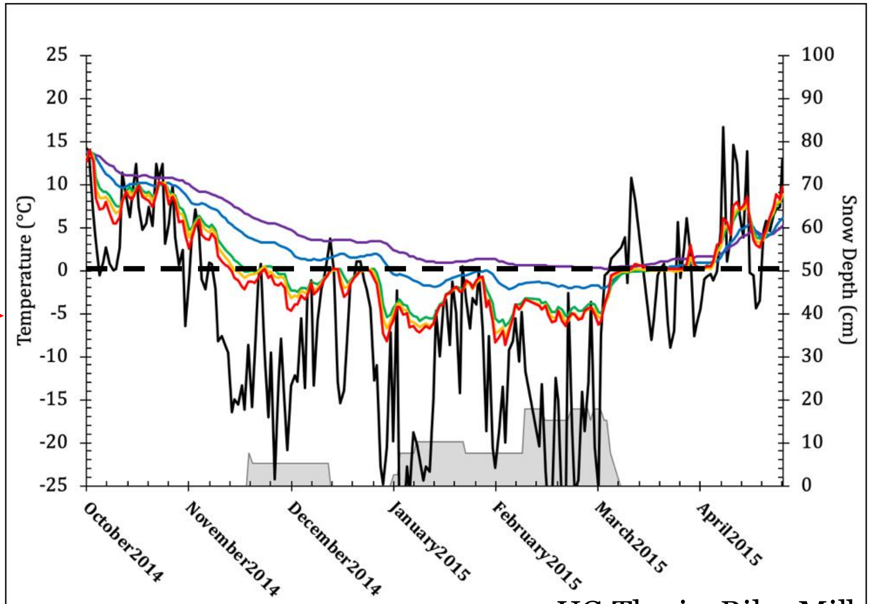
→ **Colder soil temperatures** due to loss of the insulating snowpack

→ Influence on soil moisture

→ More frequent **Freeze-Thaw Cycles** over the **winter and shoulder seasons**

USDA SCAN Station Data: Glacial Ridge, Minnesota

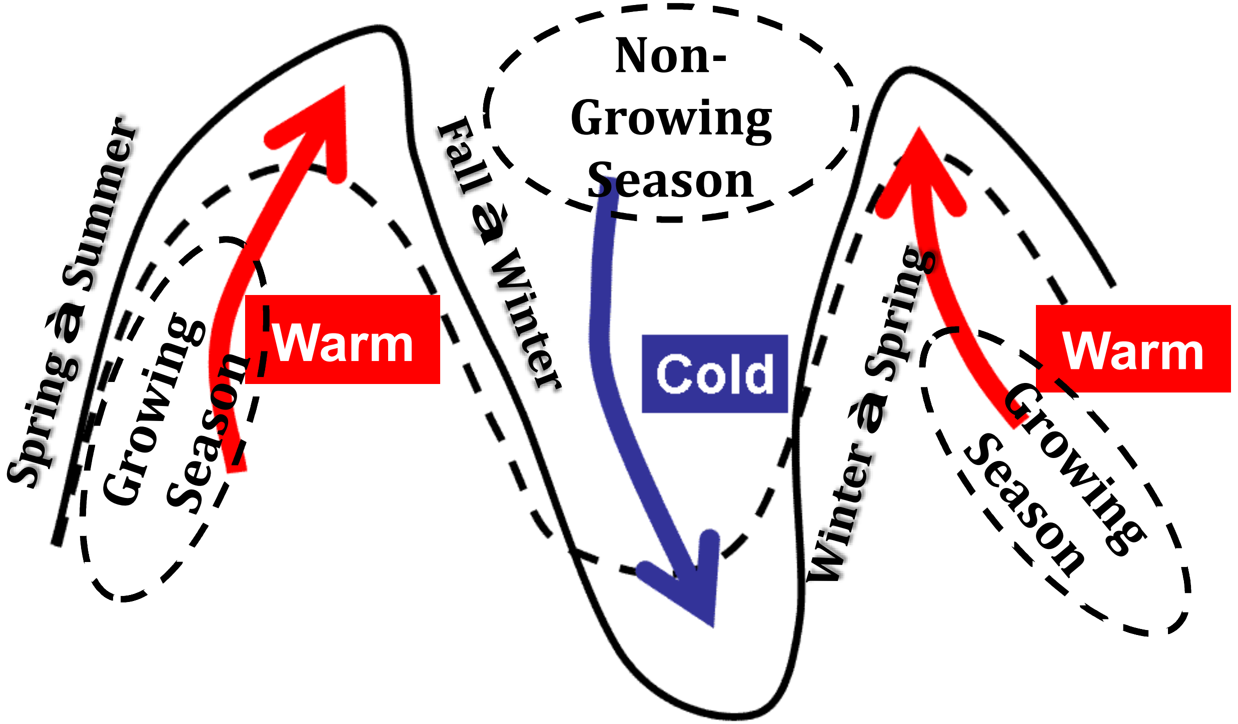




UG Thesis: Riley Mills

Winter and Shoulder Seasons

Cold – Warm – Cold – Warm



Photos taken by Cameron Irvine

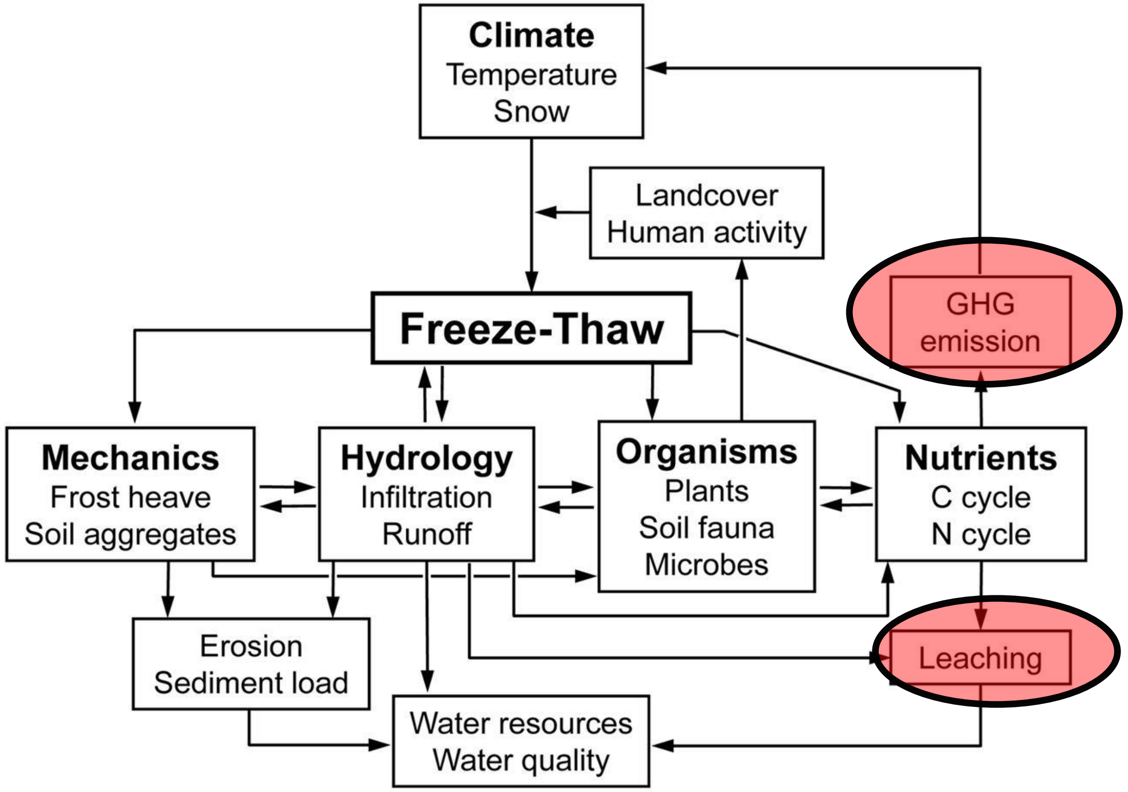
Winter and Shoulder Seasons

→ Non-Growing Season (NGS)

Freeze-Thaw Cycles & Soil Processes

Freezing and Thawing Cycles →

Soil Physical, Chemical and Biological Processes



Hayashi *et al.*, 2010

Importance of **Winter Soil Processes** on the export of carbon and nutrients (N, P, S, Fe) to **Groundwater**, **Surface Water** and **Lakes**

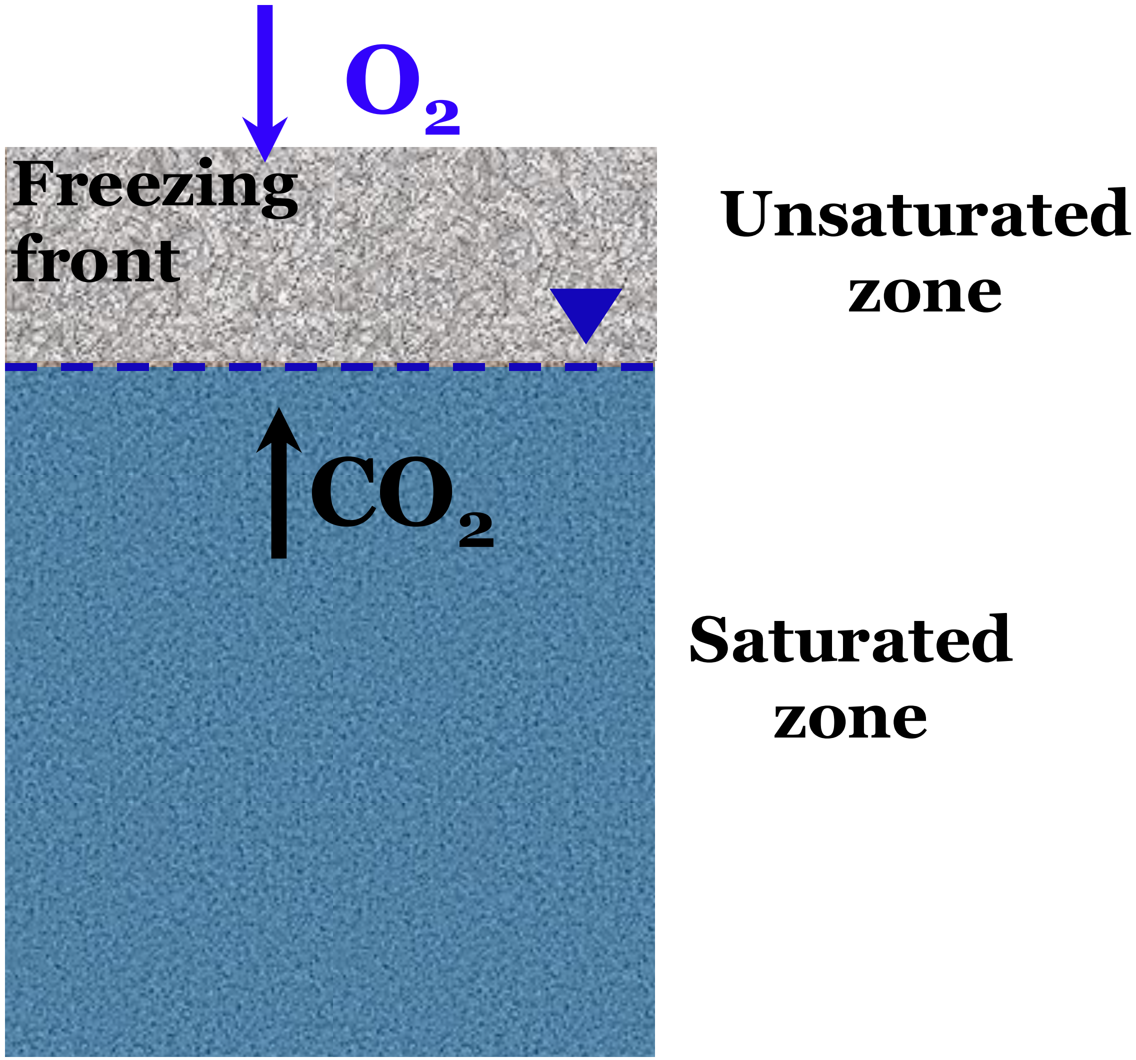
Hypothesis: GHG and Nutrients Dynamics

FROZEN PERIOD:

1) Ice as physical barrier to GHG (CO_2, N_2O, CH_4) exchange

2) Large amount of the soil microbial biomass will die off

3) Anaerobic respiration promoted under frozen condition (*e.g.*, sulfate reduction, denitrification, methanogenesis)

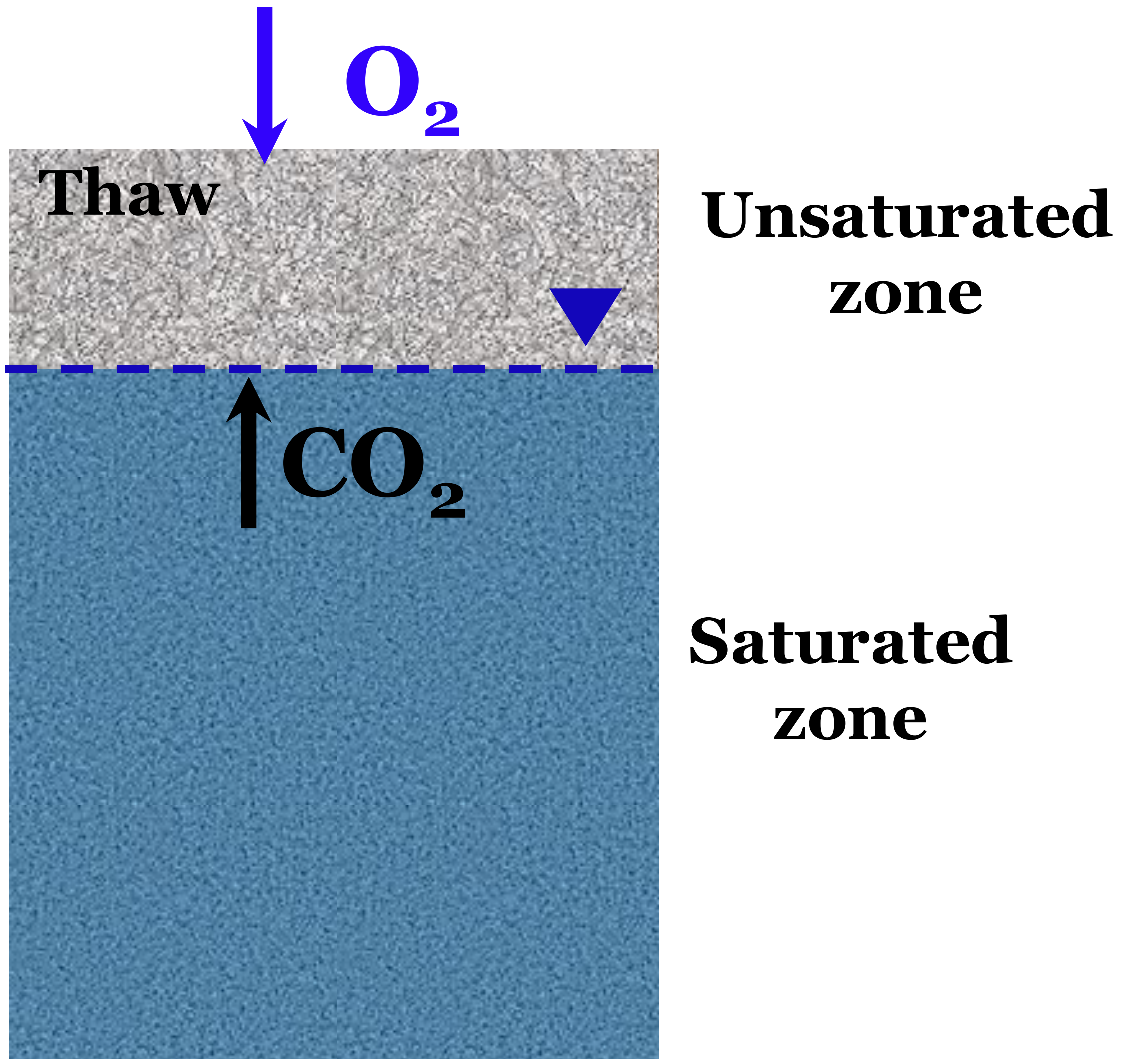


Hypothesis: GHG and Nutrients Dynamics

THAW PERIOD:

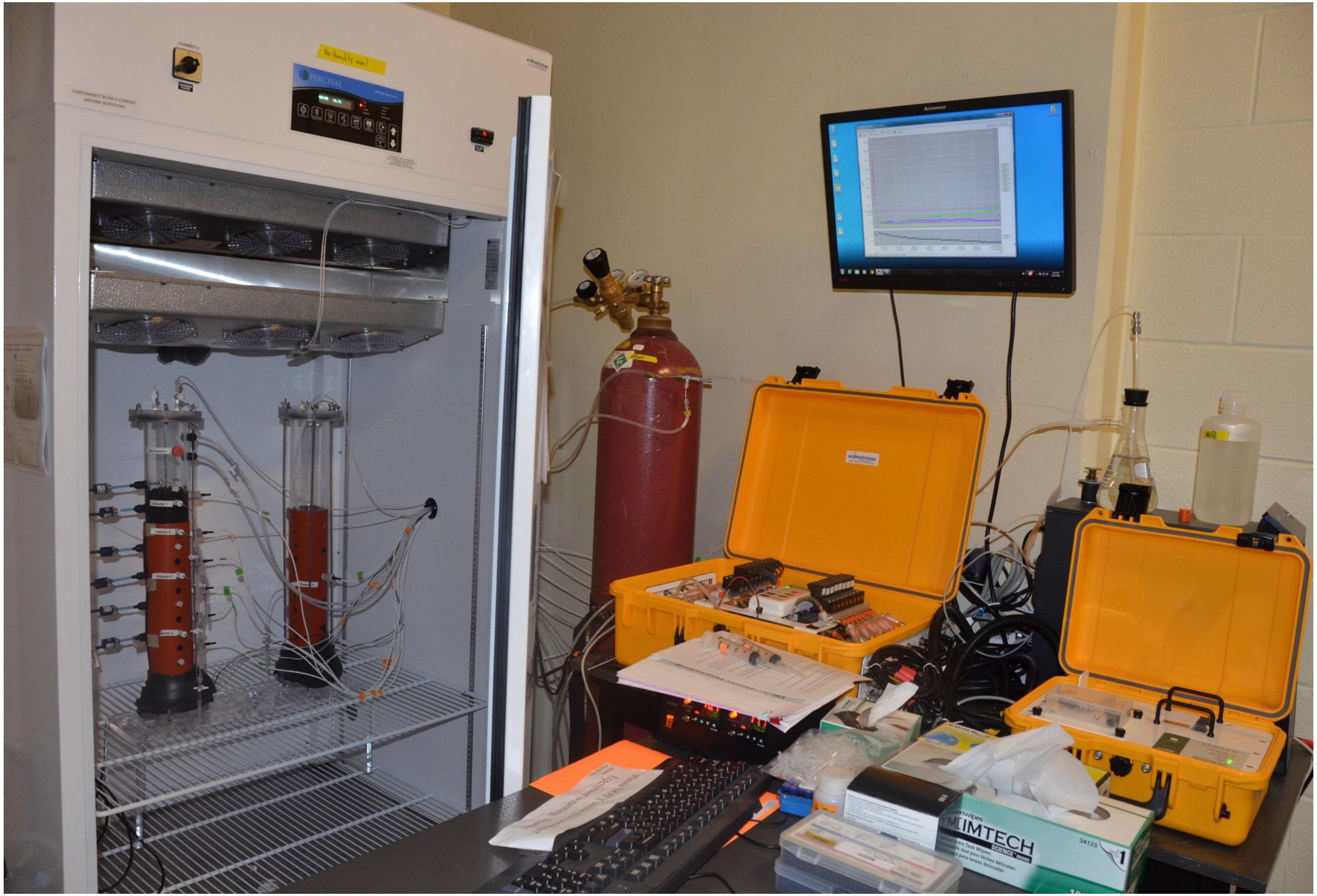
1) Physical barrier removed, gas exchange possible

2) Aerobic respiration restart



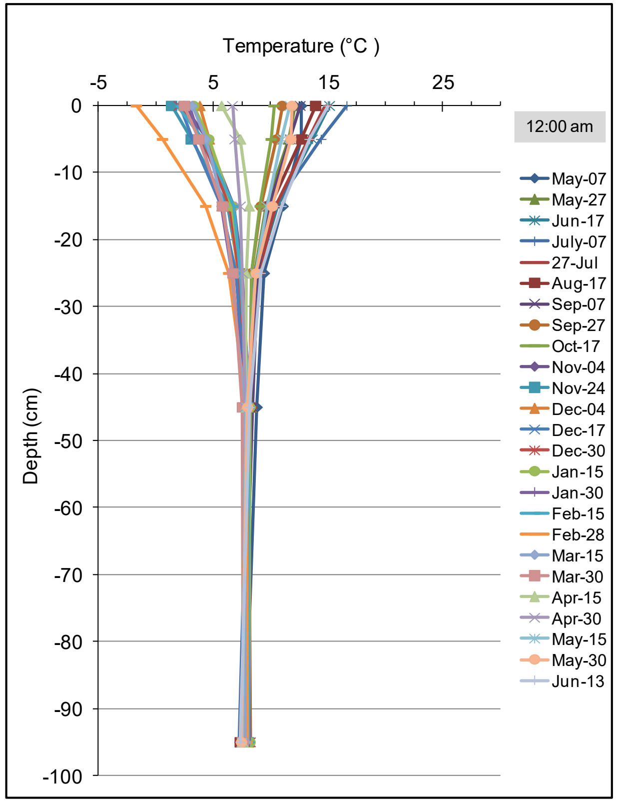
→ **Need for process/mechanistic-based understanding**

Freeze-Thaw Cycle Soil Column System

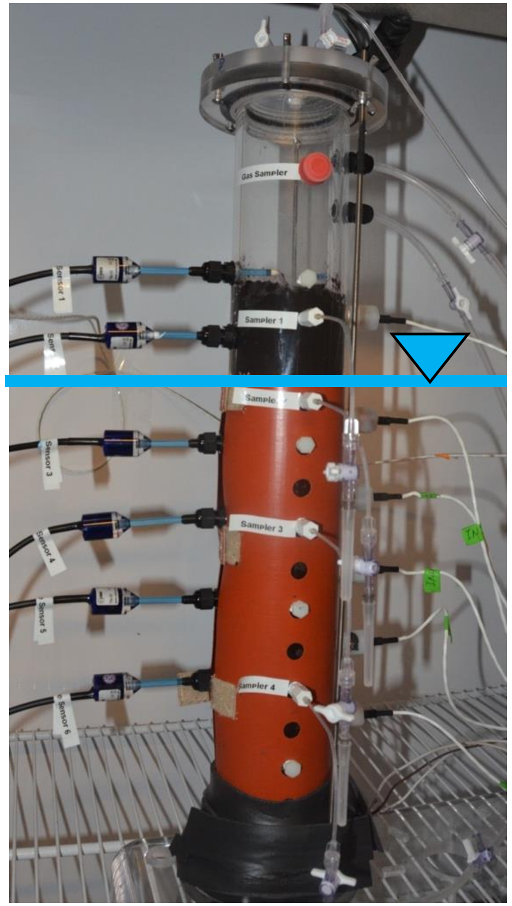


Realistic Soil Temperature Profile

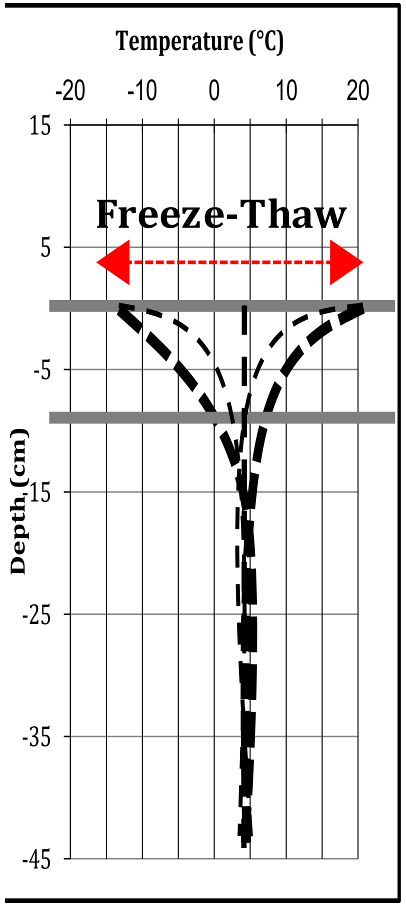
Field

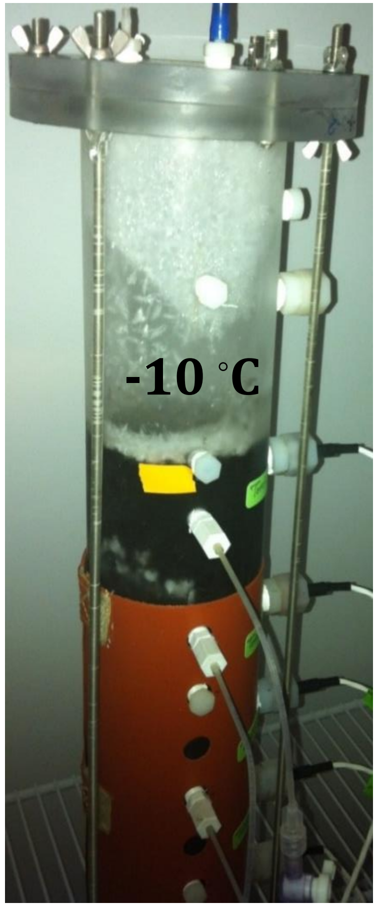


rare site, Cambridge, Canada



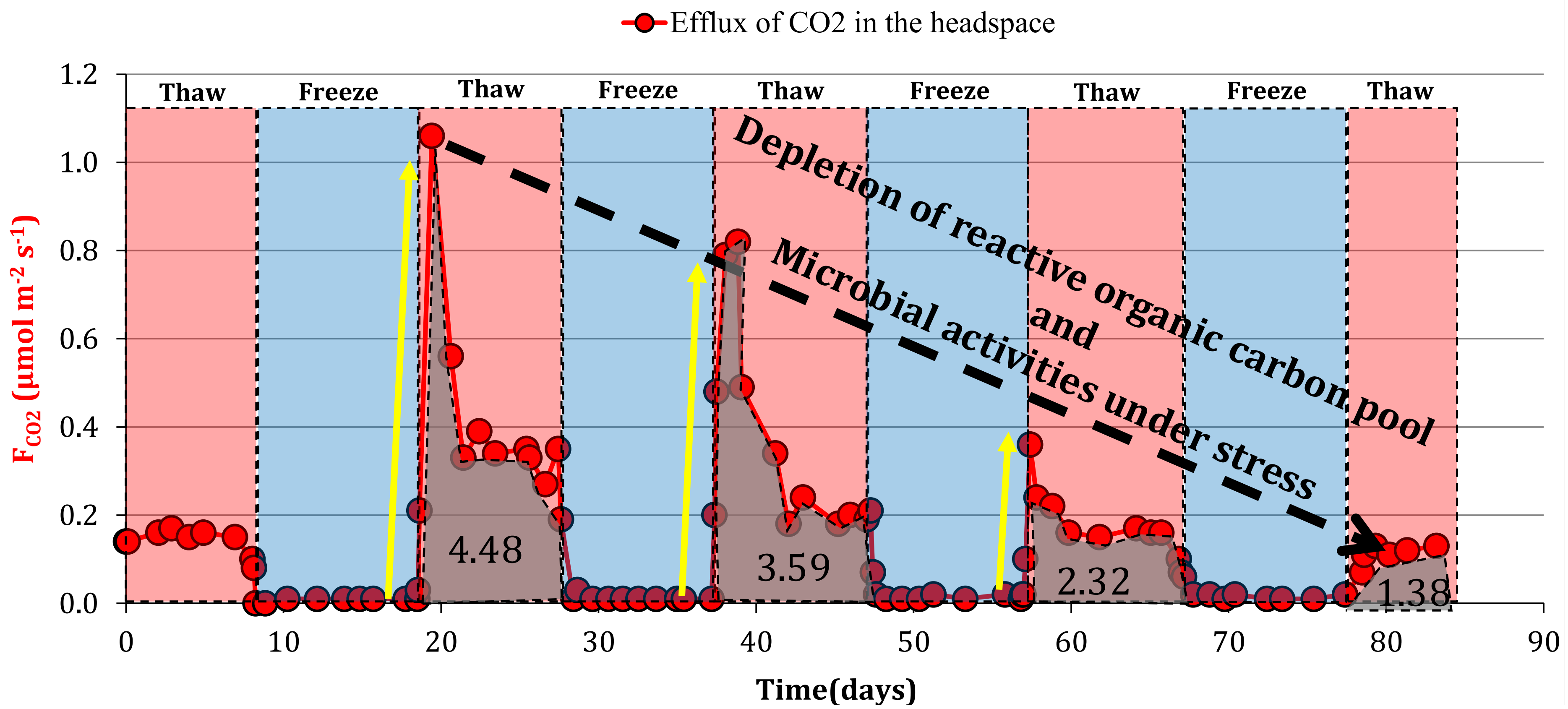
Lab





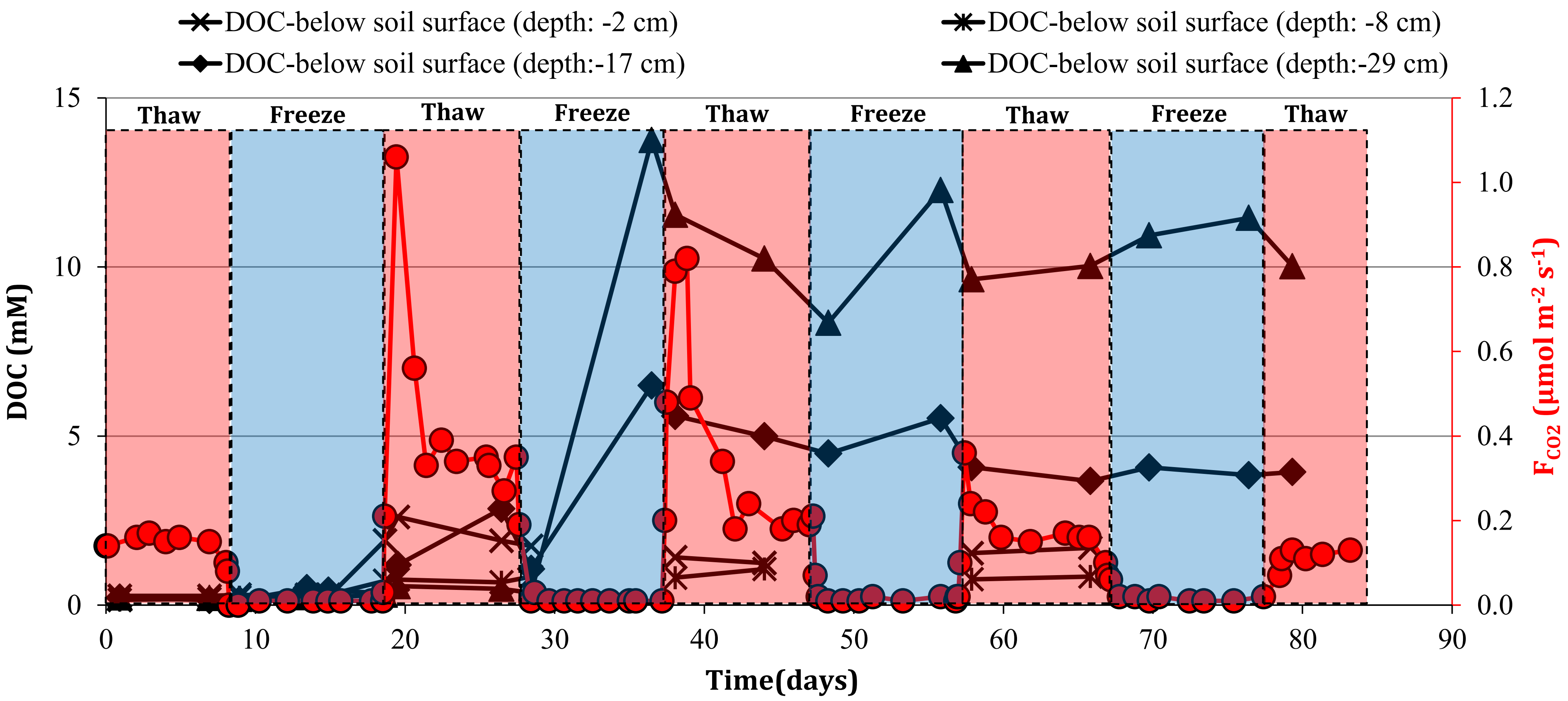
✓ Realistic Soil Temperature Profile

Freeze-Thaw Cycles & CO_2 Fluxes



- CO_2 lower under frozen conditions
- Pulse with onset of thaw
- Decrease CO_2 fluxes with time → No fresh reactive C_{org}

Freeze-Thaw Cycles & DOC/DIC



- Export of Dissolved Organic and Inorganic Carbon (**DOC/DIC**) to **groundwater (and river)** under successive freeze-thaw cycles

Take Home Message

Sensitivity of soil biogeochemical processes to climate change through **winter processes**

Winter is a critical period for carbon and nutrient cycling in soils