Final Technical Report
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Title: Effects of Rapid Permafrost Thaw on CO2 and CH4 Fluxes in a Warmer and Wetter Future
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PROJECT OVERVIEW

When ice-rich permafrost thaws, the ground subsides, creating thermokarst landscapes with dramatically different soil conditions and carbon fluxes than the original ecosystem. Roughly 20% of the northern permafrost region is susceptible to thermokarst formation (Olefeldt et al., 2016). Thermokarst formation is often rapid; tens of meters of permafrost can thaw within a few years (Schuur et al., 2015). In topographically low areas, thermokarst thaw converts boreal forest or tundra dry shrub ecosystems into sedge or *Sphagnum* moss wetlands (Olefeldt et al., 2016). While this type of landscape transformation releases carbon stored in permafrost into the atmosphere, on longer time scales, it facilitates sequestration of atmospheric carbon in plant biomass because permafrost thaw releases plant-available nutrients and wetlands are highly productive (M. C. Jones et al., 2017). However, wetlands also generate methane, which is a potent greenhouse gas. Methane emissions from thermokarst wetlands can cause these carbon-sequestering systems to have a positive global warming potential (Johansson et al., 2006; Turetsky et al., 2007).

Our project objective was to improve Earth System and environmental predictability by advancing understanding of how CO_2 and CH_4 flux in permafrost thaw-induced wetlands (thermokarst) will change in the future as temperatures and climate conditions shift. Northern latitudes are expected to get warmer and wetter (IPCC 2013), and initiation and expansion of thermokarst thaw is expected to increase (Jorgenson et al. 2006; Zhang et al. 2017). Given these expected changes, our work sought to address three broad questions:

Q1) How will northern latitude CO2 and CH4 emissions respond to warming temperatures?
Q2) What is the impact of precipitation on permafrost thaw and carbon emissions?
Q3) How do CO2 and CH4 emissions change as wetlands age after permafrost thaw?

To answer these questions, we took both a modeling and measurement approach. Modeling work was conducted with DOE's Energy Exascale Earth System Model (E3SM) land model (ELM). Empirical work took place in two primary locations. The first was a thermokarst site near Fairbanks, AK. The site is part of the Bonanza Creek Long Term Ecological Research program and is well instrumented (Neumann et al., 2019). The second was an isolated thawing permafrost wetland located on Kenai Peninsula — Brown's Lake bog (B. M. Jones et al., 2016) — where the current climate is representative of what is expected at higher latitudes in the future. This site provides an ideal opportunity to test our hypotheses about how thermokarst wetland dynamics will respond to future environmental conditions. In addition, the project collaborated with researchers asking similar questions who were collecting measurements in high latitude post-glacial lakes located in collaborators tackling similar questions in Sweden (Stordalen Mire) (Emerson et al., 2021).

Project efforts directly aligned with the stated goal of the funding opportunity announcement (FOA), which was “to improve the understanding and representation of terrestrial ecosystems in ways that advance Earth system model parameterizations and capabilities... thereby improving the quality of Earth and environmental model projections and providing the scientific foundation needed to support DOE’s science and energy missions.” Specifically, the project improved sophistication and accuracy of the Energy Exascale Earth System Model (E3SM), which is being developed primarily at DOE National Laboratories to support scientific research and decision-making.

QUESTION 1

How will northern latitude CO2 and CH4 emissions respond to warming temperatures?

We used DOE’s Energy Exascale Earth System Model (E3SM) land model (ELM) to address this question. We chose to focus on temperature changes during the cold season because while permafrost regions have undergone persistent warming during recent decades (Pithan & Mauritsen, 2014), the most severe warming has occurred during the cold season (Cohen et al., 2014) . Further, cold-season carbon emissions from the Arctic tundra could potentially offset warm-season net carbon uptake under 21st century warming climate (Commane et al., 2017).

The first step in our effort required improving ELM. Most earth system land models, including ELM prior to our efforts, do not accurately reproduce cold-season CH4 and CO2 emissions, especially over the shoulder (i.e., thawing and freezing) seasons. In Tao et al. (2021a), we improved the soil water phase change scheme, environmental controls on microbial activity, and the methane module within ELMv1-ECA (land model version 1). Results demonstrated that both soil temperature and the duration of zero-curtain periods (i.e., the fall period when soil temperatures linger around 0 ◦C) simulated by the updated ELMv1-ECA were greatly improved. These improvements lead to better simulation of CH4 and CO2 emissions during the cold season.

We then used the improved model to explore CO2 emissions over the Alaskan North Slope tundra under current and future (RCP8.5) climates. Tao et al. (2021b) published the results of the modeling effort in a paper titled, “Warm-season net CO2 uptake outweighs cold-season emissions over Alaskan North Slope tundra under current and RCP8.5 climate.” Results supported the findings of previous investigation, showing that the recent seven-decades warming trend of cold-season soil temperature was three times that of the warm-season. The climate sensitivity of warm-season net CO2 uptake, however, was threefold greater than for the cold-season net CO2 loss. This response was mainly due to stronger plant resilience than microbial resilience to hydroclimatic extremes. Consequently, the modeled warm-season net CO2 uptake had a larger positive trend than that of cold-season CO2 emissions between 1950 to 2017. With continued warming and elevated CO2 concentrations under the representative concentration pathway (RCP) 8.5 scenario, the increasing rate of warm-season net CO2 uptake was more than twice the rate of cold-season, making the modeled Alaskan Arctic tundra ecosystem a net CO2 sink by 2100.

Work by our collaborators in Sweden at the Stordalen Mire complex was also addressing this broad research question, and they requested support from PI Neumann for interpreting microbial rates from isotope data based on previous work (Neumann et al., 2016). They were studying the temperature sensitivity of methane emissions from northern post-glacial lakes (Emerson et al., 2021). They found temperature-associated increase in CH4 emissions was greater in lake middles—where methanogens were more abundant—than edges, and sediment communities were distinct between edges and middles. Microbial abundances, including those of CH4-cycling microorganisms and syntrophs, were predictive of porewater CH4 concentrations. Results suggested that deeper lake regions, which currently emit less CH4 than shallower edges, could add substantially to CH4 emissions in a warmer Arctic and that CH4 emission predictions may be improved by accounting for spatial variations in sediment microbiota.

QUESTION 2

What is the impact of precipitation on permafrost thaw and carbon emissions?

Work to address this question was conducted at two different field sites. The first was a well-established thaw-bog comples located outside of Fairbanks, AK. This complex is part of the Bonanza Creek LTER program. PI Neumann has worked at this site in 2014 (Neumann et al., 2016). The second site is a degrading permafrost plateau in south-central Alaska located in the western Kenai Peninsula lowlands (B. M. Jones et al., 2016). Both sites were instrumented with high-resolution soil temperature sensors, water content sensors, and wells. Data from the Fairbanks site is still under interpretation. Data from the Kenai site have been analyzed and a publication is in press.

At the Kenai site, our study (2020-2022) captured three of the snowiest years and three of the four wettest years since the site was first studied in 2015. We found that average permafrost thaw rates along an across-site transect increased nine-fold from 6±5 cm/year between 2015 and 2020 to 56±12 cm/year between 2020-2022. This thaw was not uniform. Hummock locations, residing on topographic high points with relatively dense canopy, experienced only 8±9 cm/year of thaw, on average. Hollows, topographic low points with low canopy cover, and transition locations, which had canopy cover and elevation between hummocks and hollows, thawed 44±6 cm/year and 39±13 cm/year, respectively. Mechanisms of thaw differed between these locations. Hollows had high warm-season soil moisture, which increased thermal conductivity, and deep cold-season snow coverage, which insulated soil. Transition locations thawed primarily due to thermal energy transported through subsurface taliks during individual rain events. Most increases in depth to permafrost occurred below the ~45 cm thickness seasonally frozen layer, and therefore, expanded site taliks.

Results highlight the importance of canopy cover and microtopography in controlling soil thermal inputs, the ability of subsurface runoff from individual rain events to trigger warming and thaw, and the acceleration of thaw caused by consecutive wet and snowy years. As northern high-latitudes become warmer and wetter, and weather events become more extreme, the importance of these controls on soil warming and thaw is likely to increase.

The ability of precipitation and runoff to transport thermal energy, which was documented to facilitate warming and permafrost thaw at the Kenai site (described above), is being investigated at the Fairbanks site. We are investigating if this thermal energy transport supports permafrost warming and thaw or if it enhances bog methane emissions. Prior work at the Fairbanks site indicated that runoff from rain early in the growing season warmed bog soils, which in turn fueled methane production and emissions (Neumann et al., 2019). In addition, at the Fairbanks site we are also assessing if runoff transports nutrients into the bog, which support microbial activity or plant growth. Enhanced microbial activity and plant growth are both connected with increased methane emissions (McEwing et al., 2015; Nielsen et al., 2017; Whiting & Chanton, 1993).

QUESTION 3

How do CO2 and CH4 emissions change as wetlands age after permafrost thaw?

This question was addressed at the same thaw bog complex located outside of Fairbanks, AK that was instrumented for Question 2. At this site, Waldrop et al. (2021) selected three different collapse-scar bogs based on size (assuming younger bogs are smaller), overflight photography (to identify bogs that previously had established forest cover), and plant community composition (younger bogs would have more sedge cover and standing dead trees while older bogs would have a small woody plants and no standing dead trees). The three bogs were termed “young,” “intermediate,” and “old” based on their assumed ages. Macrofossil dating indicated that the old collapse-scar bogs began thawing and expanding 140 years before sampling. Both the young bog and intermediate bogs began to thaw within the past 50–75 years. However, the young bog only began to expand in the last 2 decades, while the intermediate bog has been slowly expanding throughout this time

Multiple field and laboratory-based assays were conducted on all three bogs. The youngest collapse-scar bog had the highest CH4 production potential in soil incubations, and, based upon temporal changes in porewater concentrations and 13C isotopic composition of CH4 and CO2, had greater summer *in situ* rates of respiration, methanogenesis, and surface CH4 oxidation. These patterns appeared related to greater C and N availability in the young bog relative to the older bogs. In alignment with these results, field diffusive CH4 fluxes from the young bog were 4.1 times greater in the shoulder season and 1.7–7.2 times greater in winter relative to the two older bogs. However, no difference in field diffusive flux existed during summer between the bogs. It was hypothesized that the relatively greater CH4 flux rates in the shoulder season and winter were due to less CH4 oxidation during these colder periods compared to the summer.

In net, all of the collapse-scar bogs were sources of C to the atmosphere due in large part to winter C fluxes. The winter was found to be a critical period when differences in bog age translated to differences in surface fluxes.

SUMMARY

Our project found the following answers to the posed questions.

How will northern latitude CO2 and CH4 emissions respond to warming temperatures?
Our modeling work indicated the Alaskan Arctic tundra ecosystem is currently a net CO_2 sink and will continue to the a net CO_2 sink into the future, assuming other geomorphological and ecological disturbances (e.g. abrupt permafrost thaw, thermokarst development, landscape-scale hydrological changes, wildfire, and insects) that were not considered in the model shift the source/sink balance.

Work conducted by our collaborators, which we contributed to, indicated that methane emissions from Arctic lakes will likely increase as temperatures warm due to a strong temperature-CH_4 response from deeper lake regions.

What is the impact of precipitation on permafrost thaw and carbon emissions?
Fieldwork from the Kenai peninsula captured the ability of subsurface runoff from individual rain events to trigger warming and thaw, and the acceleration of thaw caused by consecutive wet and snowy years. Thus, wetter conditions were linked with permafrost thaw at this site. Data collected at the Fairbanks site that is currently being analyzed will identify how precipitation affects carbon emissions at this more northern study site.

How do CO2 and CH4 emissions change as wetlands age after permafrost thaw?
Younger collapse-scar bogs at the Fairbanks site supported greater rates of microbial activity and emitted, on net, more methane. The greater methane flux in younger bogs was due to fluxes in the winter and shoulder season. Thus, we found that as bogs age, net methane emissions decrease.

PRODUCTS

<u>Peer Reviewed Manuscripts</u>

Tao, J., Zhu, Q., Riley, W. J., & Neumann, R. B. (2021a). Improved ELMv1-ECA simulations of zero-curtain periods and cold-season CH4 and CO2 emissions at Alaskan Arctic tundra sites. The Cryosphere, 15(12), 5281–5307. https://doi.org/10.5194/tc-15-5281-2021

Tao, J., Zhu, Q., Riley, W. J., & Neumann, R. B. (2021b). Warm-season net CO2 uptake outweighs cold-season emissions over Alaskan North Slope tundra under current and RCP8.5 climate. Environmental Research Letters, 16(5), 055012. https://doi.org/10.1088/1748-9326/abf6f5

Emerson, J. B., Varner, R. K., Wik, M., Parks, D. H., Neumann, R. B., Johnson, J. E., et al. (2021). Diverse sediment microbiota shape methane emission temperature sensitivity in Arctic lakes. Nature Communications, 12(1), 5815. https://doi.org/10.1038/s41467-021-25983-9

Waldrop, M. P., McFarland, J., Manies, K., Leewis, M. C., Blazewicz, S. J., Jones, M. C., et al. (2021). Carbon Fluxes and Microbial Activities from Boreal Peatlands Experiencing Permafrost Thaw. Journal of Geophysical Research: Biogeosciences. https://doi.org/10.1029/2020JG005869

Manuscripts in Press

Eklof, J., Jones, B., Dafflon, B., Devoie, E., Ring, K., English, M., Waldrop, M., Neumann, R.B. Canopy Cover and Microtopography Control Precipitation-Enhanced Thaw of Ecosystem-Protected Permafrost. Environmental Research Letters (in press).

Manuscripts Actively in Preparation

Eklof, J., Lundquist, J.D. , Waldrop, M.P., Tao, J., Dafflon, B., Ring, K., Neumann, R.B. Environmental Interactions Controlling Thermal Regimes and Permafrost Progression in Interior, Alaska. (in preparation).

Eklof, J., Lundquist, J.D. , Waldrop, M.P., Tao, J., Dafflon, B., Ring, K., Neumann, R.B. The Watershed-Bog Connection: How Water, Energy, and Nutrient Inputs from the Permafrost Plateau Impact Bog Methane Emissions. (in preparation).

Publicly Available Datasets

Eklof J ; Jones B ; Dafflon B ; Ring K ; English M ; Neumann R (2023): Soil temperature and soil moisture raw data, permafrost table depths, and accompanying environmental variable data, Kenai Wildlife Refuge, 2019-2022. Effects of Rapid Permafrost Thaw on CO2 and CH4 Fluxes in a Warmer and Wetter Future, ESS-DIVE repository. Dataset. doi:10.15485/2204548 accessed via https://data.ess-dive.lbl.gov/datasets/doi:10.15485/2204548 on 2024-01-19

Conference Presentations

Eklof, J., J.D. Lundquist, M.P. Waldrop, B. Dafflon, J. Tao, B.M. Jones, K. Ring, R.B. Neumann. "Environmental interactions controlling thermal regimes and permafrost progression in Interior, Alask." American Geophysical Union, San Francisco (December 2023).

Eklof, J., Jones, B., Dafflon, B., Ring, K., Waldrop, M., English, M., Neumann, B. "Environmental Controls on Thaw Rates of a Vegetation-Protected Permafrost Plateau." ESS PI Meeting, Baltimore, MD (March 2023).

Eklof, J., J.D. Lundquist, M.P. Waldrop, J. Tao, B. Dafflon, K. Ring, R.B. Neumann. "Thermals Regimes Observed at a Discontinuous Permafrost Site in Interior, Alaska." American Geophysical Union, Chicago, IL (December 2022).

Tao, J., Q. Zhu, W.J. Riley, G. Bisht, J. Eklof, R.B. Neumann. "The role of advective heat transfer in affecting permafrost thaw and methane emissions at a hillslope thermokarst bog." 2021 American Geophysical Union Fall Meeting, New Orleans, LA (December 2021).

Eklof, J.F., MP. Waldrop, B. Dafflon, B.M. Jones, J. Tao, R.B. Neumann. "High-Resolution Thaw Dynamics of Two Latitudinally Distant Alaska Thermokarst Sites: A Field Study." American Geophysical Union Fall Meeting, New Orleans, LA (December 2021).

Neumann, R.B., J. Eklof, M.P. Waldrop, B.M. Jones, C.J. Moorberg, J. Lundquist, J. Turner, J.W. Mcfarland, E.S. Euskirchen, C. Edgar, M.R. Turetsky. "Thermal transport by rain into thawing permafrost landscapes (invited)." 2020 American Geophysical Union Fall Meeting, remote (December 2020).

Tao, J., Q. Zhu, W.J. Riley, R.B. Neumann. "The increasing trend in warm-season net CO2 uptake outweighs that in cold-season emissions from the Alaskan Arctic tundra under a warming climate." 2020 American Geophysical Union Fall Meeting, remote (December 2020).

Eklof, J., M.P. Waldrop, B.M. Jones, J. Lundquist, R.B. Neumann. "Ability of thermal energy from rainfall to warm and thaw soils at a thermokarst site in south-central Alaska." 2020 American Geophysical Union Fall Meeting, remote (December 2020).

Eklof, J.F., MP. Waldrop, B. Jones, R.B. Neumann. "Thaw dynamics of a rapidly degrading isotlated permafrost plateau in south-center Alaska. 2019 American Geophysical Union Fall Meeting, San Francisco, CA (December 2019).

Invited Seminars

Neumann, Rebecca, University of Minnesota, St. Anthony Falls Laboratory Bi-weekly seminar series, Transport of thermal energy by rain in thawing permafrost landscapes. (March 2020)

Neumann, Rebecca, Massachusetts Institute of Technology, Department of Civil & Environmental Engineering Seminar Series, Transport of thermal energy by rain in thawing permafrost landscapes. (September 2020)

Neumann, Rebecca and Eklof, Joel. Interagency Arctic Research Policy Committee, Transport of thermal energy by rain in permafrost landscapes. (April 2020)

PARTICIPANTS

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Joanne Emerson, Associate Professor, UC Davis
Ruth Varner, Professor, University of New Hampshire
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Neumann, R. B., Moorberg, C. J., Lundquist, J. D., Turner, J. C., Waldrop, M. P., McFarland, J. W., et al. (2019). Warming Effects of Spring Rainfall Increase Methane Emissions From Thawing Permafrost. *Geophysical Research Letters*, *46*, 1393–1401. https://doi.org/10.1029/2018GL081274

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Tao, J., Zhu, Q., Riley, W. J., & Neumann, R. B. (2021b). Warm-season net CO2 uptake outweighs cold-season emissions over Alaskan North Slope tundra under current and RCP8.5 climate. *Environmental Research Letters*, *16*(5), 055012. https://doi.org/10.1088/1748-9326/abf6f5

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