Next-Generation Ecosystems Experiment (NGEE Arctic): Progress and Plans

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The Next-Generation Ecosystem Experiments (NGEE Arctic) project seeks to improve the representation of tundra ecosystems in Earth System Models (ESMs) through a coordinated series of model-inspired investigations conducted in landscapes near Utqiaġvik (formerly Barrow) and Nome, Alaska. In Phase 1 (2012 to 2014), we tested and applied a multiscale measurement and modeling framework in a coastal tundra ecosystem on the North Slope of Alaska. In Phase 2 (2015 to 2019), three additional field sites were established on the Seward Peninsula in western Alaska. Integrated field, laboratory, and modeling tasks allowed our team to focus on understanding (1) the effect of landscape structure on the storage and flux of C, water, and nutrients, (2) geochemical mechanisms responsible for CO_2 and CH_4 fluxes across a range of permafrost conditions, (3) variation in plant functional traits across space and time, and in response to changing environmental conditions and resulting consequences for ecosystem processes, (4) controls on shrub distribution and associated biogeochemical and biophysical climate feedbacks, and (5) changes in snow processes and surface and groundwater hydrology expected with warming in the 21st century. A major outcome of our Phase 1 and 2 research was an integrated set of in situ and remotely sensed observations that quantify the covariation of hydro-thermal, ecosystem, vegetation dynamics, and biogeochemical function. Now in Phase 3 (2020 to 2022) we build upon our research at sites on the North Slope and in western Alaska, while also adding a cross-cutting component on disturbance. Field campaigns, modeling, and data synthesis are used to target improvements in simulating disturbance-related processes (e.g., wildfire and abrupt permafrost thaw) and connections to dynamic vegetation (e.g., shrubs) that are missing from or poorly represented in ESMs. Our vision strengthens and extends the connection between process studies in tundra ecosystems and high-resolution landscape modeling and scaling strategies developed in Phases 1 and 2. Safety, national and international collaboration, and a commitment to diversity and inclusion continue to be key underpinnings of our research approach and team philosophy in the Arctic.

Integrating Arctic Vegetation Types into the E3SM Land Model Using Above- And Below-Ground Field Observations

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Accurate simulations of high latitude ecosystems are critical for confident Earth system model projections of carbon cycle feedbacks to global climate change. Land surface models, including the E3SM Land Model (ELM), simulate vegetation growth and ecosystem responses to changing climate and atmospheric CO_2 concentrations by grouping heterogeneous vegetation into plant functional types (PFTs), which can be defined at varying levels of detail. Many ecosystem models represent high-latitude vegetation using only two PFTs representing shrubs and grasses, thereby missing the diversity of vegetation growth patterns in the Arctic. This study used field observations of above- and belowground vegetation biomass and traits across a gradient of plant communities on the Seward Peninsula in northwest Alaska to incorporate nine Arctic-specific PFTs into ELM. The newly developed PFTs included: 1) mosses and lichens, 2) deciduous and evergreen shrubs of various height classes, including an alder shrub PFT, 3) graminoids, and 4) forbs. Improvements relative to the original model configuration included greater belowground biomass allocation, persistent fine roots and rhizomes of nonwoody plants, and better representation of variability in total plant biomass across sites with varying plant communities and depths to bedrock. Simulations through 2100 showed alder-dominated plant communities gaining more biomass and lichen-dominated communities gaining less biomass compared to original model PFTs. Our results highlight how representing the diversity of arctic vegetation and confronting models with measurements from varied plant communities improves the representation of arctic vegetation in terrestrial ecosystem models.

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Alaskan Carbon-Climate Feedbacks to Press and Pulse Disturbances

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Land carbon-climate feedbacks represent a significant uncertainty in predicting atmospheric carbon concentrations under a changing climate. This study applies a well-tested mechanistic land model to examine how different disturbances can lead to non-linear feedbacks to the carbon cycle in high-latitude ecosystems. We first examine the Alaskan ecosystem response to warming. Short-term field experiments project warming to stimulate soil organic matter decomposition, and promote a positive feedback to climate change. We simulate both decade-long, acute warming experiments, and multi-decadal, chronic warming consistent with a changing climate. Herein, we show that the tightly coupled, nonlinear nature of high-latitude ecosystems implies that short-term (<10 year) warming experiments produce emergent ecosystem carbon stock temperature sensitivities inconsistent with emergent multi-decadal responses. In particular, short-term warming manipulations do not capture the non-linear, long-term dynamics of vegetation, and thereby soil organic matter, that occur in response to thermal, hydrological, and nutrient transformations belowground under chronic changes in climate. We expand on this work by examining the impact of pulsed disturbances (i.e., wildfire) on Arctic carbon cycling occurring against a backdrop of warming, altered precipitation, and elevated CO_2. Alongside rapid periods of warming, tundra ecosystems have experienced an increased frequency of fire in recent decades, and this trend is predicted to continue throughout the 21st Century. The post-fire recovery of these ecosystems is underpinned by complex interactions among microbial functional groups that drive carbon and nutrient cycling following a fire. We applied a series of climate change simulations with and without fire to ascertain how tundra ecosystems recover post-disturbance. These model scenarios include two temporally distinct ecosystems: (1) an early century, graminoid dominated ecosystem consistent with current conditions and (2) a late century ecosystem with elevated shrub abundance. We use the model to demonstrate an acceleration of the nitrogen cycle post-fire that is driven by changes in niche space and microbial competitive dynamics. Post-fire recovery is slower at the beginning of the 21st century compared to the onset of fire later in the century, due to warming-induced elevated nutrient availability. We conclude that consideration of distinct microbial metabolisms related to carbon and nutrient cycling are important when considering ecosystem recovery rates following disturbance.

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High-Resolution Modeling of Permafrost Dynamics in Seward Peninsula, Alaska

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We apply a transient temperature dynamic model to investigate the spatiotemporal evolution of permafrost conditions on the Seward Peninsula, Alaska—a region currently characterized by continuous permafrost in its northern part and discontinuous permafrost in the south. We calibrate model parameters using a data assimilation technique exploiting historical ground temperature measurements collected across the study area. The model is then evaluated with a separate control set of the ground temperature data. Calibrated model parameters are distributed across the domain according to ecosystem types. The forcing applied to our model consists of historic monthly temperature and precipitation data and climate projections based on the Representative Concentration Pathway (RCP) 4.5 and 8.5 scenarios. Simulated near-surface permafrost extent for the 2000–2010 decade agrees well with existing permafrost maps and previous Alaska-wide modeling studies. Future projections suggest a significant increase (3.0°C under RCP 4.5 and 4.4°C under RCP 8.5 at the 2 m depth) in mean decadal ground temperature on average for the peninsula for the 2090–2100 decade when compared to the period of 2000–2010. Widespread degradation of the near-surface permafrost is projected to reduce its extent at the end of the 21st century to only 43% of the peninsula's area under RCP 4.5 and 8% under RCP 8.5.

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Thawing Permafrost May Cause Headwater Streams to Cool

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The presence, continuity, and depth of permafrost significantly affects the flow of water through Arctic landscapes and thus potentially impacts stream discharge and thermal regimes. Analyses [1] of July water temperatures from 11 headwater streams in Alaska revealed higher temperatures in catchments with more near-surface permafrost. We used [1] the fully coupled cryohydrology model ATS [2,3] to investigate if deeper flow paths caused by thawing permafrost could create the same trend in the temperatures of groundwater discharging from hillslopes to streams. ATS simulates surface energy and water balances, snow thermal processes, and integrated surface/subsurface water flow and energy transport. We configured ATS to represent two-dimensional hillslopes with varying permafrost extent and found that hillslopes with continuous permafrost have shallower flow paths and twice as high rates of evapotranspiration, compared to hillslopes with no permafrost. For our simulated cases, the horizontal water flux moving through the top organic soil layers was more than ten times greater in continuous permafrost compared to permafrost-free cases. The deeper flow paths in the permafrost-free cases buffer seasonal temperature extremes. As a result, the summer groundwater temperatures discharging to streams are highest with continuous permafrost, consistent with the observations. Our results suggest that permafrost thaw will alter groundwater flow paths, reduce evapotranspiration, and result in more and cooler groundwater discharge to streams in the summer. The cooler groundwater discharging to stream will at least partially compensate for greater stream heating by warmer air, which has important implications for temperature-sensitive fish species. The previously unidentified negative feedback process will be strongest for headwater streams that are dominated by groundwater inflows. Additional work is required, however, to quantify the relative importance of direct stream heating and cooler groundwater inflows and how the relative importance changes with stream order.

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Future Increases in Arctic Lightning and Fire Risk for Permafrost Carbon

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Lightning is expected to increase at high latitudes under expected 21st century climate change. Using satellite-observed lightning flash rate and a climate reanalysis product, we found that summer lightning over northern circumpolar regions currently exhibits a strong positive relationship with the product of convective available potential energy (CAPE) and precipitation. Using Climate Model Intercomparison Project Phase 5 (CMIP5) climate projections for the RCP8.5 scenario, we identified increases in CAPE (86 ± 22%) and precipitation (17 ± 2%) in areas underlain by permafrost by the end of the century; these changes will cause summer lightning to increase by 112 ± 38%. Future flash rates at the northern treeline are comparable to current levels 480 km to the south in boreal forests. We are extending this work by simulating these increases in flash rates and thereby fires across Alaska in the *ecosys* model to explore effects on carbon cycling. Our preliminary results indicate that warmer climate, and elevated atmospheric CO_2 resulted in greater gains in plant biomass. However, increased soil organic carbon (SOC) losses resulted from (1) wildfire combustion and (2) rapid SOC decomposition primed by vegetation changes that led to increased deciduous litter. These SOC carbon losses offset the modeled plant carbon gains, leading to Alaska becoming a net carbon source to the atmosphere after year 2100.

Reference

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Arctic Soil Patterns Analogous to Fluid Instabilities

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Slow-moving arctic soils form patterns resembling those found in common fluids, such as paint and cake icing drips. Though these features impact hillslope stability, carbon storage and release, and landscape response to climate change, no mechanistic explanation exists for their formation. Inspired by fluid instabilities, we develop a new conceptual model for soil patterns and use mathematical analysis to predict their wavelength. We propose that soil patterns arise due to competition between gravity and cohesion, or the "stickiness" of soil grains. We compare our theoretical predictions with a large new data set of soil features from Norway, finding that soil patterns are controlled by both fluid-like properties as well as climate. We also present a comprehensive compilation of solifluction velocity profiles found in the literature and calculate the effective viscosity of soil for field sites across the globe. This informs our understanding of soil rheology, and therefore how soil may respond to changes in climate and hydrologic forcing. Our work proposes a new framework for thinking about Arctic soil stability. Findings may be used as a launching point to improve modeling efforts that predict cohesion-controlled topographic roughness and its role in modulating hillslope hydrology, slope stability, and carbon storage and release. More broadly, results provide the first physical explanation for a common pattern on both Earth and Mars, with implications for our understanding of landscapes and complex materials composed of both granular and fluid components.

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Geophysical Monitoring Shows that Spatial Heterogeneity in Thermohydrological Dynamics Reshapes Transitional Permafrost Systems

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Climate change is causing rapid changes of Arctic ecosystems. Yet, data needed to unravel complex subsurface processes are very rare. Using geophysical and in situ sensing at the NGEE-Arctic Teller Watershed near Nome, AK, we closed an observational gap associated with thermo-hydrological dynamics in discontinuous permafrost systems. Monitoring for more than 2 years, our data highlight the impact of vegetation, topography and snow thickness distribution on subsurface thermo-hydrological properties and processes. Large snow accumulation near tall shrubs insulates the ground and allows for rapid and downward heat flow during snowmelt and rain events. Thinner snowpack above the graminoid leads to surficial freezing and prevents water from infiltrating into the subsurface. Analyzing short-term disturbances such as snowmelt or heavy rainfall, we found that lateral flow could be a driving factor in talik formation. Linking our field data with laboratory derived property-relationships, we show that deep permafrost temperatures increased by about 0.2°C over 2 years. By highlighting the link between above and below ground properties and processes in the Arctic, our results will be useful for improving predictions of Arctic feedback to climate change. They also show that Arctic warm permafrost systems are changing rapidly. For instance, our data suggests that permafrost at our study site could disappear within the next decade. This process could be accelerated by changes in subsurface permeability, snowpack distribution and rainfall patterns. Building upon this work and in order to study dynamics across a range of vegetation type and landscape positions, we installed an additional monitoring transect at a nearby location characterized by colder subsurface temperature. The data from the two sites allow us to compare thermal-hydrological dynamics across elevation, slope, and vegetation types, and is supported by a network of depth-resolved temperature measurements that were deployed through the watershed. Using this data, we will quantify links between surface features and subsurface conditions and processes, which will allow us to upscale our site-scale observations to a regional scale, and will further improve our observational understanding of the impact of climate warming on the thermo-hydrological characteristics of Arctic environments.

Reference

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Topographical Controls on Hillslope-Scale Hydrology Drive Shrub Distributions on the Seward Peninsula, Alaska

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Observations indicate shrubs are expanding across the Arctic tundra, mainly on hillslopes and primarily in response to climate warming. However, the impact topography exerts on hydrology, nutrient dynamics, and plant growth can make untangling the mechanisms behind shrub expansion difficult. We examined the role topography plays in determining shrub expansion by applying a coupled two-dimensional version of a mechanistic ecosystem model (ecosys) in a tundra hillslope site in the Seward Peninsula, Alaska. Modeled biomass of the dominant plant functional types agreed very well with field measurements ($R^2 = 0.89$) and accurately represented shrub expansion over the past 30 years inferred from satellite observations. In the well-drained crest position, canopy water potential and plant nitrogen (N) uptake was modeled to be low from plant and microbial water stress. Intermediate soil water content in the mid-slope position enhanced mineralization and plant N uptake, increasing shrub biomass. The deciduous shrub growth in the mid-slope position was further enhanced by symbiotic N_2 fixation primed by increased root carbon allocation. The gentle slope in the poorly drained lower-slope position resulted in saturated soil conditions that reduced soil O_2 concentrations, leading to lower root O_2 uptake and lower nutrient uptake and plant biomass. A simulation that removed topographical interconnectivity between grid cells resulted in (1) a 28% underestimate of mean shrub biomass and (2) over or underestimated shrub productivity at the various hillslope positions. Our results indicate that land models need to account for hillslope-scale coupled surface and subsurface hydrology to accurately predict current plant distributions and future trajectories in Arctic ecosystems.

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Iron and Iron-Bound Phosphate Accumulate in Surface Soils of Ice-Wedge Polygons in Arctic Tundra

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The arctic tundra stores large quantities of soil organic carbon (C) that can be converted to greenhouse gases and released to the atmosphere as tundra soils warm. Conversely, increased plant growth under warming could remove C from the atmosphere and sequester it in plant biomass. Nutrient availability modulates ecosystem response to warming by influencing both plant growth and decomposition of soil organic matter, but the net effects of nutrient cycling on ecosystem C budgets are not well constrained. Phosphorus (P) is a limiting nutrient to plants and microorganisms in many ecosystems including the arctic. Soil minerals such as iron (Fe) oxyhydroxides strongly adsorb or co-precipitate with phosphate, the bioavailable form of P, but the potential for mineral-bound phosphate to limit P bioavailability has not been established for the organic-rich soils that dominate arctic tundra. Here, we characterized soil Fe and P species as a function of depth in the active layer (<30 cm) of low-centered and high-centered ice-wedge polygons at the Barrow Environmental Observatory on the Alaska North Slope. Our results demonstrate that Fe-bound phosphate is a large and ecologically relevant P reservoir in this system. Surface organic horizons were enriched in Fe and P relative to mineral horizons across all microtopographic features (trough, ridge, center). Soil Fe was dominated by organic-bound Fe and short-range ordered Fe oxyhydroxides, while soil P was primarily associated with oxides and organic matter in organic horizons but apatite and/or calcareous minerals in mineral horizons. Iron oxyhydroxides and Fe-bound phosphate were most enriched at the soil surface and decreased gradually with depth, and Fe-bound phosphate was more than four times greater than bioavailable water-soluble phosphate. These results are consistent with the observation that many tundra and boreal ecosystems exhibit accumulations of Fe oxyhydroxides and Fe-bound phosphate at presumed redox interfaces. However, the spatial and temporal variations in Fe-P interactions remain to be explored. We contend that Fe oxyhydroxides regulate phosphate solubility under fluctuating redox conditions in the arctic tundra and may serve as important controls on P bioavailability.

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Anaerobic Respiration Pathways and Response to Increased Substrate Availability of Arctic Tundra Soils

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The availability of labile organic carbon (C) compounds in Arctic tundra wetland soils is expected to increase due to thawing permafrost and increased fermentation as a result of decomposition of soil organic matter with warming. How microbial communities respond to this change will affect the balance of CO_2 and CH_4 emitted during anaerobic organic matter decomposition, and ultimately the net radiative forcing of greenhouse gas emissions from these soils. While soil water content limits aerobic respiration, the factors controlling methanogenesis and anaerobic respiration are poorly defined in suboxic Arctic soils. We conducted incubation experiments on two tundra soils from field sites on the Seward Peninsula, Alaska, with contrasting pH and geochemistry to determine the pathways of anaerobic microbial respiration and changes with increasing substrate availability upon warming. In incubation of soils from the circumneutral Teller site, the ratio of CO_2 to CH_4 dropped from 10 to < 2 after 60 days, indicating rapid depletion of alternative terminal electron acceptors (TEAs). Addition of acetate stimulated production of CO_2 and CH_4 in a nearly 1:1 ratio, which is indicative of methanogenesis. The composition of the microbial community shifted to favor clades capable of utilizing the added acetate such as the Fe(III)-reducing bacteria *Geobacter* and the methanogenic archaea *Methanosarcina*. In contrast, both CO_2 and CH_4 production declined with acetate addition during incubation of soils from the more acidic Council site, and fermentative microorganisms increased in abundance despite the high availability of fermentation products. These results demonstrate that the degree to which increasing substrate availability stimulates greenhouse gas production in tundra wetlands may vary widely depending on soil pH and geochemistry. Divergent soil biogeochemical conditions will mediate a range of possible pathways and fates for the abundant labile organic C released during permafrost thaw and thus influence radiative forcing of tundra soils.

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Timing and Duration of Hydrological Transitions in Arctic Polygonal Ground from Stable Water Isotopes

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The evolution of Arctic ecosystems in a changing climate will be strongly influenced by the temporal shifting of seasonal transitions and the cascading consequences of an earlier annual thaw and later annual freeze. The transition of the seasons in the Arctic are exceptionally abrupt and result in similarly abrupt landscape hydrological transitions as the landscape freezes and thaws with the seasons. Correspondingly, land surface models (LSMs) and earth system models (ESMs) that include Arctic landscapes must be able to capture these abrupt hydrological transitions that occur during the annual thaw and the deepening of the active layer. The goal of this work was to improve the representation of polygonal surface water hydrology to inform the development of process based LSMs and ESMs, particularly with respect to the timing and duration of hydrological transitions during the annual thaw. Daily surface water samples were collected from 11 locations across the Barrow Environmental Observatory and across arctic tundra morphologies (low centered polygon troughs, high centered polygon troughs, lakes, and drainages) during spring and summer of 2013. Stable water isotopes (δ^2H and δ^{18}O) were then used to appraise the hydrologically significant transitions at the Barrow Environmental Observatory (Utqiaġvik, Alaska) and relate them to shifts in the landscape energy balance, made apparent by the characteristic progression of physical changes during the annual thaw. Rayleigh fractionation models are used throughout to quantify the water balance in various hydrogeomorpologies characteristic of the Barrow Environmental Observatory.

Reference

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A Multi-Sensor Unoccupied Aerial System Improves Characterization of Vegetation Composition and Canopy Properties in the Arctic Tundra

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Climate change can strongly influence vegetation distribution, structure, and function of terrestrial ecosystems, with potentially significant regional and global climate feedbacks. In the Arctic, climate is warming twice as fast as the global average, creating a complex mosaic of vegetation biophysical and landscape changes across the Arctic biome, including increased woody shrub cover, altered surface energy balance, and longer growing seasons. The heterogeneity of these vegetation responses requires new approaches capable of quantifying the fine- to larger-scale changes that are driving ecosystem-scale feedbacks. However, commonly used ground-based measurements are limited in spatial and temporal coverage, and differentiating low-lying tundra plant species is challenging with coarse-resolution satellite remote sensing. On the other hand, Unoccupied aerial systems (UASs) have the potential to fill this critical scaling gap between ground-based and satellite observations. To address this need, we developed a cost-effective multi-sensor UAS (the 'Osprey') using off-the-shelf instrumentation. The Osprey provides simultaneous collection of hyperspectral, optical, thermal, and structural data of vegetation canopies. We describe the deployment of the Osprey in the Arctic at our study site located in the Seward Peninsula, Alaska. A case study is presented to demonstrate the application of Osprey data products for characterizing the key biophysical properties of tundra vegetation canopies. We show that plant functional types (PFTs) representative of arctic tundra ecosystems were mapped with an overall accuracy of 87.4%. The Osprey image products identified significant differences in canopy-scale greenness, canopy height, and surface temperature among PFTs, with deciduous low to tall shrubs having the lowest canopy temperatures while non-vascular lichens had the warmest. The analysis of our hyperspectral data showed that variation in the fractional cover of deciduous low to tall shrubs was effectively characterized by Osprey reflectance measurements across the range of visible to near-infrared wavelengths. Therefore, the development and deployment of the Osprey UAS, as a

state-of-the-art methodology, has the potential to be widely used for characterizing tundra vegetation composition and canopy properties to improve our understanding of ecosystem dynamics in the Arctic, and to address scale issues between ground-based and airborne/satellite observations.

Reference

Yang D, R Meng, BD Morrison, A McMahon, W Hantson, DJ Hayes, AL Breen, VG Salmon, and SP Serbin. 2020. A multi-sensor unoccupied aerial system improves characterization of vegetation composition and canopy properties in the Arctic tundra. Remote Sensing 12: 2638. https://doi.org/10.3390/rs12162638