Iron speciation at the permafrost-active layer boundary

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To understand landscape-scale watershed dynamics in arctic regimes, it is critical to investigate abiotic and biotic interactions in the transition zone, where the active layer meets the permafrost. Permafrost, which is a considerable component of arctic soils, contains a unique interface at the transition zone characterized by a sharp redox gradient and a phase change from liquid water to ice. The biogeochemical composition and environmental conditions at this interface influence reactivity—i.e., as permafrost thaws, a higher proportion of interfacial water may be present, disrupting the localized microenvironment. Associated changes in the amount of unfrozen water present will likely affect redox environment, microbial activity and diversity, speciation, water density, conductivity, and soil wettability.

Imnavait Creek is a tundra stream on the North Slope of Alaska where we collected soil and water samples across seasonal thaw and coupled ground penetrating radar (GPR) and electrical resistivity tomography (ERT) to characterize watershed active layer thickness and identify permafrost extent across the stream, respectively. Our work shows the permafrost-active layer interface is a reducing zone highly susceptible to mass flushing of redox active elements (e.g. iron; Fe) if thawed and this mass flush will likely occur in late fall/early winter. Additionally, we observed high concentrations of Fe in the nearby surface water in late fall/early winter corresponding to when the soil surface is frozen, but the active layer is at its' deepest annual depth. As permafrost degradation accelerates, there will be rapid changes to the first 1-2 meters of the soil with potentially significant chemical and biological changes occurring near the permafrost-active layer interface.

Understanding the drivers, dynamics, and regional patterns of terrestrial ecosystem CO2 fluxes across the Arctic-Boreal Zone

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The Arctic-Boreal Zone (ABZ) is experiencing rapid changes with pronounced impacts on the terrestrial carbon cycle due to climate change. Non-growing season carbon emissions have recently been shown to be larger than previously thought. On the other hand, growing season plant productivity and carbon uptake are increasing in areas that are not undergoing major disturbances related to fires, permafrost thaw, and drought. Despite the importance of these ABZ fluxes for global carbon budgets, we lack a comprehensive understanding of their dynamics that would integrate the extent, magnitude, and drivers of these fluxes and their changes in different seasons and regions. Here, we aim to fill this knowledge gap by studying the drivers and spatiotemporal patterns of spring, summer, autumn, and winter carbon dioxide (CO2) fluxes and budgets. We use a recently compiled database of monthly Arctic-Boreal terrestrial ecosystem CO2 fluxes (ABCflux, n=6309) and upscale fluxes across the ABZ over the past four decades using machine learning models and a wide array of geospatial data describing, for example, climate, snow, vegetation, soil moisture, and disturbance conditions. We present maps of gross primary productivity, ecosystem respiration, and net ecosystem exchange aggregated over monthly intervals at 1 km spatial resolution from 2000 to 2020 and at 8 km from 1981 to 2017. We use these maps and site-level information to synthesize recent changes in ABZ CO2 fluxes, their sensitivity to various environmental conditions, and what these mean for the CO2 uptake strength of this region in the near future.

Landscape connectivity and dissolved organic matter in a degrading permafrost polygonal landscape

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In Arctic landscapes dominated by ice-wedge polygons, the degradation of these ice wedges leads to dramatic, interconnected changes in both the physical environment and biogeochemical cycling. As ice wedges thaw, poorly drained, low-centered polygons transform into well-drained high-centered polygons, surrounded by connected water-filled troughs that develop above degrading ice wedges. Thermokarst resulting from ice-wedge degradation allows for substantial re-mineralization of preserved organic matter, but can also cause changes in the lateral transport of dissolved organic carbon (DOC), both in terms of quantity and composition. As yet, it is poorly understood how the connectivity of ice-wedge polygon landscapes contributes to in situ losses of dissolved organic matter (DOM) and the lateral movement of DOM through a watershed. We sampled surface water along a field-mapped flowpath at a study site with actively degrading ice wedges near Prudhoe Bay, Alaska, in July 2019. Our goal is to understand how DOM is mobilized and transformed, from a mid-point in the sub-watershed to an outlet into a drained lake basin. The flowpath ran through a series of troughs and ponds that formed in thermokarst depressions surrounding high-centered polygons, differentiated by water depth, presence of submerged and emergent vegetation, and width between polygon rims. We measured DOC, chromophoric dissolved organic matter (CDOM), dissolved nitrogen, and temperature at each site. Repeat aerial imagery, high-resolution GPS data, and soil cores from this site show clear signs of ice-wedge degradation and increased water connectivity over the past fifty years, including the thawing of previously stable ice wedges to form deep ponds within a six year time period. DOC concentrations were lowest at the outlet, and increased going upstream along the flowpath. There was no difference in either DOC concentration or DOM composition between troughs and ponds, indicating the importance of connectivity. The linkages between hydrology, permafrost thaw, and landform change will be key to understanding the altering carbon and nitrogen cycles in a warming Arctic.

Snow-to-Rain Shifts Regulate Carbon Emissions From pan-Arctic Permafrost Regions

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The phase of precipitation (i.e., rain or snow) reaching the ground surface is dominantly determined by atmosphere temperature and humidity. The warming atmosphere temperature has caused precipitation to fall more as rainfall than snowfall, i.e., snow-to-rain shifts, leading to decreases in snow fraction of total precipitation. Snow-to-rain shifts directly lead to increases in rainfall fraction and rain-on-snow events, causing significant impacts on terrestrial water storage. The precipitation phase shifts have also decreased snow coverage and snow depth over some permafrost regions in the Northern Hemisphere. With decreased snow depth, the level of snow thermal insulation to the ground is expected to be reduced, which allows more energy to escape from soils to the atmosphere during the cold season, resulting in cooling effects to soil temperature. This cooling effect offsets the warming cold-season air temperature to some extent. Meanwhile, declined snow coverage and snow-season length results in decreased land surface albedo and thus increasing solar radiation absorption and nonlinearly impacts soil temperature, heterotrophic respiration, and carbon emissions. However, due to the opposite effects of decreased snow depth and decreased snow coverage on soil temperature, the integrated net impact of changes in snow conditions on soil warming is highly uncertain.

Despite the critical role of snow conditions in affecting terrestrial hydrology and ecosystem biogeochemical cycling, the integrated impact of snow-to-rain shifts on permafrost carbon-climate feedback remains unclear. In this study, we used the Energy Exascale Earth System Model (E3SM) land model (ELMv1) to 1) improve understanding of how snow-to-rain shifts impact carbon emissions from pan-Arctic ecosystems via analyzing the sensitivity of ELM-simulated snow water equivalent, active layer thickness, warm-season net CO2 uptake, and cold-season net CO2 emissions to climate forcing and precipitation-phase partitioning methods (PPMs); 2) evaluate the ELM-simulated SWE and CO2 and CH4 emissions against observationally-constraint datasets, and 3) predict trends of snow-to-rain shifting and cold-season carbon emissions over the pan-Arctic ecosystems under the Representative Concentration Pathway (RCP) 8.5 scenario. Simulations demonstrated good agreements with observation-derived SWE and CO2 emissions over tundra ecosystems. Results also show a larger sensitivity to climate forcing (i.e., CRUJRA, CRUNCEP, and GSWP3) than PPMs. The integrated impacts of snow-to-rain shifts on carbon emissions vary spatially over the permafrost regions. Under RCP 8.5 scenario, the predicted cold-season snowfall fraction will be only around 10% of the total precipitation by the end of the 21st century, strongly modulating permafrost water-carbon-climate interactions and feedback.

The Vulnerability of Permafrost Carbon to Climate Change: Key Findings from a Decade of Synthesis

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Factors that control terrestrial carbon storage in arctic and boreal ecosystems are changing. Surface air temperature has risen 2.5 times faster in the Arctic compared to the whole Earth, and permafrost temperatures have been increasing over the last 40 years. Disturbance by fire (particularly fire frequency and extreme fire years) is higher now than in the middle of the last century. Soils in the northern circumpolar permafrost zone store 1,460 to 1,600 petagrams of organic carbon (Pg C), almost twice the amount contained in the atmosphere and about an order of magnitude more carbon than contained in plant biomass (55 Pg C), woody debris (16 Pg C), and litter (29 Pg C) in the boreal forest and tundra biome combined. This large permafrost region soil carbon pool has accumulated over hundreds to thousands of years, and there are additional reservoirs in subsea permafrost and regions of deep sediments that are not added to this estimate because of data scarcity. Following the current trajectory of global and Arctic warming, 5% to 15% of the organic soil carbon stored in the northern circumpolar permafrost zone is considered vulnerable to release to the atmosphere by the year 2100. In addition to changing soil organic carbon pools, there is heightened recognition that release rates from inorganic carbon reservoirs in the form of methane hydrates and geologic methane seeps may be increasing due to the opening of new pathways to the atmosphere through degrading permafrost. Many of the abrupt processes that thaw permafrost and release carbon are not represented by Earth System Models but have been described by reduced complexity models. These simplified models project up to 50% additional carbon release by abrupt thaw mechanisms, but often do not include the response of vegetation that can offset carbon release. An Earth System Model intercomparison project suggested that additional plant carbon uptake, growth, and deposition of new carbon into soil would together completely offset any soil carbon loss this century, and that it would take several centuries before cumulative losses from soils would overwhelm new carbon uptake. Despite these differences, the intercomparison and other studies have indicated that future scenarios with limited human greenhouse gas emissions would reduce changes to high latitude ecosystems.

Temperature sensitivity of permafrost carbon release mediated by mineral and microbial properties

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Temperature sensitivity (Q10) of permafrost carbon (C) release upon thaw is a vital parameter for projecting permafrost C dynamics under climate warming. However, it remains unclear how mineral protection interacts with microbial properties and intrinsic recalcitrance to affect permafrost C fate. Here, we sampled permafrost soils across a 1000 km transect on the Tibetan Plateau and conducted two laboratory incubations over 400-day and 28-day durations to explore patterns and drivers of permafrost C release and its temperature response after thaw. We find that mineral protection and microbial properties are two types of crucial predictors of permafrost C dynamics upon thaw. Both high C release and Q10 are associated with weak organo-mineral associations but high microbial abundances and activities, whereas high microbial diversity corresponds to low Q10. The attenuating effects of mineral protection and the dual roles of microbial properties would make the permafrost C-climate feedback more complex than previously thought.

Representing pH buffering in Arctic soils: The roles of water, organic carbon, and proton binding

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Biogeochemical processes that degrade soil organic carbon (SOC) and release CO_2 and CH_4 are sensitive to soil pH. pH varies with depth and microtopography at Arctic field sites, and pH often changes significantly when these soils are incubated. However, current biogeochemical schemes implemented in Earth System Models (ESMs) do not explicitly account for dynamic pH changes or differences in the buffering capacity of pH among various soils. Process-based representation of pH dynamics via parameterization of soil pH buffering capacity (β) could decrease uncertainty in ESM-simulated CO_2 and CH_4 fluxes. The objectives of this study are to (1) develop representations for β in carbon-rich Arctic soils using simple soil proxies, including water availability and SOC, and (2) evaluate sensitivity of biogeochemical reaction rates to different β representations. pH titrations were conducted to determine β of 21 Arctic soils (both active layer and permafrost) across three Alaskan sites. A weak relationship for β and %SOC was observed (R^2=0.362), whereas gravimetric water content (θ_g) showed a stronger correlation (R^2=0.848). Soil water retention curves developed for a subset of eight soils further supported this trend; higher β was associated with higher water retention during drying (at -1 MPa, R^2 = 0.827). One explanation is that higher concentrations of organic ligands involved in proton binding promote water retention. A mechanistic model - The Windermere Humic Aqueous Model (WHAM7) was also used to predict β for each soil. Simulations demonstrated high sensitivity to the fraction of soil organic carbon involved in proton binding (f_{SOCb}), which varied substantially among soils. Empirical correlations with water availability could be an important, simple proxy for β in ESMs. Continued work to understand the relationships between water retention and β could help improve future development of ESMs.

Estimating greenhouse gas production in thermokarst lagoons of Bykovsky Peninsula, Siberia

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Thermokarst lagoons, forming when thermokarst lakes are inundated by the sea, are an transition stage where terrestrial permafrost is introduced into the subsea realm. Here, permafrost and lacustrine carbon pools are transformed along Arctic coasts. During thaw previously frozen organic carbon can be converted into the greenhouse gases (GHG) carbon dioxide (CO2) and methane by microorganisms and leading to further climate warming. Especially for transition ecosystems like thermokarst lagoons it is largely unknown how GHG release is changing and whether thermokarst lagoons are a carbon source or sink.

For getting a first glimpse of the consequences of saltwater inundation, we mimic the inundation of coastal permafrost in an experiment by incubating permafrost and thermokarst samples with artificial sea water under controlled conditions (4°C, dark, anaerobic) for 12 month. We used terrestrial samples from a 2.5 m high Yedoma outcrop, a thermokarst lake core, as well as samples from two neighboring thermokarst lagoons (a nearly-closed and a semi-closed) from the Bykovsky Peninsula, Northeast Siberia.

By applying two different scenarios we aim to estimate (1) future GHG releases from newly formed Arctic lagoons by adding artificial seawater with a constant concentration and (2) the impact of increasing salinity on GHG production by incubating the samples under freshwater, brackish and marine conditions.

Here we present (1) total organic carbon and dissolved organic carbon content for deep-drilled sediment cores (~ 30m) and (2) preliminary results on GHG production (methane and CO2) rates measured over 6 month.

First results show that (1) GHG production is higher for inundated terrestrial sediments than for inundated lagoon sediments and (2) increasing salinity is favoring carbon dioxide production while methane production is low.

In conclusion newly formed thermokarst lagoons, if upscaled to the thermokarst affected shorelines, are likely produce a significant amount of GHG under our experiment set-up.