Topography Drives Variability in Circumpolar Permafrost Thaw Pond Expansion

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One of the most conspicuous signals of climate change in high-latitude tundra is the expansion of thermokarst pools. These small but abundant water features form rapidly in depressions caused by the melting of ice wedges (*i.e.*, meter-scale bodies of ice embedded within the top of the permafrost). Pool expansion not only signals permafrost degradation, but strongly impacts subsequent thaw rates through a series of complex positive and negative feedbacks which play out over timescales of decades, the net effect of which may accelerate carbon release from the underlying sediments. Despite the importance of thermokarst pool expansion to assessments of contemporary permafrost thaw, historical observations are limited in spatial and temporal frequency. Here we present the most geographically extensive and temporally dense measurements yet compiled of recent pool expansion, in which changes to pool area from 2008—2020 were quantified through satellite-imagery analysis at twenty-seven landscapes dispersed throughout the circumpolar tundra. The results revealed instances of rapid thermokarst pool expansion at 44% of survey areas and in temperature settings that ranged from very cold to mild. The sites that experienced the greatest net change tended to be those with the greatest topographic relief (tens of meters of variation within an area of eight square kilometers). This pan-Arctic relationship was associated with an enhanced vulnerability of ice wedges near hilltops, as within most sites, the fastest growing pools were found on convex points on the land surface. These findings indicate the necessity of including topographic controls in global projections of permafrost thaw.

Spatial Patterns of Snow Distribution in the Sub-Arctic

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The spatial distribution of snow plays a vital role in sub-Arctic and Arctic climate, hydrology, and ecology due to its fundamental influence on the water balance, thermal regimes, vegetation, and carbon flux. However, the spatial distribution of snow is not well understood, and therefore, it is not well modeled, which can lead to substantial uncertainties in snow cover representations. To capture key hydro-ecological controls on snow spatial distribution, we carried out intensive field studies over multiple years for two small (2017-2019, ~2.5 km^2) sub-Arctic study sites located on the Seward Peninsula of Alaska. Using an intensive suite of field observations (>22,000 data points), we developed simple models of spatial distribution of snow water equivalent (SWE) using factors such as topographic characteristics, vegetation characteristics based on greenness (normalized different vegetation index, NDVI), and a simple metric for approximating winds. The most successful model was the random forest using both study sites and all years, which was able to accurately capture the complexity and variability of snow characteristics across the sites. Approximately 86% of the SWE distribution could be accounted for, on average, by the random forest model at the study sites. Factors that impacted year-to-year snow distribution included NDVI, elevation, and a metric to represent coarse microtopography (topographic position index, or TPI), while slope, wind, and fine microtopography factors were less important. The models were used to predict SWE at the locations through the study area and for all years. The characterization of the SWE spatial distribution patterns will be used to validate and improve snow distribution modelling in the Department of Energy's earth system model, and for improved understanding of hydrology, topography, and vegetation dynamics in the sub-Arctic and Arctic regions of the globe.

Dynamic Soil Columns Simulate Arctic Redox Biogeochemistry

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Arctic soil represents a large reservoir of organic carbon that is vulnerable to decomposition and release as carbon dioxide (CO_2) and methane (CH_4). Thawing permafrost landscapes are especially sensitive, with thermokarst formation dramatically changing Arctic hydrology and altering soil temperature regimes, oxygen availability, and biogeochemical redox cycling. There is limited understanding of how rapid redox transitions in Arctic soils will impact the magnitude and timing of CO_2 and CH_4 release. As ecosystem scale models advance to incorporate process-based soil redox biogeochemistry, improved mechanistic understanding of the links between hydrology, redox conditions, and microbial organic carbon decomposition will be required. This study identified shifts in Arctic soil microbial metabolisms due to changing oxygen availability during soil saturation and drainage. Dynamic soil column experiments were used to change the water level in soil and permafrost collected from an inundated thermokarst channel and the adjacent upland tundra near Council, Alaska. Soil columns (50 cm length, 7.5 cm diameter) were instrumented to continuously measure volumetric water content and oxygen concentrations and were operated at field-relevant temperatures and water contents. Discrete porewater samples were taken from MicroRhizon samplers and measured for ferrous and total iron, pH, dissolved organic carbon, and major cations, anions, and organic acids. Headspace samples were also taken to determine CO_2 and CH_4 soil fluxes. Relative to upland soils, thermokarst soils were expected to release more CH_4 and less CO_2 during draining and promote more efficient microbial iron reduction during saturation. Initial results indicate that thermokarst soil does release more CH_4 and less CO_2 during draining than upland soil, which is undoubtedly related to faster soil drainage (~3x initial drainage rate) in the upland soil. This trend could also be partially attributed to prior adaptation of upland and thermokarst microbial communities to more oxic and oxygen-depleted conditions, respectively. Iron cycling – from reduction during saturation to oxidation during draining – was observed in both soil types, and the links between carbon and iron cycling are being evaluated in terms of organic electron donors and iron mineral-associated organic carbon. This column study will help constrain the relative importance and timing of aerobic respiration, anaerobic respiration through iron oxidation/reduction, fermentation, and methanogenesis on carbon cycling in Arctic soils undergoing redox transitions. This dataset will also inform integration of redox processes impacted by transport and changing oxygen availability into reactive transport models, such as PFLOTRAN, which are being coupled to terrestrial components of Earth system models.

Environmental Controls on Observed Spatial Variability of Soil Pore Water Geochemistry in Small Headwater Catchments Underlain with Permafrost

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Permafrost thaw in the Arctic is causing significant changes to landscape structure, hydrology, vegetation, and biogeochemistry. The integrated hydrogeochemical effect of these environmental changes are already apparent in the chemistry of the large Arctic rivers, where fluxes of carbon and nutrients are increasing, leading to enhanced nutrient loadings, with strong implications for the global carbon cycle. While the watershed areas of large Arctic rivers are vast, recent studies suggest that solute concentrations in these large rivers are likely controlled by solute generation processes occurring at much smaller scales. In this sense, changes in hydrogeochemistry in small Arctic catchments not only impact hydrogeochemistry at much larger scales, but also prognosticate the future hydrogeochemistry of larger Arctic rivers. While there is a rapidly growing body of literature focused on observing and understanding the impacts of Arctic warming on landscape structure, hydrology, vegetation, and biogeochemistry, relatively few studies directly address the existing spatial variability. In this study, we quantitatively evaluate the spatial variability of soil pore water geochemistry within two distinct catchments underlain with permafrost, and then seek to identify the source of the observed spatial variability. The soil pore water geochemistry of 18 locations spanning two small Arctic catchments were examined for spatial variability and its dominant environmental controls. The primary environmental controls considered were vegetation, soil moisture/redox condition, water/soil interactions and hydrologic transport, and mineral solubility. The sampling locations varied in terms of vegetation type and canopy height, presence or absence of near-surface permafrost, soil moisture, and hillslope position. As source areas for geochemical fluxes to the broader Arctic hydrologic system, geochemical processes occurring in these environments are particularly important to understand and predict with regards to such environmental changes.

Assessing Dynamic Vegetation Model Parameter Uncertainty Across Alaskan Arctic Tundra Plant Communities

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As the Arctic region moves into uncharted territory under a warming climate, it is important to refine the terrestrial biosphere models (TBMs) that help us understand and predict change. One fundamental uncertainty in TBMs relates to model parameters, configuration variables internal to the model whose value can be estimated from data. We incorporate a version of the Terrestrial Ecosystem Model (TEM) developed for arctic ecosystems into the Predictive Ecosystem Analyzer (PEcAn) framework. PEcAn treats model parameters as probability distributions, estimates parameters based on a synthesis of available field data, and then quantifies both model sensitivity and uncertainty to a given parameter or suite of parameters. We examined how variation in 21 parameters in the equation for gross primary production influenced model sensitivity and uncertainty in terms of two carbon fluxes (net primary productivity and heterotrophic respiration) and two carbon (C) pools (vegetation C and soil C). We set up different parameterizations of TEM across a range of tundra types (tussock tundra, heath tundra, wet sedge tundra, and shrub tundra) in northern Alaska, along a latitudinal transect extending from the coastal plain near Utqiaġvik to the southern foothills of the Brooks Range, to the Seward Peninsula. TEM was most sensitive to parameters related to the temperature regulation of photosynthesis. Model uncertainty was mostly due to parameters related to leaf area, temperature regulation of photosynthesis, and the stomatal responses to ambient light conditions. Our analysis also showed that sensitivity and uncertainty to a given parameter varied spatially. At some sites, model sensitivity and uncertainty tended to be connected to a wider range of parameters, underlining the importance of assessing tundra community processes across environmental gradients or geographic locations. Generally, across sites, the flux of net primary productivity (NPP) and pool of vegetation C had about equal uncertainty, while heterotrophic respiration had higher uncertainty than the pool of soil C. Our study illustrates the complexity inherent in evaluating parameter uncertainty across highly heterogeneous arctic tundra plant communities. It also provides a framework for iteratively testing how newly collected field data related to key parameters may result in more effective forecasting of Arctic change.

Effect of Slope Topography on the Above- and Below-ground Traits in Tundra Biome: Case Study at the Seward Peninsula

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Slope terraces are a widespread feature on the Seward Peninsula. These landforms affect the redistribution of snow during the winter season and control soil temperature and moisture regime, thus influencing vegetation and soil development. To study these mechanisms, we conducted research at one of such terraces at milepost 28 of the Teller Road. Our field activities included soil, vegetation, and snow surveys along a 70-meters long transect parallel to the terrace tread, biomass productivity assessment, decomposition experiment, and continuous measurements of the ground temperature and soil moisture at three points located in the rear, middle and front parts of the terrace. Our results showed mean annual ground temperature at the depth of 1.2 meters in 2019 gradually decreases from 1.9-4.2°C at the rear part to 0.1-0.5°C with a potential for a perennial frozen layer at the terrace's edge. Such a pattern in the ground thermal regime is most likely caused by the difference in winter temperature due to snow redistribution. The soil moisture regime is identified as Ustic at the rear and middle parts and Udic at the front of the terrace. Across the tread of the terrace vegetation changes from Mesic graminoid-herb meadow in the rear part to Cassiope dwarf shrub tundra in the middle and Ericaceous-lichen dwarf shrub tundra at the front. Aboveground bioproductivity increases from the rear (449.6 g/m^2) to the front part (1099.76 g/m^2) of the terrace. But, because of the differences in composition of plants communities, amount of annual litter biomass decreases from the rear to the frontal part. The highest rate of litter decomposition during the summer season occurs at the middle section of the terrace and the lowest – at the front. Processes of the organic stabilization were the lowest at the rear part of the terrace. A combination of all about mentioned factors and processes explain the pattern in soil sequence. The most developed soil profile (Ustic Haplocryols) can be found at the rear part of the terrace replaced with the Typic Humicryepts at the middle and Typic Dystrogelepts/Haplogelepts at the front. All of these processes also create the patterns of spatial variability of carbon budget and the greenhouse gases fluxes.

Dispersal and Fire Limit Arctic Shrub Expansion

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Arctic shrub expansion has been widely reported in recent decades, with large impacts on carbon budgets, albedo, and warming rates in high latitudes. However, predicting shrub expansion across regions remains challenging because the underlying controls remain unclear. Observational studies and models typically use relationships between observed shrub presence and current environmental suitability (bioclimate and topography) to predict shrub expansion, but such approaches omit potentially important demographic processes and non-stationary response of shrubs to changing climate. Here, we investigated controls on shrub expansion as part of the NGEE Arctic project. We used long-term high-resolution satellite imagery across Alaska and western Canada to show that observed shrub expansion has not been controlled by environmental suitability during 1984—2014, but rather can only be explained by accounting for seed dispersal and fire. These findings provide the impetus for better observations of recruitment and for incorporating currently underrepresented processes of seed dispersal and fire in land models to project shrub expansion and future climate feedbacks. Integrating these dynamic processes with projected fire extent and climate, we estimate that shrubs will expand into 25% of the non-shrub tundra by 2100, in contrast to 39% predicted using a relationship with increasing suitability alone. Thus, using environmental suitability alone likely overestimates and misrepresents the spatial pattern of shrub expansion and its associated carbon sink.

Climatic and Environmental Controls on Recent Arctic Tundra Shrubification

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Vegetation composition shifts, and in particular, shrub expansion across the Arctic tundra are some of the most important and widely observed responses of high-latitude ecosystems to rapid climate warming. These changes in vegetation potentially alter ecosystem carbon balances by affecting a complex set of soil–plant–atmosphere interactions. We synthesized the literature and found that shrub expansion is affected by several interacting factors including climate warming, accelerated nutrient cycling, changing disturbance regimes, and local variation in topography and hydrology. Under warmer conditions, tall deciduous shrubs can be more competitive than other plant functional types in tundra ecosystems because of their taller maximum canopy heights and often dense canopy structure. We also examined the role topography plays in determining shrub expansion by applying a coupled transect version of a mechanistic ecosystem model (*ecosys*) in a tundra hillslope site across the Kougarok watershed, Alaska. We found that intermediate soil water content in the mid-slope position enhanced mineralization and plant N uptake, thereby increasing shrub 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 differences in plant traits that control competition and hillslope-scale coupled surface and subsurface hydrology to accurately predict current shrub distributions and future trajectories in Arctic ecosystems.

Impact of Short-term Warming on Carbon and Nitrogen Cycling Along the Plant-Soil Continuum

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The majority of plant biomass is located belowground in Arctic ecosystems, and plant roots are responsible for the uptake of nutrients that limit plant growth in these ecosystems. Despite performing a crucial role connecting primary producers to the soil, plant roots are relatively understudied in the Arctic and their functional response to rapidly warming climate is unknown. We therefore decided to assess whether one growing season of elevated temperature would have an impact on belowground carbon (C) and nitrogen (N) dynamics in the tundra. We conducted two field campaigns in Utqiaġvik, AK where we were able to sample Zero Power Warming Chambers deployed by NGEE Arctic. These chambers elevate air temperatures by around 4°C and surface soil temperatures by around 1°C during the peak growing season. To understand the impact of the warming treatment on both C and N dynamics, in 2018 we quantified the uptake of $^{15}N\text{-}NH_4$ from the soil by the arctic grass *Arctagrostis latifolia*. In 2021, we looked at the aboveground uptake of $^{13}C\text{-}CO_2$ by the sedge *Carex aquatilis*. Together, these experiments allow us to trace the path of N up from the soils through plant tissues as well the path of C downward from plant leaves, through roots, and into the rhizosphere. In 2018, we found that soil N and P availability increases significantly with warming, but biomass N and P pools of *A. latifolia* do not. Uptake of N by this grass species was not significantly impacted by warming, but we did see a strong relationship between soil NH_4 availability and uptake provided these variables were expressed in spatially explicit units (NH_4 per cm^3 soil & uptake per m fine root). In 2021, in addition to sampling plant tissues, our team also collected daily leaf samples, daily soil porewater samples, and measured soil microbial biomass at the end of a one-week incubation period. Preliminary observations from the 2021 campaign include the formation of iron-oxide plaques on root surfaces, indicating that oxygen (O) is flowing from the plant roots to the rhizosphere. Future analyses will quantify the transfer of recent photosynthate to soil porewater and the soil microbial community as well as allocation of this photosynthate within plant tissue. This research highlights the important role that interactions between plants, soils, and microbes play in determining local biogeochemistry.

Fine-scale Vegetation Composition and Structure Drives Variation in Spatial and Temporal Dynamics of Surface Albedo in Low Arctic Tundra

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Albedo, a measure of the solar reflectivity, is an important biophysical property of the land surface that influences local heating, regulates vegetation-atmosphere interactions and is a strong determinant of Earth's energy balance. In the Arctic, rapid climate warming is driving dramatic changes in vegetation distribution and land surface structure, including a rapid expansion of shrub and tree species into the Arctic tundra. This widespread replacement of vegetation species and structure is expected to have strong impacts on albedo, and as a result, on ecosystem energy balance. At the same time, Arctic vegetation distribution is strongly tied to the presence of permafrost, moisture and nutrient gradients, and fine-scale topographic features resulting in a high degree of spatial heterogeneity. This inherent variability combined with climate-driven changes in vegetation cover creates complex albedo responses in the Arctic. Traditional methods used to quantify albedo change and spatial patterns have been limited by their relatively low spatial resolution (e.g., > 250 m), requiring new, multi-scale observations to characterize the direction and rate of change in surface albedo. In this study, we address this need by combining remote sensing data across scales, from unoccupied aerial systems, high-resolution topography data, to piloted airborne and satellite observations to investigate the links between vegetation composition, structure, functional properties, and topographic features on the resulting spatio-temporal patterns of albedo in western Alaska. We used a time-series (2013 – 2020) Landsat albedo product across three watersheds located in the Seward Peninsula to investigate how sub-pixel patterns influence regional albedo. We observed strong regional albedo seasonality, but also significant differences in albedo patterns across the plant functional types, with tree and shrub species showing lower albedo than low-stature plants. In the winter, albedo is primarily a function of vegetation height, likely because taller vegetation, which is darker than the surrounding snow, extends above the snow layer. In the summer season, vegetation composition and topographic position, a strong driver of tall shrub distribution, were more important for explaining albedo variation than vegetation structure. Our results suggests that changes in vegetation composition and structure will create increasingly complex albedo patterns across the Arctic, and our dataset can be used to inform and benchmark process models predictions of Arctic albedo.

Near-Surface Hydrology and Soil Properties Drive Heterogeneity in Permafrost Distribution, Vegetation Dynamics, and Carbon Cycling in a Sub-Arctic Watershed

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Discontinuous permafrost environments exhibit strong spatial heterogeneity in subsurface thermal states, vegetation cover, and carbon fluxes, with sharp transitions that occur at scales too small to be driven by weather forcing or to be captured by Earth System Models. Here we analyze – using field observations and an ecosystem model – the effects of observed spatial heterogeneity in soil and vegetation properties, hydrology, and thermal dynamics on ecosystem carbon dynamics in a watershed on the Seward Peninsula in Alaska. First, we quantify the controls on soil thermal regimes across the watershed using a dense network of distributed temperature profiling systems (DTP). The DTP data indicates that the soil thermal regimes are primarily driven by snow depth and co-vary with vegetation type with near-surface permafrost and talik present under graminoid and shrub covered area, respectively. Further, we evaluate the mechanisms driving this co-variability and its impact on carbon dynamics by applying a Morris global sensitivity analysis (GSA) to a process-rich, successfully tested terrestrial ecosystem model, *ecosys*. The GSA outputs cover the observed ranges of soil temperatures, soil moisture, and surface CO_2 fluxes observed in the watershed and confirm that landscape heterogeneity has a strong impact on soil temperatures, permafrost distribution, and vegetation composition. Snow depth, O-horizon thickness, and near-surface water content control the soil thermal regime more than an air temperature gradient corresponding to a 140 km north-south distance. High shrub productivity is simulated only in talik (perennially unfrozen) soils with high nitrogen availability Through these effects on PFT and permafrost dynamics, landscape heterogeneity impacts ecosystem productivity. We find that model runs with near-surface taliks have higher microbial respiration (by 78.0 gC m^{-2} yr^{-1}) and higher net primary productivity (by 104.9 gC m^{-2} yr^{-1}) compared to runs with near-surface permafrost, and simulations with high shrub productivity have outlying values of net carbon uptake. We explored the prediction uncertainty associated with ignoring observed landscape heterogeneity and found that watershed net carbon uptake is three times larger when heterogeneity is accounted for. Our results highlight the complexity inherent in discontinuous permafrost environments and demonstrate that missing representation of subgrid heterogeneity in TEMs could bias predictions of high-latitude carbon budget.

Integrating Arctic Vegetation and Biogeochemical Processes into the E3SM Land Model

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Earth system models are a critical tool for projecting future changes in climate and ecosystems. A major goal of the NGEE Arctic project is to integrate improved scientific understanding of Arctic systems into the Energy Exascale Earth System Model (E3SM) to connect scientific discoveries from observations, experiments, and detailed modeling of the Arctic into global-scale predictive models. New understanding of Arctic processes is being incorporated into hydrological, physical, biogeochemical, and vegetation process modules in the E3SM Land Model (ELM) through multiple integrative modeling efforts as part of NGEE Arctic Phase 3. I will highlight recent progress in two of these integrative modeling efforts. First, improvements to ELM with the goal of better representing vegetation traits by integrating nine tundra-specific plant functional types (PFTs); several that are new to the model, including nonvascular mosses and lichens, graminoids, forbs, and shrubs of various height classes as well as a nitrogen fixing alder shrub. These developments leverage extensive field sampling of vegetation species distributions and biomass and are now being integrated with remote sensing of vegetation communities and traits to configure ELM model simulations of tundra vegetation carbon and nutrient cycling across the Seward Peninsula of Alaska. Second, we have implemented new soil biogeochemical capabilities with the goal of better representing greenhouse gas production across complex tundra landscapes. We have developed a reaction network in the geochemical simulator PFLOTRAN including pH dynamics, iron redox cycling, oxygen consumption, methanogenesis, and soil nitrogen cycling informed by experimental and field measurements of tundra soil processes. Furthermore, we have coupled this reaction network to ELM representation of soil organic matter decomposition within a coupled ELM-PFLOTRAN framework, allowing fully integrated simulations of complex biogeochemical cycling within E3SM. Altogether, these developments translate discovery science from a range of observations, experiments, and detailed modeling studies within the NGEE Arctic project into concrete improvements in E3SM modeling capabilities.

Arctic Alder Nodule Microbe: Insights into Nitrogen Fixation

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This project uses state of the art sequencing and imaging technologies to resolve complex plant-microbe interactions governing the nitrogen fixation in tundra biomes to better inform efforts to decipher arctic nitrogen cycling. Plant roots are home to beneficial microbes where microorganisms help plants to obtain nutrients, tolerate stress and sustain growth. Nitrogen (N) fixation is a common mutualistic symbiosis where the plant provides the N-fixing bacteria with sugars and a variety of minerals, and the bacteria provide the host with N. We investigated the nodule microbiome of alder *Alnus viridis* spp. *fruticosa*, an N-fixing deciduous shrub and an important contributor to N-cycling in the tundra. *Frankia alni* and its relatives form a symbiotic relationship exclusively with trees in the genus *Alnus* but this actinorhizal symbiosis is not as well characterized as the agriculturally important legume-rhizobia symbiosis, especially in the Arctic. The Kougarok study site is situated in the Seward Peninsula, AK. At this location alder is found as two distinct communities: short and dispersed alder growing in lowland areas ("alder savanna") and tall alder growing as dense, tall shrublands along the rocky ridge of the hillslope ("alder shrubland"). We collected root free soil samples next to the plants and nodules from both alder communities. We extracted and sequenced the whole community DNA from both nodules and surrounding soils resulting several hundred metagenome assembled genomes (MAGs) and viral genomes (vMAGs) of bacteriophages. We coupled metagenomics with analysis of intra-nodule biochemistry via synchrotron fourier transform infrared (SR-FTIR) spectral imaging at the Berkeley Infrared Structural Biology beamline of the Advanced Light Source. The alder microbiome was dominated by a novel *Frankia* strain. Both alder communities contained non-*Frankia* bacteria but alder shrubland had a higher bacterial diversity than alder savanna. Non-*Frankia* bacteria in alder nodules contained carbohydrate degradation genes involved in hemicellulose, mannose and xylose degradation. Bacteriophages associated with alder nodule microbiome carry carbohydrate degradation genes specific to cellulose, xylose and pectin degradation. SR-FTIR analysis showed that despite differences in microbiomes alder nodules both communities had similar biochemical in the composition at a functional group level where metabolites involved in N-fixation was dominating the chemical spectra. However, we also observed strong intra-plant and -nodule variation which was decoupled from N-fixation processes. Arctic alder nodules house a diverse microbiome and has a rich biochemical composition. This diversity can be associated with plant growth and inputs of biologically-available N into nutrient-poor Arctic ecosystems.

Integrating Field Observations and Multi-scale Remote Sensing to Understand Tall Shrub Distribution in Arctic Tundra

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The Arctic region has experienced some of the most rapid climate warming on Earth. In response to this warming and associated permafrost thaw, an increase in the abundance of tall shrubs (those that can potentially grow greater than 2 m tall) has been observed across the Arctic, with significant implications on Arctic biodiversity, energy balance, and the biogeochemical cycling of carbon, water, and nutrients. However, uncertainties persist in quantifying the primary drivers of the distribution and rate of shrub expansion in Arctic tundra. While warming temperatures and permafrost thaw are expected to be a key driver, shrub distribution is also likely limited by other biotic and abiotic factors that do not favor their growth (e.g., topographic control and soil moisture). Changes in these limiting factors could have larger or more direct impacts on shrub expansion. In this study, we combined ground observations and multi-scale remote sensing data, including occupied aerial system (UAS; 5 cm), NASA's Airborne Visible / Infrared Imaging Spectrometer (AVIRIS-NG; 5 m), ArcticDEM (30 m), high-resolution down-scaled climate data (60 m), and model simulated soil data (500 m), to investigate the drivers and limits of tall shrub distribution in Western Alaska. We first mapped the fractional cover (FCover) of two key tall shrub genera (alder and willow) using AVIRIS-NG imagery collected on the Seward Peninsula and a vegetation cover scaling approach that we have developed for AVIRIS-NG. We then combined the alder and willow FCover maps with topographic, climate, and soil moisture data to investigate the primary determinants of tall shrub distribution. We found that topography is a primary control on tall shrub distribution in the Arctic. The distribution of alder is strongly limited by elevation and slope, with a higher cover found within the 100 - 300 m, MSL elevational band. In contrast, the distribution of willow is more closely tied to surface wetness. To understand the biological mechanisms of these differences, we further examined their biochemical and physiological traits, and found that willow has a lower instantaneous water-use efficiency than alder, suggesting why willow is found in wetter conditions. These findings suggest that different shrub species may respond to the climate change differently. Improved understanding of the controls on tall shrub distribution is important to accurately forecast the response of arctic ecosystems to current and future climate change.