NWT LTER VII
Long-term Research on the Dynamics of High-Elevation Ecosystems:
A Framework to Understand Ecological Responsiveness to Climate Change

Year 6 Annual Report
2021 – 2022

Photo caption: *LTER Technicians apply a thin layer of black sand to a n ongoing NWT experiment to increase growing season length (credit K. Simpkins; https://www.colorado.edu/today/2022/09/12/study-impacts-longer-hotter-summers-ecologists-haul-5000-pounds-sand-mountain)*

In LTER VII, our overarching goal is to better understand where and when climate change results in ecological change, and to elucidate the mechanisms that lead to both sensitivity and buffering in ecological systems. Our objectives are to (a) continue to characterize how ecosystems are changing with climate variation, (b) test hypotheses about the underlying drivers of this variation, and (c) use this information to enhance forecasting and management in mountain areas.

We have framed our work by extending two bodies of ecological theory. First, we utilize work aimed at predicting vulnerability to climate change at regional scales, which emphasizes that response is a function of the magnitude of climate change experienced (exposure), the intrinsic ability to tolerate a given amount of change (sensitivity), and the degree to which elements can shift in response to the change (adaptive capacity) (Dawson et al. 2011, Dickinson et al. 2014). We extend these ideas to spatial variation at the landscape scale, where complex terrain (Q1, below) and biophysical effects of biota (Q2) modulate climate, creating a heterogeneous backdrop of resource supply changing both over the course of the growing season and across years due to climate variation. Second, we utilize work focused on responses to changing temporal variation as well as spatial connectivity across landscape positions, outlining how responsiveness to different patterns of temporal (Q3) or spatial (Q4) variability aggregates to other levels (e.g., population to community, patch to catchment). We extend these ideas to how integration, interaction, and connection buffer or amplify responsiveness. We specifically designed our work to address four questions:

Q1) SHIFTING LIMITATIONS. How do terrain-related differences in exposure, by shifting the limiting resources and abiotic stressors, affect ecological response? We expect that complex terrain, by altering the magnitude of climate exposure experienced at a location, will shift how climate variation impacts the relative supply of different resources and the occurrence or frequency of stress. These shifts will result in both positive and negative responses, depending on the strength and nature of the limitations, and influence process rates across levels of organization, including at the ecosystem (productivity), community (species turnover) and population (abundance, recruitment) levels.

Q2) BIOTIC INFLUENCE. How do structure-forming biota attenuate climate exposure to influence ecological response? We also expect that biota can influence climate exposure through effects on the physical environment. Because these effects will occur at a relatively fine scale, we expect that structure-forming biota will increase heterogeneity within a habitat, influence the number of species able to coexist, and create micro-refugia in the face of a changing climate.

Q3) ADAPTATION STRATEGIES. How do different strategies for managing temporal variability and uncertainty at the organism and population levels aggregate to influence community and ecosystem processes? We expect that terrain- and biota-related differences in exposure, in addition to modulating average conditions (Q1 and Q2), will influence environmental variability and predictability. Species' sensitivities reflect evolutionarily constrained responses to past climate, and constraints at the organism and population levels should be reflected in community and ecosystem responses.

Q4) CATCHMENT INTEGRATION. How do responses across space aggregate to affect catchment response? Water quality and quantity leaving a catchment represents an integrated signal of the biotic and abiotic processes occurring along flow paths. We expect that shifts in hydrological connectivity along these paths (where some areas of the catchment may contribute in some years but not in others) should influence net water quality and quantity. Our fourth hypothesis represents a critical line of thinking for LTER VII because it links much of the fine- scale work in terrestrial sphere with the aquatic through water quality and quantity. To make this linkage, we are

working to scale up to the catchment scale – integrating spatial heterogeneity in response emphasized in the previous hypotheses – and then relating these dynamics to catchment-wide responses that we know influence the lake ecosystems: water discharge, nutrient export, and DOM inputs. This inquiry also enables a longer-term linkage by incorporating vegetation/land cover change at the catchment scale.

We have unified our investigations of ecological responsiveness by focusing on climatic change in
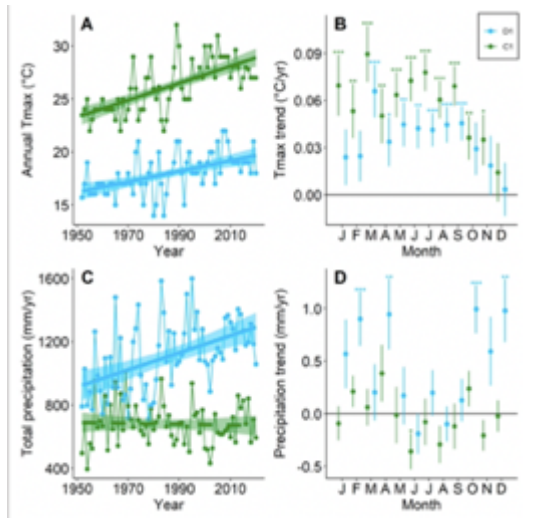

Figure 1. (A, B) The maximum annual temperature (T_{Max}) has increased in both alpine (D1) and subalpine (C1) sites at NWT. (C, D) Total annual precipitation is highly variable in both time and space, increasing slightly in the alpine with no detectable change in the subalpine. Temporal trends by month (B, D) illustrate within-year variation in the rate at which temperature and precipitation has changed since 1950, with warmer springs and summers and more precipitation (as snow) in winter. <u>Data sources</u>: 184.5, 185.2, 186.3, 187.2, 411.13, 412.11, 414.13, 415.14

these high-elevation snow-governed ecosystems. While we started NWTVII focused on the **EXTENSION OF SUMMER,** climate trends over the past 6 years indicate that the strongest trends in temperature, with highly variable temporal patterns in growing season length (snow-free cover) and precipitation. Our long-term records identify a strong temporal trend of warming (Bueno de Mesquita et al., 2021; McGuire et al., 2012) with an annual maximum temperature increase of ~0.5°C/decade over the past 70 years in both subalpine (C1) and alpine (D1) environments (**Fig. 1**). Over the same time period, precipitation (75% of which falls as snow at NWT) shows high interannual variability, with no overall trend in the subalpine. In the alpine, a step increased occurred in the 1980s, reflecting decadal shift in atmospheric circulation 1980s (Kittel et al., 2015) (**Fig. 1 C, D**). During the period covered by LTER observations, there has been no overall trend in precipitation.

Prior to 2000, warming at NWT was coupled with longer, drier growing seasons, spurring our focus on extended summers in NWT VII. Updated analyses using recent climate records show the decoupling between summer temperature and length of frost-free season (Bueno de Mesquita et al., 2021), with temperatures continuing to rise without changes in season length. Consequently, we leverage the decoupling between temperature and snowfall to explore the interacting effects of climate controls across heterogeneous terrain.

In snow-dominated systems such as NWT, climate determines the onset and development of snow cover (snowfall), the conditions responsible for its ablation (solar radiation, air temperature), and its redistribution across the heterogeneous terrain (wind) (Jennings et al., 2018; Jennings and Molotch, 2020; Sexstone et al., 2018). Higher temperatures have increased snowmelt before maximum snowpack in the winter, consistent with regional patterns (Musselman et al., 2021), and causing streams to begin flowing earlier in warmer springs. Rising temperatures have substantially increased

the length of the ice-free period in NWT lakes: since 1983, the ice-free period in the Green Lake Valley has increased an average of 0.5 days/year (Christianson et al., 2021).

In the following sections, we detail our accomplishments and our next steps towards meeting or stated objectives for each of our four main research question. Our structure follows the order of the work plan in our proposal, with sections on outreach and information management following the sections on research.

1. SHIFTING LIMITATIONS. How do terrain-related differences in climate exposure affect ecological response? In our first hypothesis, we proposed that complex terrain, by altering the magnitude of climate response at a location, will shift how climate variation impacts the relative availability of different resources and the occurrence or frequency of stress. To test this idea, we proposed a series of studies using observed patterns in long-term datasets (**A**), modeling (**B**), and experimentation (**C**) for LTER VII. Here, we detail our expectations and progress to date for each in the following sections.

A. Continued monitoring of tundra, forests, chickadees, pikas, pollinators, streams, and lakes. Across a broad range of ecological systems, we have examined ecological responses to changing climate conditions at NWT. While correlational, this step leverages patterns in long-term data to confirm and guide expectations. It also highlights the varied responses across landscape position, organism, and level of organization.

Tundra plant communities. We have continued to follow tundra plant production and compositional change in established tundra (88-plot saddle grid) as well as in sensor network in the Saddle Catchment. Analysis of our long-term records show that the rates at which plant community composition changes with warming varies among community types in Niwot's tundra vegetation (Spasojevic et al., 2013; Suding et al., 2015; Yang et al., 2020).

Over the last 30 years, compositional turnover with warming has been fastest in the communities that experience the most extreme abiotic conditions: wet meadow and snowbed, which experience the most persistent snowpack, shortest growing seasons, and highest soil moisture during the summer; and fellfields, which experience the least snow and longest, driest growing season (**Fig. 2**, Oldfather, in review). In contrast, dry and moist meadows (average snow conditions) show more minimal turnover with warming (**Fig. 2**). Further, we found divergent community trajectories across a local gradient of snow persistence – wind-blown areas that accumulate little snowpack have shifted toward more stress-tolerant, cold- and drought-adapted communities, while areas with more persistent snowpack have shifted toward more warm-adapted communities (thermophilization). The shift to more cold adapted species with warming in parts of the landscape with less persistent snowpack may reflect an increasing benefit of drought-tolerant traits that also increase cold tolerance, and are consistent with a shift toward more conservative, stress-tolerant traits including lower specific leaf area (SLA) and increased water use efficiency (Huxley and Spasojevic, 2021).
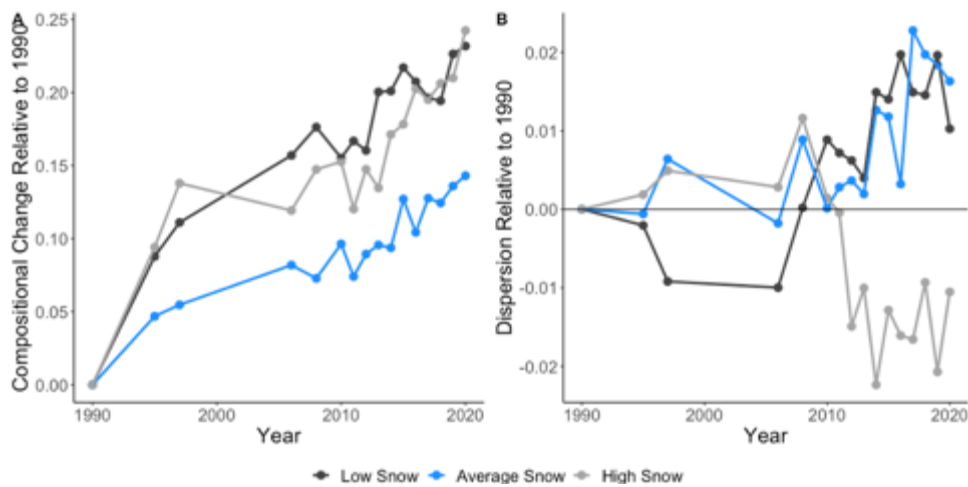
Figure. 2 (A) The magnitude of compositional change through time relative to the vegetation communities in 1990 for three snow persistence groups. Points for each time-point represent the shift in the centroid of all plots in ordinations space. A relative compositional change value of .25 indicates a 25% shift through time. (B) Beta-diversity (dispersion) through time relative to the beta-diversity in 1990 across the snow persistence groups.
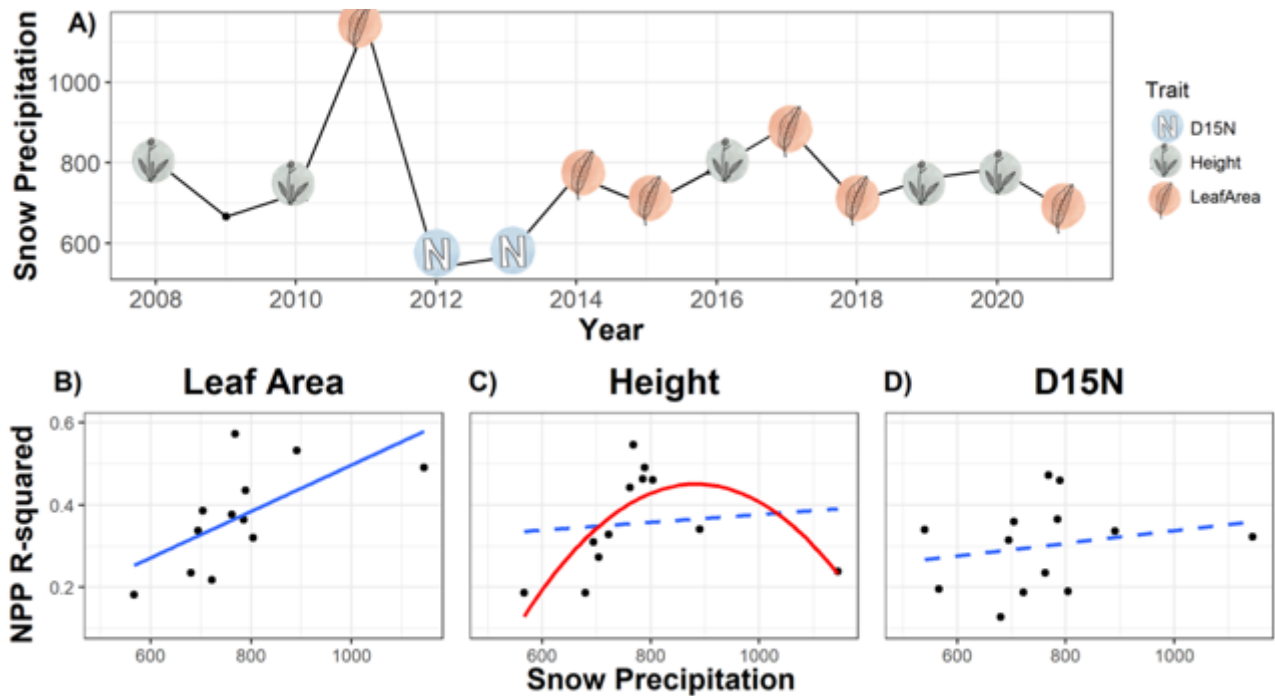

Figure 3. (A) Annual precipitation falling as snow from 2008-2021, shapes show the identity of the trait model which best predicted ANPP in each year. Panel two shows the relationship between ANPP R-squared values and Annual snow precipitation for trait models incorporating Leaf Area (B), Height (C), and δ15N (D). Lines of best fit from linear regressions between snow precipitation and ANPP are shown for B-D. Solid lines indicate significant relationships while dashed lines indicate a non-significant relationship. For Height, a quadratic linear regression (shown in red) is also included as this model provided better sit than a simple linear regression.

In the saddle grid, we previously found that production in the established tundra exhibits little direct response to extended summer climate conditions. However, in year 6, we examined if the functional mechanisms underlying the biodiversity-ecosystem function (B-EF) relationship (mass ratio effects and niche complementarity effects) and which traits drive these mechanisms change dynamically with changing environmental conditions. In every year at least one SEM exhibited good fit, explaining between 19.6 – 57.2% of the variation in ANPP. However, the identity of the trait which best explained ANPP and the relative importance of mass ratio or niche complementarity effects changed depending on the amount of annual precipitation. In years with higher annual snowfall, leaf area best predicted NPP (**Fig. 3**), with mass ratio effects strongly influencing ANPP and niche complementarity effects having little impact. In intermediate snowfall years, plant height best predicted ANPP. The predictive power of these models severely declined in years with low annual snowfall, and foliar nitrogen isotope content ($\delta^{15}N$) instead best predicted ANPP (**Fig. 3**) with mass ratio effects once again exerting a stronger impact on ANPP than niche complementarity effects. Our results show that the explanatory power of functional traits, and the specific functional mechanisms underpinning ecosystem functions may vary dynamically through time. Importantly, our findings suggest the future work should consider temporal variability in the B-EF relationship, particularly how the predictive power of functional traits for ecosystem functions may vary or degrade as climate change accelerates (Huxley and Spasojevic, in review).

Finally, we have initiated an observational study to determine scale dependence in the processes that structure alpine plant communities across Niwot Ridge. Using a fractal sampling design, we sampled species composition and soil fertility across a range of scales (from $0.5m^2$ to $300m^2$). We expect to complete this sampling next summer.

Soil moisture-mediated responses in tree populations. In the subalpine forest, warmer climate conditions have been broadly associated with decreased seedling establishment (Andrus et al., 2018) and increased tree mortality (Andrus et al., 2021). However, these responses are contingent upon temporal variation in the degree of aridity: since 1982, seedling recruitment events have been episodic, only occurring in cool, wet summers (Andrus et al., 2018) and moisture largely compensates for the negative effects of warming on establishment above treeline (Conlisk et al., 2018). Topographically-mediated moisture availability and stand age were shown to predict aboveground live tree biomass production in NWT permanent plots over a 35-year time period (Chai et al., 2019; 1982-2016), with radial growth increasing with higher summer temperature in hydric sites, but not xeric sites. Collectively, these results indicate that the rate at which forest stands respond to warming via recruitment, mortality, and above-ground biomass production at Niwot will hinge on water availability, which varies among years and across the subalpine terrain.

Shrub expansion. Consistent with global patterns (Elmendorf et al., 2012), shrubs (predominantly *Salix* sp.) have rapidly expanded into alpine tundra at NWT (Bueno de Mesquita et al., 2018; Formica et al., 2014; Scharnagl et al., 2019). Bueno de Mesquita (2018) calculated that shrub cover in the alpine at NWT has increased by nearly 8% per decade between 1972 and 2008. This encroachment is correlated with warming trends at NWT and linked to rising temperatures by experimental work (Formica et al., 2014). Shrubs change fine-scale patterns of snow accumulation and microclimate, plant community composition, and the nature of species interactions under their canopy (L. Brigham, thesis 2022).

Variable zooplankton responses. Rising temperatures over time are associated with longer ice-free seasons in the alpine lakes of the Green Lakes Valley (Christianson et al., 2021). In year 6, we continued our long-term measurements of alpine lakes (Green Lake 1 and 4) and enhanced our understanding of seasonal mechanism through continuous, year-round measurements of physical and biological data via an in-situ sensor array in GL4. The two dominant zooplankton species in these lakes – *Daphnia pulicaria* and *Hesperodiaptomus shoshone* – respond to longer ice-free seasons at different rates, with *Daphnia* showing strong, rapid increases in biomass while *Hesperodiaptomus* exhibits no significant response (Loria et al., 2020a; **Fig. 4**). We are continuing our investigation of how extended summer conditions influence planktonic communities and lake food webs through ongoing long-term surveys at two alpine lakes in addition to our megacosm experimental manipulation.

Figure 4. The densities of two abundant zooplankton species in Green Lake 4 respond at different rates, with H. shoshone *responding less strongly than* D. pulicaria. *Solid line indicates a significant relationship.* <u>Data sources</u>: *157.6, 161.3*

Figure 5. Stream locations within the Green Lakes Valley sampled in 2021 and 2022 (a), and variation in stream macroinvertebrate community structure in relation to elevation and water sources, based on NMDS (b).

Alpine Streams and Ponds. In summers of 2021 and 2022, Dr. Dan Preston (CSU) surveyed nine stream locations in the Niwot Ridge LTER along an elevational gradient from below treeline to the outflow of the Arikaree Glacier, near the Continental Divide. They found that variation in elevation (3221 to 3719 meters), water sources (glacial melt, snowmelt, and lake outflows), and corresponding environmental factors (e.g., temperature and hydrology) affect community structure of stream periphyton and aquatic macroinvertebrates (**Fig. 5**). Additionally, the Anderson lab at UC Riverside sampled macroinvertebrate communities in smaller ponds in and near the Boulder Creek Watershed

to explore whether community composition is influenced by elevation, environmental factors, and connectivity to other freshwater bodies. Samples were taken early, mid-, and late season to better characterize community composition over the course of the ice-off season.

Pika. We use the American pika (*Ochotona princeps*) as a model for studying climate sensitivity in small, herbivorous mammals that exploit subsurface habitats. We expect loss of subsurface ice, increasingly warm temperatures during the period of juvenile dispersal, and cold events in the absence of insulating snowpack will all be detrimental to pika populations and other species in this guild. Pika recruitment (juvenile:adult ratio) at NWT has declined with warmer temperatures since 1980 (**Fig. 6**). Variation in stress hormones also appears to be driven in part by subsurface talus temperatures (Whipple et al. 2020 and in press), which appear to have risen even faster than air temperature in a talus slope at NWT where we analyzed a rare set of historical data on subsurface temperature: recent temperatures measured >1 m below the surface have been up to 12°C higher than they were in 1964, while free-air temperatures have increased by 7°C (Monk & Ray 2022) (**Fig. 7**). These patterns suggest that the pika's rapid response to warming may be at least partially driven by physiological responses to amplified thermal changes in its subsurface refugia.
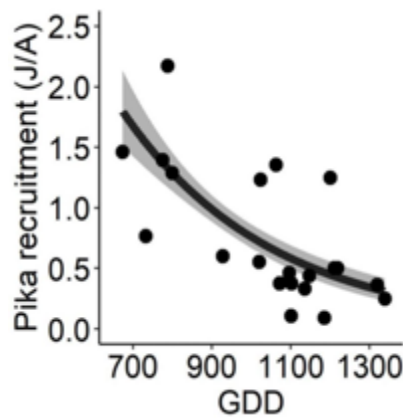
Figure 6. Pika recruitment, defined as the number of juveniles per adult (J/A) captured on the West Knoll of Niwot Ridge, modeled as a function of growing degree days (GDD). Curve and shaded 95% confidence interval represent a negative binomial regression based on 1980-2021 trapping data and accounting for interannual variation in trapping dates.

Figure 7. Mean daily temperature by month in (a) free air (1.5 m above the surface of a talus slope) and (b) deep talus (1.5 m below the surface) during a single historical year (July 1963-June 1964, black dots) and a range of recent years (2009-2021, red dots) at a pika study site on Niwot Ridge. Cure and shaded 95% confidence interval represent a generalized additive model of recent (2009-2021) mean daily temperature by month.
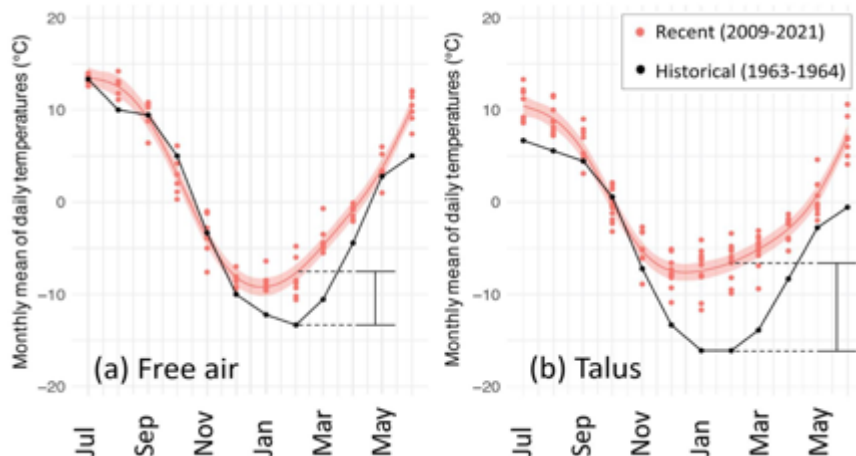
Chickadees. We have monitored the population dynamics of a small bird, the Mountain Chickadee (*Poecile gambeli*), for four years in collaboration with Dr. Scott Taylor. We are now monitoring 400 nest boxes that have been installed along an elevational gradient that includes Niwot Ridge and will

allow us to determine the relationship between breeding success of this boreal specialist and forest productivity. We are also monitoring interactions between the Mountain Chickadee and a close relative, the Black-capped Chickadee (*P. atricapillus*), which hybridize at low frequencies where they co-occur. Our initial work on this topic was recently published in Global Change Biology. We expect that extended summer conditions will alter the distributions of both species, via both direct climate effects as well as indirect effects via changes in sub-alpine forest food resources.

Pollinators and Arthropods: We continued to characterize the pollinator community across Niwot Ridge by surveying pollinators at each site with a Black Sand experimental plot (Soddie, Trough, Saddle, East Knoll, Lefty, Audubon) using bee bowls (Shapiro et al. 2014) and blue vane traps (Kimoto et al. 2012). In these same sites, we have also started a project examining the diversity of arthropods. In 2021, 4,794 arthropods were counted across 130 taxa, and 4,805 arthropods across 149 taxa in 2022. While the data is still being analyzed and the specimens identified, there has been a noticeably high diversity of *Melanopus* grasshopper species. In addition, leafhoppers in the family Cicadellidae were found in great abundance with several species. We are also finalizing the identification of *Formica podzolica* between several visually identical morphs within *podzolica* or are different species. Collected specimens and pictures will continue to be identified as the most abundant specimens will be sorted to genus and species, while less abundant specimens to family.

Although the work aimed to also evaluate if these changes occur through changes in plant nectar nutrients (carbohydrates, amino acids), pollen nutrients (amino acid profiles), and nectar/plant allelochemicals, it has been difficult to sample small alpine flowers. In summer 2023, destructive sampling of flowers may need to be employed, or we may decide to shift the focus to leaf tissue/allelochemicals.

Tundra carbon flux. We are continuing to measure tundra carbon flux using a pair of towers in the dry meadow tundra. Temporal analysis of the first seven years of alpine flux data indicates the potential for increasing alpine carbon emissions with time. Together with respiration of aged soil carbon from solifluction lobes associated with discontinuous permafrost, this also supports a paradigm of permafrost thaw associated with warming air temperatures that may be relaxing limitations on subsurface winter biological activity (Knowles et al. 2019). This is the longest continuous alpine eddy covariance dataset in the world, and the first to suggest an alpine analog to the well-established arctic tundra permafrost warming feedback to climate change.

B. Modeling studies to explore limitation across space and time on Niwot Ridge.
In Year 6 we developed and parameterized an implementation of the representative hillslope hydrology configuration of the Community Land Model (CLM; Lawrence et al. 2019; Swenson et al. 2019) for the Saddle at Niwot Ridge. Building on our previous work, we use gap filled measurements from the Saddle meteorology and T-Van Ameriflux sites (US-NR3 and US-NR4) as atmospheric input data that are needed to run single point simulations with CLM (Wieder et al. 2017). Additional Niwot data products are used for input data, model parameterization and model evaluation (**Fig. 8**), and a briefly summarized below.

To approximate the wind redistribution of snow that structures vegetation communities at Niwot Ridge we modified wintertime precipitation inputs to dry and moist meadow columns in our idealized hillslope simulations. We updated the default parameterization of Arctic C3 grasses with measurements of community weighted mean traits that characterize moist, wet, and dry meadow communities. Additional phenological parameters in the model were calibrated with new phenocam measurements. Model simulations were evaluated with LTER measurements of gross primary production (GPP, estimated from the T-van eddy covariance towers), snow depth and aboveground net primary production (ANPP, from the Saddle Grid), and soil temperature and soil moisture measured across the saddle sensor network) (Jay and Wieder, in prep).
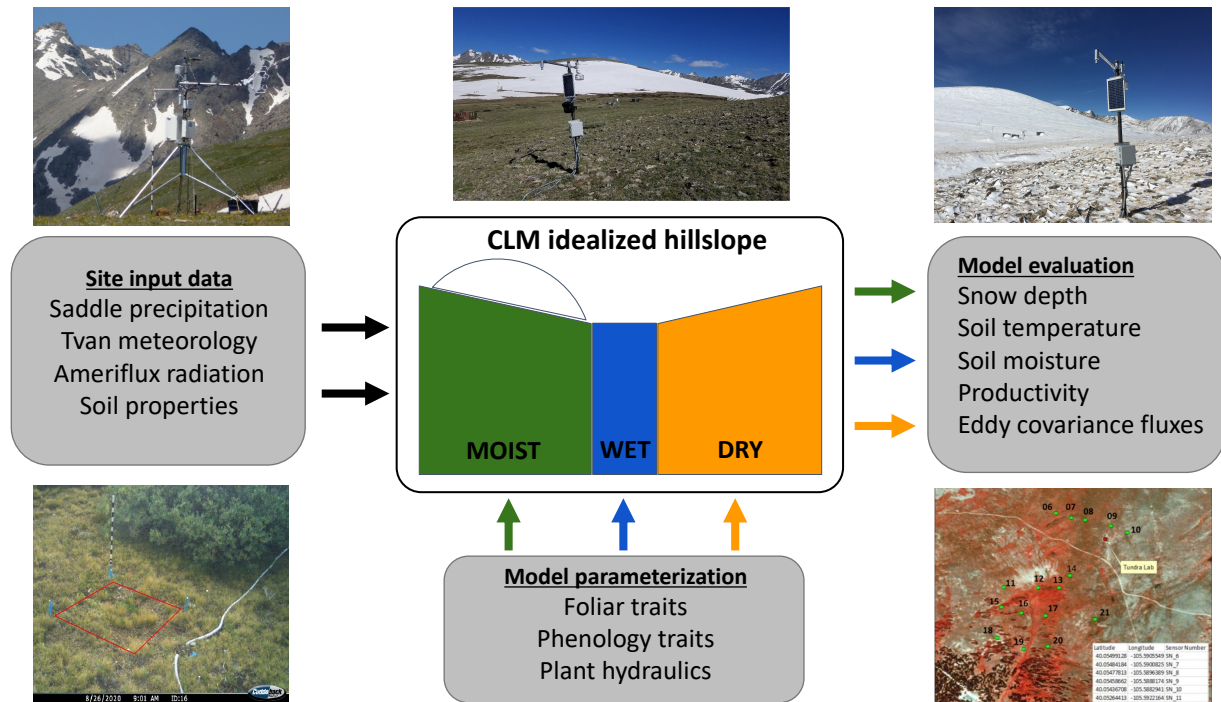
Figure 8. *Summary of the Niwot Ridge LTER data products (grey boxes) that are used as for model inputs, parametrizations, and evaluation in single point simulations with the representative hillslope hydrology configuration of the Community Land Model. Niwot data include T-Van metrology and eddy covariance flux measurements (top left photo), saddle snow depth and productivity data (top center photo) sensor network data on soil temperature and moisture (right photos) and phenocam measurements (lower left photo).*

Separately, Wieder et al. (2022) looked at how ecohydrological variability will change under a climate change scenario. This work was motivated by questions at the Niwot Ridge LTER about how ecohydrological variability may shift with climate change. The models used for this type of work, however, function at much coarser resolution, accordingly Wieder et al used a single model large ensemble of simulations generated by the Community Earth System Model (CESM2-LE). They found that across historically snow-covered landscapes the CESM2-LE projects pervasive alterations to the variability of water fluxes, water storage, and disturbance by the end of this century. Projected warming will reduce winter snow accumulation and increase the fraction of snow that melts during winter, blurring the seasonal distinction between periods of winter snow accumulation and its subsequent melt in the spring and summer. Notably, they found that in the future, runoff quantity and timing will be less predictable from snow, more closely reflecting the stochastic character of precipitation—findings that have critical implications for water resource management. **Fig. 9** shows these model projects of snow water equilivent (SWE) and runoff for a

representative 1-degree grid cell in the Central Rockies of Colorado. This work was highlighted by several local and national news outlets, including the Boulder Daily Camera, 9 News, ABC News, and Forbes. Building on this analytical approach, Wieder also generated datasets for use in a statistics class in the School of Business at CU Boulder, and a dataset that is being used by social scientists at Oregon State University who are working with farmers in the Willamette Valley on climate adaptation strategies.
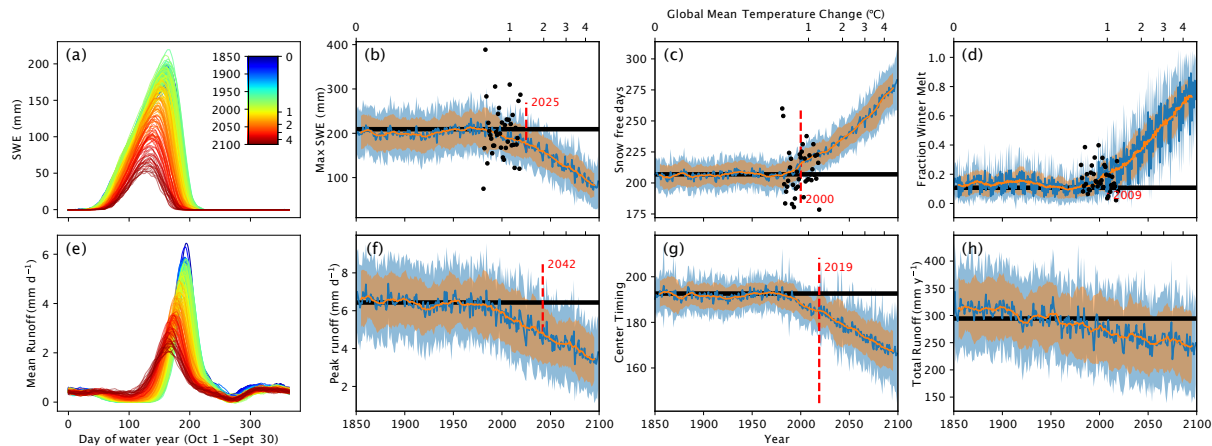
Figure 9. Declining snowpack and increased variability in winter snowmelt and runoff. Ensemble mean annual cycle of daily (a) snow water equivalent (SWE) and (e) runoff for a grid cell in the central Rocky Mountains, USA, with line colors corresponding to simulation years and associated changes in global mean temperature. Other panels show time series, and changes in global mean temperature, of the ensemble mean ± 2 SD (lines and shading, respectively) for snow and runoff related metrics (top and bottom rows, respectively) including the: (b) maximum SWE (mm); (c) number of snow free days per water year; (d) fraction of winter snow melt that occurs before peak SWE; (f) peak runoff rates (mm d^{-1}); (g) date of center timing (when 50% of the annual runoff has occurred); and (h) total water year runoff (mm y^{-1}). The ensemble mean baseline state (1940-1969), annual ensemble mean, and ten year running mean are illustrated with black, blue, and orange lines, respectively. The time of emergence is defined as the year when the baseline model state is outside of the rolling ensemble mean ± 2 SD (dashed red line).

C. Cross-cutting terrestrial and aquatic experiments. We have established two large multi-investigator experiments – a terrestrial and an aquatic – to explicitly test our predictions for responses to extended summer climate conditions.

Tundra manipulation of growing season length. We are currently in the fifth year of our "black sand" experiment where we manipulate growing season length. We manipulate the length of the growing season by applying a thin layer of black sand to the snow surface in early spring to reduce snow albedo and enhance melt rates without concurrently affecting snowpack depth (after Blankinship et al. 2014). Snow measurements in this experiment continue to confirm that the black sand treatment increases the albedo and speeds snowmelt, with variable effects on soil moisture. We have continued measurements of species composition in a series of subplots and transects within each plot a well as measurements of soil temperature, nutrient availability, and moisture. We have continued the summer warming treatment using ITEX chambers within both treatment and control plots, enabling us to look at the interactive effects of early snowmelt and warming. Our initial analyses suggest modest responses of the plant community (in terms of taxonomic and functional composition) to our manipulations so far. We plan to complete one more season of sampling due to the accumulation of black sand and will measure species composition and functional traits this upcoming field season. Despite modest abundance changes, we have found that plant phenology has been responsive to the experimental manipulations. Moreover, we have found that our manipulation

have impacted insect visitation where day of first flowering appears to have a more significant role in shaping total insect visitation in the advanced snowmelt plots whereas the day of peak flowering appears to have stronger influence on insect visitation in unmanipulated snow melt plots (Rose-Person et al. unpublished data; **Fig 10**)

Manipulation of aquatic growing season length. The objective of this project is to test how earlier ice-off on lakes and increased dissolved organic matter (DOM) associated with encroachment of
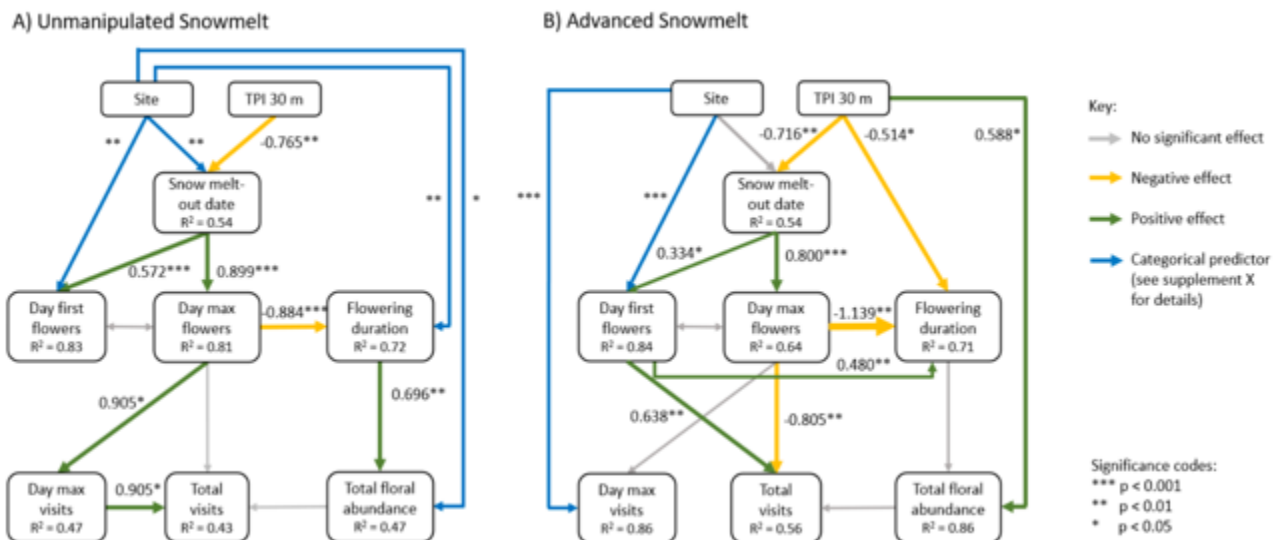
Figure 10. Results from two separate pSEM analyses: one on data from subplots with experimentally advanced snowmelt timing, and one on data from subplots with unmanipulated snowmelt timing. In both unmanipulated and advanced snowmelt pSEMs, TPI at 30 m is negatively correlated with snowmelt timing, and snowmelt timing is positively correlated with both day of first and day of peak flowering. However, in the unmanipulated snowmelt pSEM (Fig. 7a, Fisher's C = 56.299, p = 0.069), the first day of flowering, flowering duration, and total floral abundance differ among sites; day of maximum flowering is negatively correlated with day of max visitors, and day of maximum visitors drives the total number of visitors. In the unmanipulated snowmelt pSEM (Fig. 7b, Fisher's C = 35.743, p = 0.574) snow melt out date and day of first flowering vary by site; TPI at 30 meters negatively impacts flowering duration; snow meltout date positively influences day of maximum flowering; day of first flowers positively influences flowering duration and total number of visits; and day of max flowers negatively influences total visits.

terrestrial plants in the alpine watershed interact to affect aquatic food webs. In the fall of 2019, we established 20, 2600L mesocosms at Sandy Corner, a gravel clearing in the Green Lakes watershed at 3300 m ASL (40.042289, -105.584006). Tanks were left to naturally fill with snow over the winter, and after the spring thaw, megacosms were sufficiently full of water. The manipulation is a 2 x 2 randomized block design, in which we manipulated earlier ice-out (black vs. beige tank color), increased DOM (willow leaf pack added yes/no), and their interaction. The experiment included 5 replicates per treatment for 20 total mesocosms.

Early initial analyses show dark tank albedo effectively induced significantly earlier ice-out, with black tanks losing ice an average of 7 days earlier than beige tanks. Additionally, summer water temperatures in black megacosms were 0.5°C warmer on average

2. BIOTIC INFLUENCE: How Do Biotic Effects Influence Climate Exposure and Ecological Responsiveness? Our second hypothesis focuses on how biota can influence climate exposure through effects on the physical environment at smaller spatial scales than those examined in

Hypothesis 1. We propose fine-scale biotic effects can attenuate exposure to climate changes, influencing environmental heterogeneity and response at a patch-scale. Our approach involves testing for associations across space in conjunction with experimental manipulations that are linked with the climate exposure experiments described in Hypothesis 1. We focus on two well-documented patterns at high elevation: (A) in the alpine, the physical presence of particular life forms (cushion plants, shrubs, krumholz) can affect wind redistribution of snow, increase soil moisture, and modify the temperature and nutrients of the underlying soil, and (B) in aquatic environments, terrestrial subsidies of dissolved organic matter (DOM) can protect phyto- and zooplankton from harmful UV radiation and help offset nutrient limitations related to high flushing rates.

A. Biotic influence in terrestrial areas. In both tundra and upper- elevation forests, we expected that the presence of individuals that provide physical shelter from wind, causing accumulation of snow and organic matter (e.g., cushion plants, shrubs, trees), will attenuate climate exposure and be associated with shifts in population growth rates, species composition, and ecosystem processes.
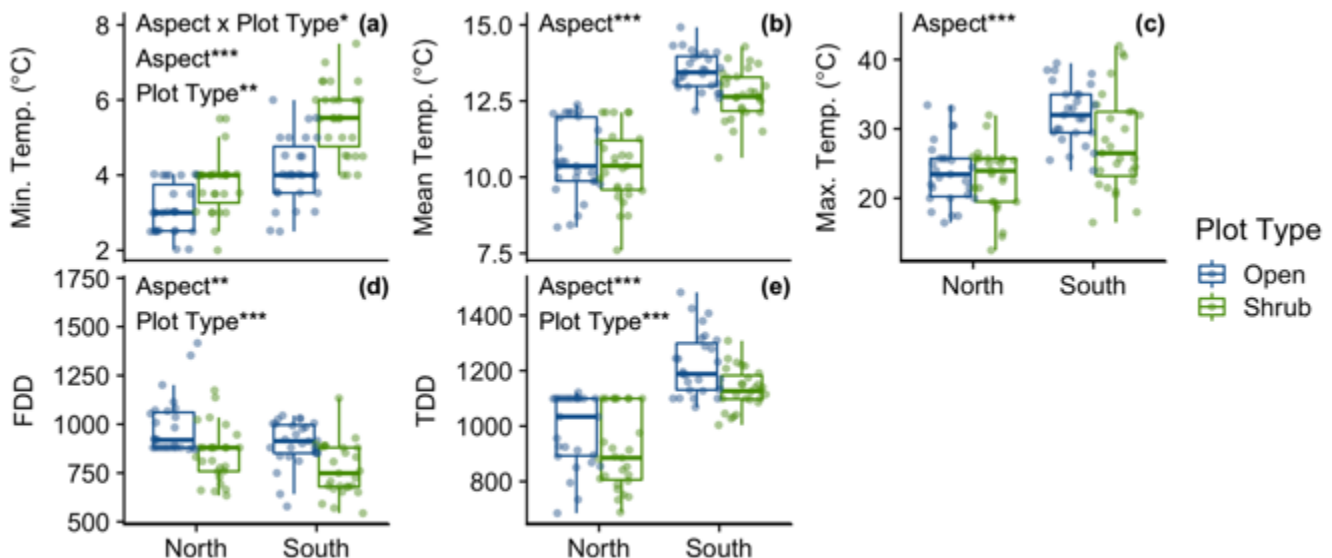

Figure 11. Minimum growing season temperatures were higher in shrub plots on the S-facing aspect (a). Growing season mean (b) and maximum temperatures (c) were higher on the S-facing aspect. There were fewer freezing degree days (FDD) (d) and total degree days (TDD) (e) in shrub plots and on the S-facing aspect. Significance codes: "***" P < 0.001, "**" 0.001 ≤P < 0.01, and "*" 0.01 ≤P < 0.05.

Observational studies. To better inform our predictions of our experimental studies below, we first quantified how shrubs (*Salix spp*.) influence microclimate and the functional traits of species associated with those shrubs in 108 plots arrayed across north and south facing aspects. Specifically, we find that the presence of shrubs buffers minimum temperatures and reduces freezing degree days and total degree days. Interesting these shrub effects parallel the effect of aspect, with the effect of shrubs making north facing aspects more similar to south facing aspects (**Fig. 11**) (Brigham et al., PhD dissertation, 2022). These effects of temperature, due to both aspect and shrubs, influence plant species composition (**Fig 12**), with the main effect of shrubs on composition occurring through its effect on freezing degree days (Moore and Brigham 2022). In appears that shrubs had only minimal

effects of flowering phenology and reproductive success (Seaver et al 2022), with the main effects driven by establishment and survival effects early and late in the growing season.

Subalpine transplant studies. These findings suggest that shrubs offer a protected microclimate that could buffer alpine communities from the very global change drivers that contribute to shrub expansion. Experimentally seedins a subalpine species, *Erigeron glacialis* and an alpine species *Deschampsia cespitosa,* indicate that establishment of both species (as well as naturally recruiting
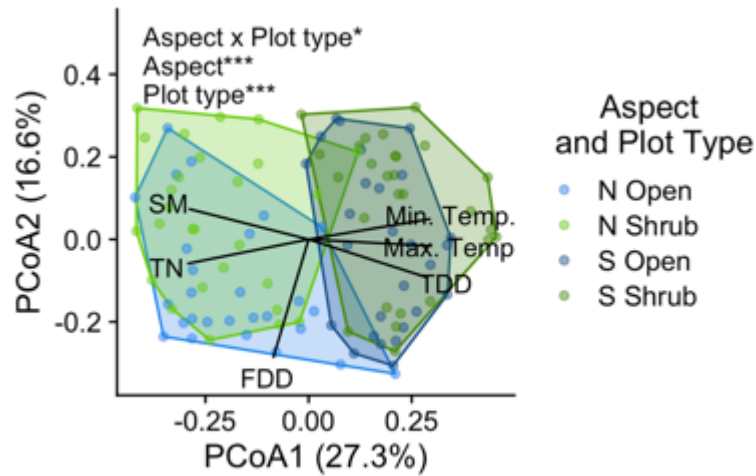
*Figure 12. An interaction between shrub presence and aspect shapes plant community composition. All continuous environmental variables were significantly related to plant community composition (P > 0.05). The PCoA was constructed using a Bray-Curtis dissimilarity matrix calculated on square-root transformed relative abundances. Significance codes: "***" P < 0.001, "**" 0.001 ≤P < 0.01, and "*" 0.01 ≤P < 0.05.*
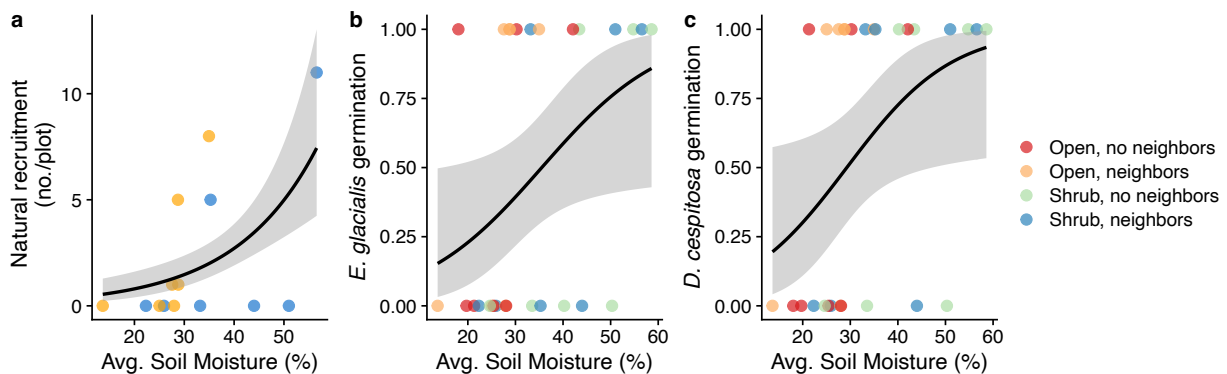

Figure 13. Natural recruitment, monitored only in plots where neighbors were not removed, increased with higher average season one soil moisture (a). The likelihood of germination for both experimentally seeded E. glacialis (b) and D. cespitosa (c) increased with higher average season soil moisture.

species) was most dependent on soil moisture rather than temperature. As shrubs had a slight effect on soil moisture, but much larger effects on temperature, it is unclear if shrubs will act as

"stepping-stones" for subalpine plants to move uphill to track their climatic temperature niche (**Fig. 13**; Brigham 2022).
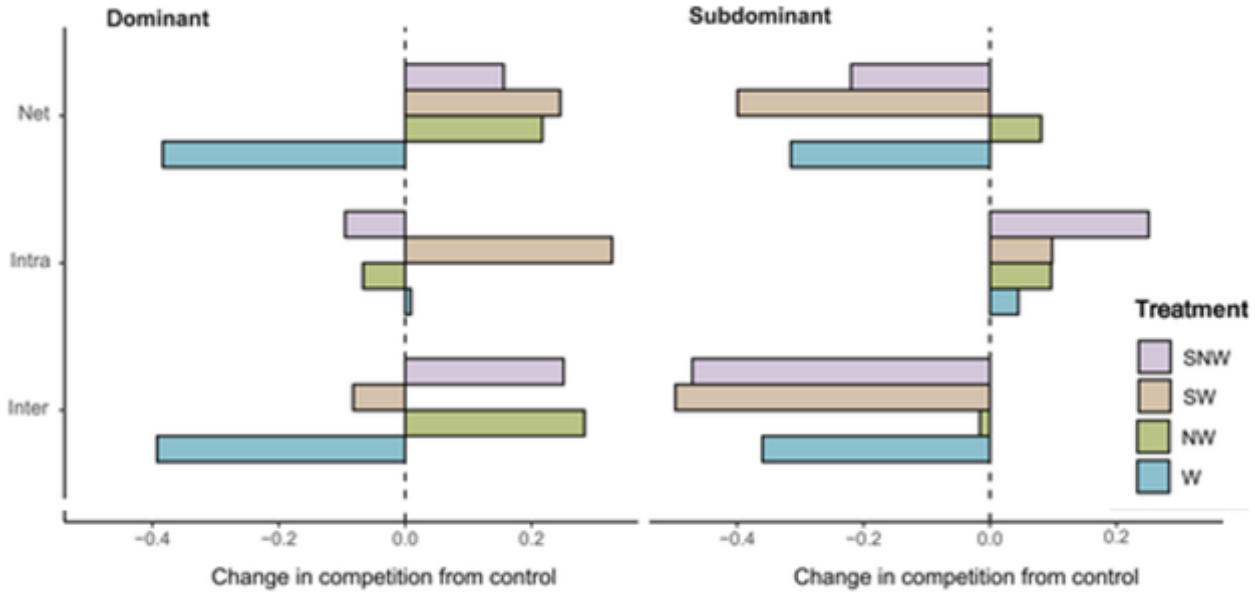

Figure 14. *Changes in the mean competitive interactions ($\Delta\alpha_\mu$) of the dominant (Deschampsia) and a group composed of the next three most abundant species (subdominant) in each global change treatment versus control. Intraspecific (intra) shows the mean change in the competition of a species group on itself (i.e. self-limitation). Interspecific (inter) shows the sum of the mean changes of all other species groups on that group. Net is the combination of intra and interspecific changes within each treatment and species group. Values to the left, right of the dotted zero line signify that competition on a species group became stronger, weaker in global change vs control conditions, respectively.*

Species associations. Plant-plant interactions. As part of H2, we also investigated how environmental change factors affect species interactions in conjunction with direct effects of environmental change. In a long-term experiment that manipulates temperature, nitrogen and snow, we used a Bayesian Hierarchical modeling approach (GJamTime) to separate density-independent and density-dependent mechanisms of abundance change over 16 years. We found density-dependent shifts in competitive interactions drove long-term changes in abundance of species-groups under global change while counteracting environmental drivers limited the growth response of the dominant species through density-independent mechanisms (**Fig. 14**). We also found that competitive interactions shifted with the environment, primarily with nitrogen and drove non-linear abundance responses across environmental gradients (Collins et al 2022). Our results highlight that global change can either reshuffle species hierarchies or further favor already-dominant species; predicting which outcome will occur requires incorporating both density-dependent and -independent mechanisms and how they interact across multiple global change factors.

Species associations. Plant-microbe interactions. Another type of interaction that we have focused on in NWT VII are plant-microbial interactions. While we find that global changes such as increase N availability affect both the plant and soil microbial community, we don't find strong evidence that it changes the interactions between plants and microbes. Utilizing an 18-year simulated N deposition and species removal experiment, for instance, we found that the soil microbial community responded

directly to N rather than indirectly through changes in the plant community (**Fig. 15**) despite N also affecting plant composition (Brigham et al. 2022). This is in contrast to Collins et al (2022) work on plant-plant interactions, where evidence shows a shift in interactions due to global changes, particularly N availability.
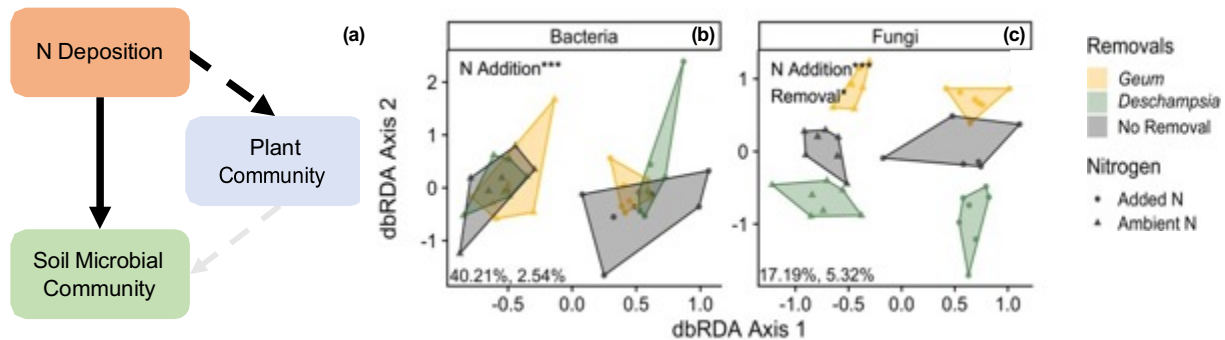

*Figure 15. Although N influenced the plant community, this did not cascade to the microbial community (**a**). Both the bacterial (**b**) and fungal (**c**) soil communities responded to N addition directly rather than an experiencing an interaction between N and our plant removal treatment, which would have suggested an influence of the plant community on microbial response to N.*

       Lastly, we investigated the role of microbes carried on seeds in germination success and timing. Across 10 common alpine plant species, we found a total of 318 bacterial and 128 fungal operational taxonomic units (OTUs) associated with seeds, with fungal richness affected by plant species identity more than sampling location (**Fig. 16**) (Lueche et al 2022). However, we did not find that seed microbes affected plant germination success and timing. In contrast, soil microbes associated with two different plant species had significant effects on plant biomass, and their effect depended both on the plant species and the location the soils were sampled from. Importantly, we found that coexistence-facilitating feedback was associated with low plant species richness, suggesting that while soil microbes may not change interactions in established tundra (e.g., Brigham et al. 2022, above) they may promote the diversity of colonizing plants during climate change and glacial recession.
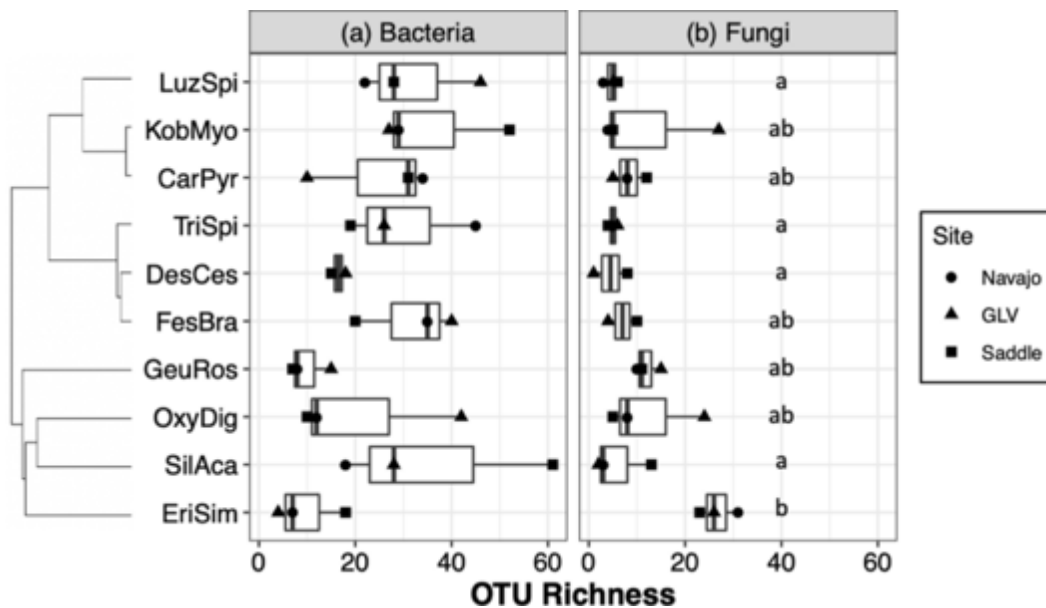
Figure 16. OTU richness for *a* bacteria from 16S rRNA gene sequencing., and b fungi from ITS sequencing. Bacterial richness was not affected by species identity. Different letters in *b* represent significant differences in fungal OUT richness among species

B. Biotic influence of UV protection in lakes. In alpine lakes, Hypothesis 2 revolves around changes in land cover due to uphill vegetation advances that will increase terrestrial subsidies of DOM into lakes. Higher DOM is expected to function as both a carbon subsidy and help to attenuate UV radiation, reducing the investment by zooplankton and phytoplankton in mitigating the deleterious effects of UV and collectively enhancing planktonic production.
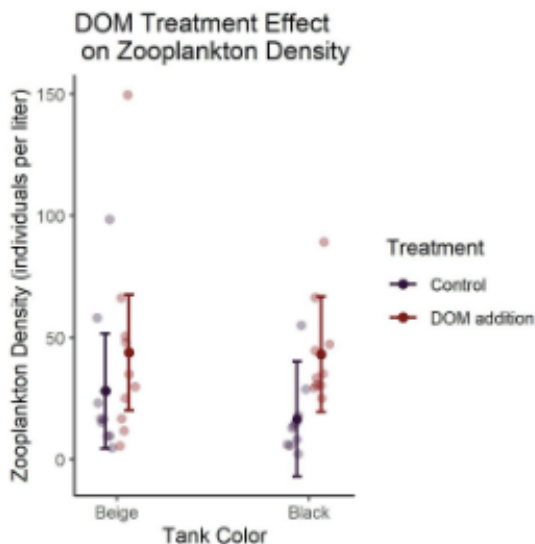

Figure 17. DOM significantly increased zooplankton density regardless of temperature treatment (tanks color). Linear mixed model, DOM treatment effect (p = 0.01)

Experimental manipulations. We have simulated the increase of terrestrial DOM input to lakes by adding DOM as an additional factorial treatment to the megacosm experiment (discussed above). The DOM treatment consists of leaf-packs composed of locally collected willow leaves enclosed within standardized nylon mesh bundles. We are currently waiting for our water chemistry samples to be analyzed, this includes Dissolved Organic Carbon (DOC) which represents all the carbon leached into the water from our willow leaf pack DOM treatments. Therefore, we do not yet have

metrics to model the effectiveness of the DOM treatments, but we know the treatment had a significant effect on zooplankton density (**Fig. 17**).

C. Observational, Experimental and Model Integration. In Year 6 we focused on improving the link to long-term climate datasets and accessibility of the terrestrial Community Land Model (CLM) and the aquatic General Lake Model (GLM). In the upcoming year, we plan to integrate the empirical results from the terrestrial and aquatic growing season manipulation field experiments with the predicted outcomes from of the CLM and GLM. This modeling and experimental iterative approach broadens our capability to quantify the mechanism of the observed responses and improve our models of the impacts of changing conditions. More broadly, we are working to articulate ways that empirical work and modeling can be better integrated in models like CLM.

3. ADAPTATION STRATEGIES. How do different strategies for managing temporal variability and uncertainty at the organism and population levels aggregate to influence community and ecosystem processes? Our third hypothesis is that population, community, and ultimately ecosystem responses to climate change will be shaped by the life history strategies that species have evolved in response to historical patterns of environmental variation and uncertainty. At Niwot Ridge, we expect that terrain- and biota-related differences in exposure cause spatial variation in the temporal variability and predictability of key environmental variables. For this hypothesis we are currently focusing on strategies and responses of plant species in the alpine tundra.

We are primarily addressing this hypothesis using data that is being collected in the terrestrial Sensor Network Array. Specifically, we are characterizing the magnitude and patterns of within-year variation in soil moisture, soil temperature, and air temperature, and among-year variation in soil moisture, soil temperature (growing degree days and freezing degree days), snow-off date, and growing season length. We are testing if and when these measures predict plant community composition and individual species distribution patterns across the heterogeneous terrain in the saddle catchment. In Year 6, we collected the fourth year of an expanded sampling design that we initiated in 2019 and have analyzed our results through 2021 (summarized below).

A. Characterizing spatial and temporal variation in tundra plant communities. Over the last reporting period, we completed an analysis of first four years (2017-2020) of vegetation and environmental data from the Sensor Network Array to test if temperature and soil moisture variation predict alpine plant community composition and species distributions. To address H3, we included two components of temporal environmental variation – variability and predictability in soil moisture and temperature – over both daily (24-hr) and seasonal (60-day) time scales in these analyses. Daily variability was quantified as the average daily coefficient of variation in soil moisture or temperature over the entire year, while seasonal variability was measured as the number of times environmental conditions crossed important thresholds for these alpine plants (0.4 °C for temperature, 13% volumetric water content for soil moisture). We represented the daily predictability as the average autocorrelation factor (ACF) in average hourly measurements with a 24-hour lag, and seasonal predictability as the average ACF among daily average values with a lag of 60 days. We examined the contributions of the mean, variability, and predictability in soil moisture and temperature in predicting spatial variation in plant community composition in the Sensor Network Array using redundancy analysis. Finally, we evaluated the importance of these environmental variables in predicting the patterns of occurrence and abundance of individual plant

species using mixed effects models with random intercepts and slopes so that the effect of each environmental variable could vary among species.

Our analyses of the SNA plant and environmental data indicate that including variability and predictability in soil moisture and soil temperature substantially improves our ability to explain variation in plant community composition over models that use mean soil moisture and temperature alone (**Fig. 18**). Daily and seasonal measures of temporal variability and predictability explained for different patterns of variation in the alpine plant community, suggesting that plants vary in the extent to which they sense and/or respond to environmental fluctuations over these two different time scales (**Fig. 18B, C**). Furthermore, individual species varied widely in their associations with different levels of variability and predictability in soil moisture and temperature (**Fig. 19**). These results suggest that the distributions of alpine plant
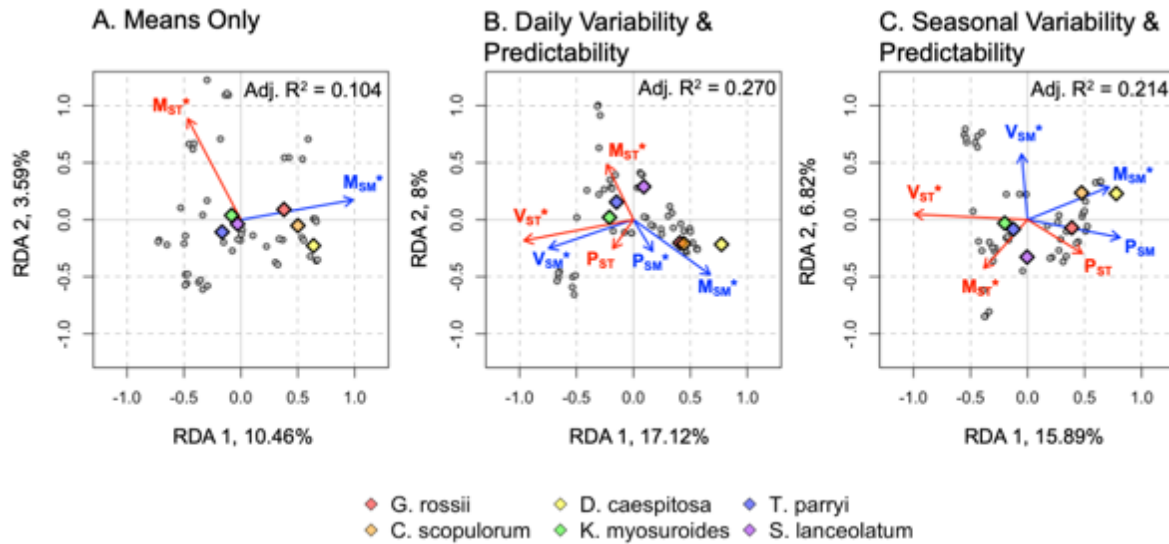

*Figure 18. Effects of soil moisture and soil temperature on community structure at Niwot Ridge. Each panel show the results of a redundancy analysis evaluating the effects of **A**) mean soil moisture (MSM) and mean soil temperature (MST), **B**) MSM, MST, and daily soil moisture and temperature variability (VSM, VST) predictability (PSM, PST), and **C**) seasonal MSM, MST, VSM, VST, PSM, and PST on community structure. In all panels, an * indicates p > 0.05 each term in the RDA model. Colored diamonds show how a few commonly occurring species correlate with environmental variables.*

species are likely influenced by spatial variation in the magnitude and patterns of temporal fluctuations, with some species specializing on locations that are relatively stable, others on locations that vary predictably over time, and still others on locations that fluctuate stochastically through time. More broadly, these results emphasize that including measures of temporal variability in environmental conditions can improve our ability to explain species distributions and patterns of community composition in heterogeneous landscapes.
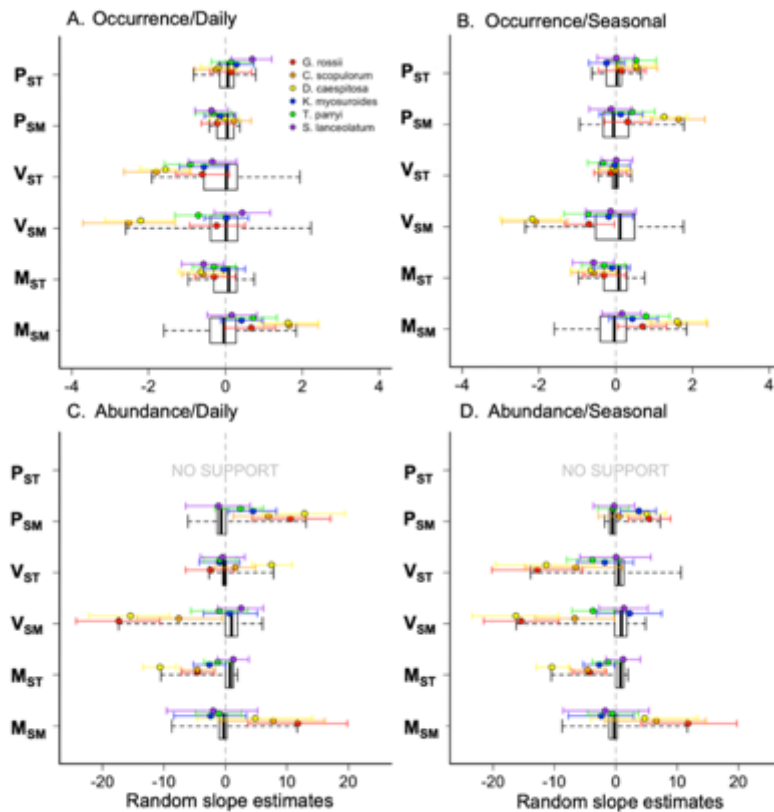
Fig. 19. Distributions of random slopes for species' responses to means, variability and predictability metrics. A) and B) summarize the slopes between species' occurrences and the mean, variability, and predictability of soil moisture and temperature measured over daily (A) or seasonal (B) timescales in the alpine vegetation of the Niwot Ridge LTER. C and D) show the estimated slopes from linear models of species abundance over daily (C) and seasonal (D) time scales. Each boxplot shows the range of random slopes generated in a model with a singular predictor variable (e.g., mean soil temperature). Colored dots correspond to the six highlighted species that are common in the alpine plant community at Niwot Ridge. Error bars show 95% confidence intervals for each random slope estimate. M=means; V=variability, P=predictability. SM=soil moisture and ST=soil temperature.

4. CATCHMENT INTEGRATION: How does hydrological connectivity affect catchment-scale processes? In our fourth hypothesis, we focus on how variability in hydrologic fluxes (e.g. snowmelt) can (1) provide a strong spatial and temporal context for the fine-scale foci of H1-H3 and (2) affect biogeochemical and ecological processes at catchment-to-landscape scales. Flow paths, water sources, and residence times will dictate connectivity between high and low elevation ecosystems (e.g., alpine to montane) as well as terrestrial and aquatic ecosystems (e.g., hillslopes to streams and lakes) (Webb et al. 2018). We expect that at the catchment scale, some areas within the terrestrial ecosystem may only meaningfully contribute water and solutes to aquatic ecosystems during particular periods of time, such as early snowmelt. Identifying how these patterns and the driving mechanisms change interannually, as well as how they will change under future forcings, requires the long-term observational record that NWT collects. In the summer of 2020, we began supplementing the long-term records of stream discharge with the installation of an additional stream gauge that began measuring discharge. This additional gauge will track missing or losing flows that we have previously observed, providing data that can more clearly constrain model estimates of the water balance to provide a clearer sense of the distribution of snow water and precipitation throughout the basin.

During the last two years, we have dug deeper into thinking about how portions of the landscape may contribute disproportionately to catchment- or ecosystem-scale processes. We adopted the framework described by Bernhardt and colleagues (2017) of assessing the function of **ecosystem control points** and how they will change over time. Ecosystem control points are those

areas within a landscape that have high rates of biogeochemical processes and therefore a disproportionately large effect on biogeochemical and ecological processes at the catchment scale (Huber, 2021). At NWT, hydrology, temperature, and substrate availability are first-order controls on biogeochemical processes (Chen et al., 2020) and, as a result, the occurrence of ecosystem control points and their distribution in space.

We expect the relative importance of different parts of the catchment to vary with climate variables (e.g., snow distribution, snow melt, and air temperature), and so we take several parallel **catchment-to-landscape scale studies** to integrate processes and temporal dynamics in response to climate conditions. In the last year, we made extensive progress determining the mass balance of snow fields at Niwot Ridge compared with Ulaan Taiga, Mongolia (see Williams et al., 2022). Importantly, this effort put Niwot Ridge in the context of other high elevation ecosystems subject to climate change. Such efforts are coupled with our **within-catchment studies** (e.g., H1-H3). While a somewhat daunting goal, in H4 we have strived to integrate hydroclimatological, biogeochemical, and ecological processes to understand the drivers of carbon, nutrient, and water export at larger scales.

A. Integrative efforts at the Saddle Catchment
Revisiting long-term monitoring of stream chemistries. In Year 6, NWT scientist Dr. Iggy Litaor published an article reanalyzing long-term stream chemistry data to determine the sources of, in particular, elevated sulfate (Litaor, 2022). Litaor determined that the multi-segment trends in stream solutes – increasing through the mid-2000s and then decreasing – were the result of permafrost thaw, climate-induced weathering, and exogenous inputs. In contrast to analyses by Crawford et al. (2019), Litaor suggests that atmospheric dust deposition may be an important driving factor for increased stream solutes. In another effort, Heil et al. (2022) compared the Green Lakes Valley Watershed to Andrews Creek, a second alpine watershed in the Colorado Rocky Mountains. They found that climate-induced weathering causes different outcomes in the trajectories of long-term stream records. They suggested that weathering of sulfide-rich minerals is an important driver of sulfate concentrations streams, which, in turn, affect mobilization and transformations of metals. These recent analyses point to a continued need for elemental, stable isotope, and hydrological approaches to understand the patterns of climate-induced weathering and drivers of stream chemistry at NWT.

B. Integrative efforts across the alpine landscape.
Investigating ecosystem controls points: their roles and connectivity across the landscape. In the summer 2020, we began investigating the function and potential changes to wetland features with global change across the alpine-to-sub-alpine landscape. Specifically, we hypothesize that wetlands—including alpine wet meadows and periglacial solifluction lobes— may have optimal conditions to support high rates of biogeochemical processes (particularly related to C, N, S, Fe, and Hg cycling) due to favorable conditions for microbial activity (e.g., temperature, water content, organic matter). During the summers of 2020, 2021, and 2022 we collected sediment depth profiles to measure these constituents in both wetlands and drier portions of the landscape. We also investigated the coupling of biogeochemical cycles, particularly C, S, and Hg, to determine whether Hg may be transformed to toxic methylmercury (MeHg) in the presence of sulfate reducing bacteria and enter the terrestrial and aquatic food webs where it could negatively affect pika, weasel, and fish populations. The latter food web study is the subject of both an ongoing Ph.D. project and two completed undergraduate honors theses. A second Ph.D. student developed a measurement technique using the radioisotope 35S to quantify rates of sulfate reduction in wetland areas at NWT,

an effort currently in progress. These studies represent efforts to dig into the processes that underlie catchment-to-landscape scale patterns, including those described in recent long-term data analyses (e.g., Crawford et al. 2020; Heindel et al. 2020).

Wetter portions of the NWT landscape have disproportionately high storage of reactive elements. Recent research by master's student Molly Huber demonstrated that alpine wetland areas—particularly alpine wet meadows and periglacial solifluction lobes—have significantly higher organic matter content as well as storage of sulfate and carbon compared with dry meadow locations ($p < 0.05$; Huber, 2021). Huber's findings are important, as they provide evidence that wetland areas, which constitute < 10% of the landscape, function differently than surrounding dry meadow areas, which are > 55% of the landscape (Hermes et al., 2020). They support the potential for disproportionately high biogeochemical activity that will affect ecosystem- or catchment-scale responses; we will begin exploring these differences in biogeochemical rates in NWT VIII.

Motivated by evidence for increased storage and transport of C and S in wetland areas at NWT, Ph.D. student Hannah Miller and undergraduate honors thesis students Clifford Adamchak and Phillip Thornton began to evaluate the potential for MeHg movement into the terrestrial and aquatic food webs, a type of landscape connectivity. Methylmercury is a potent neurotoxin that is stimulated by sulfate reduction and bioaccumulates and biomagnifies in the food chain; it is a concern in many environments, including those at high elevations. Miller, Adamchak, and Thornton measured accumulation of total mercury (THg) in plant functional groups (including some of the first measurements of Hg in alpine herbaceous plants). In addition, they found accumulation of MeHg in weasel (*Mustela* spp.) and trout (*Salvelinus fontanalis* and *Oncorhynchus clarkii*) tissues. Weasels feed both in terrestrial and aquatic ecosystems. Measurement of MeHg in pika (*O. princeps*, a food source for weasels) was minimal, while it was elevated in trout species, pointing to the importance of aquatic systems as sources of MeHg.

5. CROSS-SITE SYNTHESIS.
A. Network-level Participation. Researchers are active participants in synthesis efforts coming from the past science council meetings and are active in the IM and Outreach Network Committees, and social media communication efforts. NWT Researchers Dr. Meagan Oldfather and Dr. Marko Spasojevic are active on the LTER DEI Committee.

B. Synthesis Groups. Niwot investigators are PIs for two of the NCO-sponsored synthesis groups. Dr. Suding co-led the "Synthesizing population and community synchrony to understand drivers of ecological stability across LTER sites" group. Dr. Wieder co-led the "Advancing soil organic matter research: Synthesizing multi-scale observations, manipulations & models" group. Niwot data have also been contributed to multiple cross-site synthesis projects including two within the LTER Network (Campbell et al 2022, Gaiser et al 2022) and one from a tundra-wide synthesis (Rixen et al 2022).

C. Within-site synthesis. An ongoing within-site synthesis project focused on functional responses to environmental change across experiments at Niwot Ridge askes 1) how do global changes influence alpine plant communities?, and 2) Can we use functional traits to predict how species will respond? We used long term data from six experiments at Niwot Ridge LTER that have manipulated some combination of nutrient availability, temperature, and/or snow depth (2-4-6 Plots, ITEX plots, Snowfence plots, CoDom plots, Fert 20-10 plots, historical ITEX plots) to assess plant responses to global changes. We combined these observations with leaf and whole-plant functional

traits to determine how functional traits relate to species responses. We found that there is change happening in the control plots, although this change is mostly random and relatively small (**Fig. 20** control). However, when we look at Nitrogen addition or snow addition, we see that a few species respond strongly to these manipulations. Warming, on the other hand, has dampened species responses for the most part (even relative to the control plots). It is many of the same species that win and lose in Nitrogen and snow addition treatments. Moreover, we found that high SLA plants are increasing an abundance across the board, low LDMC plant are successful in warming, plants with high nitrogen and high water use efficiency are increasing in all experiments, and tall plants are increasing with nitrogen and additional snow.

6. OUTREACH and EDUCATION LTER VII.
A. Diversity Equity and Inclusion (DEI) Committee. Niwot Ridge LTER formed a DEI committee in the summer of 2020. We have continued or efforts of increasing diversity, equity, and
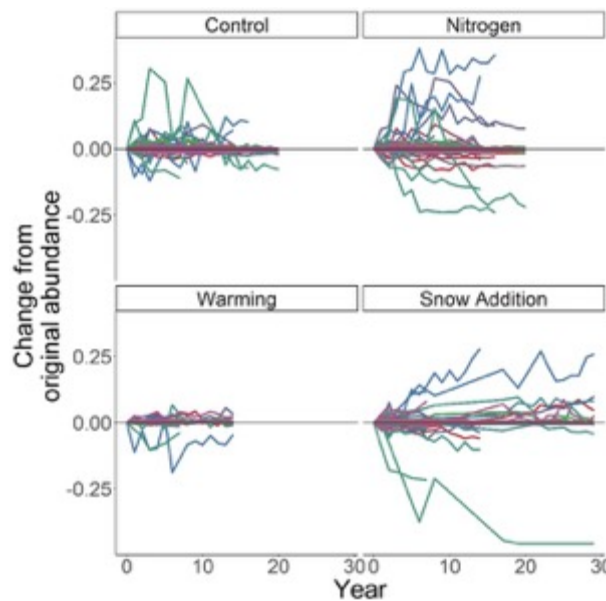

Figure 20. Species relative abundance change in global change manipulations across Niwot Ridge Long Term Ecological research site. Each line represents the average change in abundance for a species in an experiment. Colors indicate different species and there are multiple lines of the same color when species occur in multiple experiments.

inclusion at the Niwot LTER and have worked on several projects. First, we continued the annual post-field season survey to assess the community climate during field season and have passed on findings and recommendations to the leadership team. Overall trends were positive and most comments highlighted that people feel welcome and respected at Niwot. The NWT DEI committee has taken or is planning to take the following steps that focus on three main issues areas:

Preventing Unacceptable Behaviors:
- NWT plans to hold a stand-alone active bystander training for all NWT researchers in 2023. The first was completed in February 2021. We plan to continue this biannually.
- The DEI committee will reduce barriers to reporting concerns. First, the DEI committee set up an anonymous online comment "box" for people to anonymously submit issues. We still plan to train several personnel from all career stages so that an individual has multiple different people that they can approach with concerns, rather than a single supervisor.
- We have updated our website to make the code of conduct and DEI resources easier to find

Field safety:
- In conjunction with the Mountain Research Station, NWT provided a map to all field personnel that includes locations of all safety and emergency equipment and develop a general safety communication system for all researchers on the ridge.
- NWT LTER fully funded all associates to be trained in wilderness first aid and CPR.
- In conjunction with the Mountain Research Station, NWT is planning a "first aid kit day" at the beginning of the field season where we ensure all teams have up to date first aid kits.

Recruit, retain, and support a more diverse team
- NWT LTER in conjunction with the Mountain Research station are developing a gear closet to reduce barriers to field work
- One member of the DEI committee, AJ Lodge, attended the virtual annual meeting of the Society for the Advancement of Chicano and Native Americans to represent NWT, listen and learn about barrier to underrepresented groups in STEM, and recruit students from historically excluded groups to participate in the NWT LTER.
- Continue the NWT LTER Graduate Recruitment Fellowship: Advancing Inclusivity in Mountain Research, which provides 1 GRA to recruit exceptional students that self-identify along one or more targeted axes of diversity and work aligns with NWT research goals (nominated by mentors)

B. Outreach Program. In Year 6, the NWT LTER VII outreach program has maintained its focus on training graduate students in science communication and outreach and providing them with opportunities to practice their skills with K-12 and public audiences. This strategy supports our graduate students in becoming scholars who can communicate the results of their research in creative and impactful ways, prepares them for careers as engaged scholars, and makes NWT research accessible and relevant to public audiences of all ages.

K-12 Outreach and Education. Schoolyard outreach programs began to resume at pre-pandemic levels. Using graduate students trained in science communication, we hosted field trips to the Mountain Research Station and lab tours on campus for several hundred middle school students. Our partnership with Wild Bear Ecology Center (a non-profit, all-ages nature center located near NWT) and the Winter Wildlands Alliance and their Snow School program (https://winterwildlands.org/snowschool/) has grown significantly as we connected LTER scientists and CU undergraduates (via our snow science internship) with 337 children in 1st through 6th grade, and got them out on snowshoes, exploring snow science. A particular highlight of this year's Snow School was a fully scholarship supported experience for 68 students from STEM Launch K-8 school in Northglenn, Colorado. Their school is a majority non-white Title I school with 73.6% of students qualifying for free or reduced lunch.

In the summer of 2022, we were again able to conduct the Mountain Research Experience for high school students by collaborating with Cal-Wood Environmental Education center. This collaboration and another small grant from the CU Office of Outreach and Engagement allowed us to recruit 14 participants from low income, Latinx, and first-generation college student backgrounds. Students camped near the site of the Cal-Wood fire, and we spent the week discussing sub-alpine forest ecology, forest management, and wildfire impacts and restoration. Researchers from Niwot LTER, Colorado State University and The Nature Conservancy helped teach the students about forest management, fire ecology and restoration. In recognition of this work, we were awarded a 2022 Innovative Environmental Education Program Award from the Colorado Alliance for

Environmental Education. In future summers, we hope to be able to incorporate a field trip to Niwot LTER as part of this course.

Figure 21. (A) Cal-Wood Field Course, and (B, C) Snow School STEM Launch. Photo: Alex Rose

C.

Graduate and Post-doc Training
Graduate Students. We provided GRA and/or supplies funding to approximately 11 grad students this year. The cornerstone of our Education and Outreach work in the proposal was the initiation of a semester-long practicum on science communication and "engaged scholarship" for graduate students receiving LTER support. Four NWT LTER graduate students participated in the course this year, and they made demonstrations about their NWT research that they presented to public audiences on campus, at a Meet a Scientist event at the Boulder Public Library, and opportunistically at other venues.

Fired UP Program. The Niwot LTER was heavily involved in the successful first year of the FiredUP (*Field-Intensive Research Emphasizing Diversity UP in the alpine*), a novel NSF-funded graduate education program that uniquely integrates supporting diversity and early-intervention training in large-scale ecological research (https://www.ebiofiredup.com/). In the summer of 2022 program, over a dozen NWT LTER scientists provided training in field methods for 10 first-year graduate students in the Department of Ecology and Evolutionary Biology, including pika demography, subalpine tree surveys, climate sensor data, plant productivity measurements, bird monitoring, pollinator sampling, and data management. Dr. Lisa Corwin, a Discipline-Based Education Researcher at CU Boulder, is leading the collection of quantitative and qualitative data to evaluate the efficacy of the program. Though the data from the first year of the program is still being collected and analyzed, anecdotal reports from the first cohort of graduate students to participate in the program are extremely positive. Furthermore, several of the students are now planning to conduct their dissertation research at Niwot Ridge and have remained involved in the LTER community during their first semester of graduate school.

D. Public and Stakeholder Audiences. We make it a priority to share our work with the broader community. NWT has long engaged with non-academic stakeholders, including local agencies and non-profit organizations, to support conservation, management and education about mountain systems and the important societal services they provide. Faculty are regularly interviewed on print and other media; Dr. Ray's work on American pika was recently featured in an episode of *National Geographic Photo Ark*. In collaboration with the CU Mountain Research Station director and manger, Dr. Rose has been developing a series of interpretive trails at the Mountain Research Station.

Figure 22. NWT held its first day-long Mountain consortium at the Mountain Research Station September 9th, 2022. Partners from the City of Boulder Water Division, Rocky Mountain National Park, Denver Botanical Garden, and Colorado Forest Restoration Institute attended alongside NWT liaisons. Our next meeting is scheduled for January 13th, 2023. Photo: Megan OldFather.

In year 6, we have begun a formal consortium of agencies that share common interests and goals with respect to mountain systems: Rocky Mountain National Park, the Denver Botanic Gardens, City of Boulder Water, and the Colorado Forest Restoration Institute. We have identified NWT scientists as liaisons to each partner, and held our first day-long consortium meeting at the Mountain Research Station in September (**Fig. 22**). We are co-developing three primary ways to work together: (1) consortium members will have regular opportunities to share research needs/priorities with NWT researchers; (2) annual presentations of NWT graduate student research will feature topics/data relevant to invited consortium members; (3) with consortium input, NWT researchers will develop a recurring *State of the Mountain* report including NWT datasets and trend analyses that we will present during a half-day consortium workshop and then broadly distribute throughout the Colorado Rocky Mountains region. We anticipate that these efforts will lead to greater use of NWT data for local natural resource decision-making and broaden NWT's reach within the public sphere.

7. INFORMATION MANAGEMENT. The primary goals of the Information Management (IM) program are to ensure the quality, security, integrity, and timely availability of data collected at NWT LTER in order to facilitate scientific discovery. All current IM procedures are consistent with LTER network data access policy (https://lternet.edu/data-access-policy/); and generally follow guidance as laid out by DataOne's data management best practices hub

(https://dataoneorg.github.io/Education/). Niwot Ridge LTER continues to use the Environmental Data Initiative as its primary repository (hosting >99% of NWT datasets). Exceptions are made for select datasets (i.e. Ameriflux, NADP) that are part of a larger, coordinated network devoted to specific focal data types.

During the current reporting period, we added and/or updated to extended the time series in 86 datasets (Table 1). Niwot datasets were downloaded from EDI a total of 4090 times in the past year (excluding DataOne and robot records).

Title	Package ID	DOI
Streamflow data for Albion camp, 1981 – ongoing.	knb-lter-nwt.102.17	doi:10.6073/pasta/81ef15564db3a999ea28c02697550525
Streamflow for Green Lake 4, 1981 - ongoing.	knb-lter-nwt.105.15	doi:10.6073/pasta/ff6f7947279eeeeca851baed6cd6f41a
Streamflow for Green Lake 4, 1981 - ongoing.	knb-lter-nwt.105.16	doi:10.6073/pasta/3749d944650633f794fd673234274498
Lake ice clearance and formation data for Green Lakes Valley, 1968 - ongoing	knb-lter-nwt.106.4	doi:10.6073/pasta/e6123085cff2605b9079eab335aeda46
Lake ice clearance and formation data for Green Lakes Valley, 1968 - ongoing.	knb-lter-nwt.106.5	doi:10.6073/pasta/05c470f08b44e1cb2e89f35b118cce8e
Streamflow for Martinelli basin, 1982 - ongoing.	knb-lter-nwt.111.14	doi:10.6073/pasta/76fffe560f896e1e9a04ab34c114b8a5
Soil nitrous oxide and carbon dioxide concentration data for Niwot Ridge and Loch Vale watershed, 1994.	knb-lter-nwt.115.2	doi:10.6073/pasta/d0434a01dfa0b5efd11c39128911fa4f
Soil nitrous oxide and carbon dioxide flux data for Niwot Ridge and Loch Vale watershed, 1994.	knb-lter-nwt.116.2	doi:10.6073/pasta/204fa118fa2581bf76b57c6c27043197
Increased temperature, N and snowpack experiment for north of saddle, 2006 - ongoing.	knb-lter-nwt.13.5	doi:10.6073/pasta/7ff039a5d6f3fa5155c0a299a903a00a
Snow depth sensor measurement data for Upper Sub Alpine site, 2010 - 2015.	knb-lter-nwt.156.4	doi:10.6073/pasta/388c70359c8d0cd79dc3875d6510071d
Water quality data for Green Lakes Valley, 2000 - ongoing.	knb-lter-nwt.157.7	doi:10.6073/pasta/c457dc73d5179567879d78cb3a84c4e2
Aboveground net primary productivity data for Saddle grid, 1992 - ongoing.	knb-lter-nwt.16.6	doi:10.6073/pasta/b0cdc0cf7c4442f1b2ffc569e9890968
Zooplankton community composition and trait data for Green Lakes Valley, 2012 - ongoing.	knb-lter-nwt.161.4	doi:10.6073/pasta/5459a358002f2b561426538a4617aabb
Zooplankton community composition and trait data for Green Lakes Valley, 2012 - ongoing.	knb-lter-nwt.161.5	doi:10.6073/pasta/a71c0ff98abc5caea4feb7c7ab555d9f
Snowbed experiment species composition and hobo data for Niwot Ridge, 2012 - ongoing.	knb-lter-nwt.172.5	doi:10.6073/pasta/e762f2a7940d6c112f8a03d1eb25917c
Dissolved oxygen data for the Green Lake 4 buoy, 2018 - ongoing	knb-lter-nwt.175.3	doi:10.6073/pasta/808d56c2b53f487588c2fade3b5e0537
Atmospheric ozone data from Soddie, 2005 - 2017.	knb-lter-nwt.18.2	doi:10.6073/pasta/2b1189b0eff59ec6284e4f6b07b8bd83
Temperature data for the Green Lake 4 buoy, 2018 - ongoing	knb-lter-nwt.188.3	doi:10.6073/pasta/5b43ebaca633357f1456c8bb4ee6a0c0

PAR data for the Green Lake 4 buoy, 2018 - ongoing.	knb-lter-nwt.189.3	doi:10.6073/pasta/3f65a38fd50522311ee0e12f02dad7f2
Plant species composition for sensor network array, 2017 - ongoing.	knb-lter-nwt.191.4	doi:10.6073/pasta/dde8eed69de73b9c7947c778f15920ed
Time-lapse camera (phenocam) imagery of sensor network plots, 2017 - ongoing.	knb-lter-nwt.192.3	doi:10.6073/pasta/285918fbf5cc4bd2ed2c1241db9a1b2d
Ice thickness at Green Lake 4, 1984 - ongoing, monthly	knb-lter-nwt.199.3	doi:10.6073/pasta/e94519e35c73843698a1f3094b1aa267
Ice thickness at Green Lake 4, 1984 - ongoing.	knb-lter-nwt.199.4	doi:10.6073/pasta/086a4cc64df89feacd215a077641233b
Substrate Induced Respiration (SIR) from 26 sites across vegetation community gradient in and near sensor network, 2017	knb-lter-nwt.204.1	doi:10.6073/pasta/938c37639ad9f1ef4a147771306574e5
Federal sampler data for Saddle and C1, 2016 - ongoing.	knb-lter-nwt.205.4	doi:10.6073/pasta/b92a338062c656ab70b4555629438619
Ground water well elevation for Niwot Ridge Saddle, 2012 - 2018.	knb-lter-nwt.206.3	doi:10.6073/pasta/e2f95244d82dba4ce1879a25074fdd24
Climate data for saddle catchment sensor network, 2017 - ongoing.	knb-lter-nwt.210.4	doi:10.6073/pasta/598894834ea3bae61d7550c30da06565
Saddle catchment Distributed Hydrology Soil Vegetation Model Simulation (DHSVM) surface variable outputs (SWE, snowmelt, streamflow, soil moisture), 2 meter, 2000-2019.	knb-lter-nwt.218.1	doi:10.6073/pasta/15d8d9a6725b04efe32a4b839582a5d4
Plant species composition in black sand extended growing season experiment, 2018 - ongoing.	knb-lter-nwt.225.4	doi:10.6073/pasta/9a3e3402f8a64588890a1b70258515c5
Sulfate reductions rates in alpine wetlands, 2021.	knb-lter-nwt.227.1	doi:10.6073/pasta/5a3544e3bcfba0165ba3cdd97add03d7
Soil moisture, temperature, and electrical conductivity data from the black sand extended growing season length experiment, 2018 - ongoing, hourly.	knb-lter-nwt.238.3	doi:10.6073/pasta/0e38744e3e2d95a37246cb877d1f0c4b
Streamflow data for Saddle Stream 16, 2020 - ongoing.	knb-lter-nwt.239.1	doi:10.6073/pasta/cc9a8adcc7d156899153f661064e1199
Deschampsia biomass, soil microbes and endophyte root colonization for snowmelt and microbial innoculation transplant experiment in the Green Lakes Valley, 2015-2018	knb-lter-nwt.250.2	doi:10.6073/pasta/196e331170717ef6766a5b0939539ed9
Alpine and subalpine wetland soil physicochemical characteristics, summer 2020.	knb-lter-nwt.253.1	doi:10.6073/pasta/ee4a53851bb1dbbcda944073a9196e42
Temperature data for Green Lake 4 inlet and outlet, 2019 - ongoing	knb-lter-nwt.259.2	doi:10.6073/pasta/36d164651d03a4ff9078a44659eda693
Plant species composition in ITEX subplots in black sand extended growing season experiment, 2018 - ongoing.	knb-lter-nwt.261.2	doi:10.6073/pasta/2861fed3497e2b483839d5db6945a0dc
ANPP, NDVI and canopy height in black sand extended growing season experiment, 2019 - ongoing.	knb-lter-nwt.265.2	doi:10.6073/pasta/da6012356d6f43ac10c15edd2e0a8d81

Chlorophyll-a data for the Green Lake 4 buoy, 2018 - ongoing	knb-lter-nwt.267.3	doi:10.6073/pasta/0108419cf2d9da4e4eac1ad96a4e69e6
Time lapse camera photos for Green Lakes Valley, 2011 to ongoing, subdaily	knb-lter-nwt.270.3	doi:10.6073/pasta/d2cbb444e539607b8b59e9517a6b11bb
Climate data for D1 data logger (CR1000), 2014 - ongoing, 10 minute.	knb-lter-nwt.273.1	doi:10.6073/pasta/3b686091d45d354607bf6df73462f164
Climate data for saddle data logger (CR1000), 2014 - ongoing, 10 minute.	knb-lter-nwt.274.1	doi:10.6073/pasta/59c8e027b3f8c82a8369b7da10d012c7
Mercury in soil, vegetation, and organisms across Niwot Ridge, Saddle Catchment, and Green Lakes Valley, 2020 - ongoing.	knb-lter-nwt.282.1	doi:10.6073/pasta/0b155f7b38a9e27444242ff341116734
Surface temperature mapped from thermal infrared survey from UAV campaign at Niwot Ridge, 2017.	knb-lter-nwt.287.2	doi:10.6073/pasta/70518d55a8d6ec95f04f2d8a0920b7b8
Water Tower Index for Saddle Catchment, 2000 - 2018.	knb-lter-nwt.290.1	doi:10.6073/pasta/07fd204434f649c706f743e2929cc7b8
Pond environmental data for Niwot Ridge and Green Lakes Valley, 2021.	knb-lter-nwt.292.1	doi:10.6073/pasta/ac334b404f66e4b4a3b8a9b47af64ab6
Uncalibrated RGB orthomosaic imagery from UAV campaign at Niwot Ridge, 2017.	knb-lter-nwt.293.1	doi:10.6073/pasta/073a5a67ddba08ba3a24fe85c5154da7
Surface and porewater chemistry and sulfur stable isotpes for alpine and subalpine wetland sites, 2021.	knb-lter-nwt.295.1	doi:10.6073/pasta/da3e82602f603ce9528bae274b6b6626
Soil moisture, temperature and relative humidity for subalpine forest permanent plots, 2017 - 2021.	knb-lter-nwt.296.1	doi:10.6073/pasta/150de6fedd3a2103bf124bf1d66d7d45
Individual and community flowering phenology, seed counts and pollinator visitation rates in shrub and open plots across Niwot Ridge, 2019 - 2021.	knb-lter-nwt.297.1	doi:10.6073/pasta/edc4ab2faf7dd96cd1deac1544d5f2b9
Point Cloud lidar DSM from UAV campaign at Niwot Ridge, 2017.	knb-lter-nwt.298.1	doi:10.6073/pasta/2c43d15a50e56f35c4812b026f17e741
Photogrammetric Point Cloud and DSM from UAV campaign at Niwot Ridge, 2017.	knb-lter-nwt.298.2	doi:10.6073/pasta/1289b3b41a46284d2a1c42f1b08b3807
Calibrated Red/Near Infrared orthomosaic imagery from UAV campaign at Niwot Ridge, 2017.	knb-lter-nwt.299.1	doi:10.6073/pasta/dadd5c2e4a65c781c2371643f7ff9dc4
Air temperature and relative humidity data for A1 HOBO logger, 2013 - ongoing.	knb-lter-nwt.3.6	doi:10.6073/pasta/e8770a3c1112a03d30c0dff68e82447c
Saddle catchment Distributed Hydrology Soil Vegetation Model Simulation (DHSVM) precipitation and transpiration variable outputs (precipitation, total, potential and actual evapotranspiration), 2 meter, 2000-2019.	knb-lter-nwt.300.1	doi:10.6073/pasta/e9fd5d69a9ff92762474783b585cee55
Historical photos from Niwot Ridge, 1948 - 2005.	knb-lter-nwt.302.1	doi:10.6073/pasta/9c4a613007fbfd3c1649ab3fd3c46066
Future hydrologic outputs using the Distributed Hydrology Soil Vegetation Model (DHSVM) for the Saddle Catchment, 2001 - 2100.	knb-lter-nwt.303.1	doi:10.6073/pasta/3706b23cf7ee38d65cd2adc3d8621c8d

Indian Peaks Vegetation Survey, 2013.	knb-lter-nwt.304.1	doi:10.6073/pasta/c9207a04dbcef3bfe0ee75e692b6d61c
Alpine plant seed microbiomes, germination, and plant-soil feedbacks, Niwot Ridge and Green Lakes Valley, 2018.	knb-lter-nwt.306.1	doi:10.6073/pasta/9e962af87e06cba4b4f125131a0f4a08
Snow depth data for Saddle grid, 1992 - ongoing.	knb-lter-nwt.31.19	doi:10.6073/pasta/9a1f33fdc75e3ec0c3ac4fe79081f749
Snow depth data for saddle snowfence, 1992 - ongoing.	knb-lter-nwt.34.12	doi:10.6073/pasta/e4e426e4646bf69bf2dfea8bd2784ee9
Snow depth data for saddle snowfence, 1992 - ongoing.	knb-lter-nwt.34.13	doi:10.6073/pasta/a6a30132f9d4e2d9a0763e7a7faef619
Climate data for C1 data loggers (CR23X and CR1000), 2000 - ongoing, daily.	knb-lter-nwt.401.6	doi:10.6073/pasta/ff858d5b392844c17eff4e7670de6b0d
Climate data for C1 data loggers (CR23X and CR1000), 2000 - ongoing, daily.	knb-lter-nwt.401.7	doi:10.6073/pasta/b8ba49ca26f8a8077f2ca0c49ef74f50
Climate data for D1 data loggers (CR23X and CR1000), 2000 - ongoing, daily.	knb-lter-nwt.402.5	doi:10.6073/pasta/97ed9868c880396b977af42d2f2f321a
Climate data for saddle data loggers (CR23X and CR1000), 2000 - ongoing, daily.	knb-lter-nwt.405.6	doi:10.6073/pasta/51bcffaccbc73b2b8b3158c9c2c6c41d
Elevation gradient plant species composition data for A1, B1, C1, D1, 1953 - 1996.	knb-lter-nwt.407.1	doi:10.6073/pasta/5a3e022cee0d431333cf320609a4bf40
Air temperature data for C1 chart recorder, 1952 - ongoing.	knb-lter-nwt.411.14	doi:10.6073/pasta/edd9e457fd22a703a587cc8608d54bde
Air temperature data for D1 chart recorder, 1952 - ongoing.	knb-lter-nwt.412.12	doi:10.6073/pasta/1e9f40409e69299b1a41f98ac767bcd7
Precipitation data for D1 chart recorder, 1964 - ongoing.	knb-lter-nwt.415.15	doi:10.6073/pasta/5b4b03cbb345cffd6e1c660dc871d3fd
Precipitation data for Saddle chart recorder, 1981 - ongoing.	knb-lter-nwt.416.12	doi:10.6073/pasta/dc2d4b6db7133dcb651b978340e3b35a
Small mammal species composition data for Niwot Ridge, 1981 - 1990.	knb-lter-nwt.43.5	doi:10.6073/pasta/be8897e943e6b9369c32ac993fe0bc5b
Air temperature and relative humidity data for B1 HOBO logger, 2012 - ongoing.	knb-lter-nwt.5.5	doi:10.6073/pasta/9bbec175d3f695b6ee6317461b2013a2
Niwot plant functional traits, 2008 - 2018.	knb-lter-nwt.500.3	doi:10.6073/pasta/1a06bcffa07e7aa2a4b674af4c427860
Climate data for saddle data loggers (CR23X and CR1000), 2009 - ongoing, hourly.	knb-lter-nwt.57.6	doi:10.6073/pasta/e0d9c9624debdfc90a91e2c03461c58a
Co-dominant removal and N and C fertilization experiment for moist meadow tundra, 2002 - 2018.	knb-lter-nwt.6.5	doi:10.6073/pasta/97bf1ea5424a908c23a4af309616d57d
Arbuscular mycorrhizal fungi and dark septate endophytes root colonization in Upper Green Lakes Valley, 2007-2016	knb-lter-nwt.71.2	doi:10.6073/pasta/3ec2bf8bef96871ea56f9093362bcee3
Streamflow data for Saddle stream, 1999 - ongoing.	knb-lter-nwt.74.7	doi:10.6073/pasta/3abf11e44afab0e8605684549f3868a3
Plant species composition data for Saddle grid, 1989 - ongoing.	knb-lter-nwt.93.6	doi:10.6073/pasta/ef26a0dbe49eff4c9f60c1d966f04b94

Snow water equivalent data for Niwot Ridge and Green Lakes Valley, 1993 - ongoing.	knb-lter-nwt.96.18	doi:10.6073/pasta/22d8cbaa21c2cf5211b37adcb5fd1a6f
Snow grain data for Niwot Ridge and Green Lakes Valley, 1995 - ongoing.	knb-lter-nwt.97.16	doi:10.6073/pasta/c8d0512cc4439f61dffc87d757e6dc41
Snow cover profile data for Niwot Ridge and Green Lakes Valley, 1993 - ongoing.	knb-lter-nwt.98.17	doi:10.6073/pasta/840ebb6d2be2ea437df1a8c7023f4d2d
US-NR3: Niwot Ridge Alpine (T-Van West) [Ameriflux]	NA	doi:10.17190/AMF/1804492
US-NR4: Niwot Ridge Alpine (T-Van East) [Ameriflux]	NA	doi:10.17190/AMF/1804491
National Atmospheric Deposition Program (NADP) SITE CO02	NA	https://nadp.slh.wisc.edu/sites/ntn-CO02/
National Atmospheric Deposition Program (NADP) SITE CO90	NA	https://nadp.slh.wisc.edu/sites/ntn-CO90/

In 2022, we migrated all of our historical publications to a searchable, public-facing zotero library, which we will continue to maintain going forward, categorizing publications into those funded by the NWT LTER program and other relevant research from the same geographic area. We also replaced our primary server (used to retain read directly off sensors, scans of datasheets, original transcriptions, etc) with a Synology NAS. As before. This server syncs nightly to both an external hard drive and CU's petalibrary (offsite), for duplicate backup in case of hardware failure.

REFERENCES

Andrus, R. A., B. J. Harvey, K. C. Rodman, S. J. Hart, and T. T. Veblen. (2018) Moisture availability limits subalpine tree establishment. *Ecology* 99:567-575.

Andrus, RA, RK Chai, BJ Harvey, KC Rodman, TT Veblen. (2021) Increasing rates of subalpine tree mortality linked to warmer and drier summers. *Journal of Ecology* 109:2203–2218. https://doi.org/10.1111/1365-2745.1365-2745.13634

Bernhardt, Emily S., et al. "Control points in ecosystems: moving beyond the hot spot hot moment concept." *Ecosystems* 20.4 (2017): 665-682.

Blankinship, J. C., M. W. Meadows, R. G. Lucas, and S. C. Hart. 2014. Snowmelt timing alters shallow but not deep soil moisture in the Sierra Nevada. *Water Resources Research* 50:1448-1456.

Brigham, L.M., Bueno de Mesquita, C.P., Smith, J.G., Sartwell, S.A., Schmidt, S.K., and Suding, K.N. (2022). Do plant–soil interactions influence how the microbial community responds to envirotnmental change? Ecology 103. 10.1002/ecy.3554.

Campbell, J.L., Driscoll, C.T., Jones, J.A., Boose, E.R., Dugan, H.A., Groffman, P.M., Jackson, C.R., Jones, J.B., Juday, G.P., Lottig, N.R., et al. (2022). Forest and freshwater ecosystem responses to climate change and variability at US LTER Sites. BioScience, biab124. 10.1093/biosci/biab124.

Chen, Y., Wieder, W.R., Hermes, A.L. and Hinckley, E.L.S., (2020). The role of physical properties in controlling soil nitrogen cycling across a tundra-forest ecotone of the Colorado Rocky Mountains, USA. *CATENA*, *186*, p.104369.

Christianson, K. R., Loria, K. A., Blanken, P. D., Caine, N., & Johnson, P. T. (2021). On thin ice: Linking elevation and long-term losses of lake ice cover. *Limnology and Oceanography Letters*, *6*(2), 77-84.

Campbell, J.L., Driscoll, C.T., Jones, J.A., Boose, E.R., Dugan, H.A., Groffman, P.M., Jackson, C.R., Jones, J.B., Juday, G.P., Lottig, N.R., et al. (2022). Forest and freshwater ecosystem responses to climate change and variability at US LTER Sites. BioScience, biab124. 10.1093/biosci/biab124.

Crawford, J.T., Hinckley, E.L.S., Litaor, M.I., Brahney, J. and Neff, J.C. (2019) Evidence for accelerated weathering and sulfate export in high alpine environments. *Environmental Research Letters*, *14*(12), 124092.

Crawford, J. T., Hinckley, E.-L. S., & Neff, J. C. (2020). Long-term trends in acid precipitation and watershed elemental export from an alpine catchment of the Colorado Rocky Mountains, USA. *Journal of Geophysical Research: Biogeosciences*, 125, e2020JG005683. https://doi.org/10.1029/2020JG005683

Dawson, T. P., S. T. Jackson, J. I. Housepres, I. C. Prentice, and G. M. Mace. (2011). Beyond Predictions: Biodiversity Conservation in a Changing Climate. *Science* 332:53-58.

Dickinson, M. G., C. D. L. Orme, K. B. Suttle, and G. M. Mace. (2014). Separating sensitivity from exposure in assessing extinction risk from climate change. *Scientific Reports* 4.

Gaiser, E.E., Kominoski, J.S., McKnight, D.M., Bahlai, C.A., Cheng, C., Record, S., Wollheim, W.M., Christianson, K.R., Downs, M.R., Hawman, P.A., et al. (2022). Long-term ecological research and the COVID-19 anthropause: A window to understanding social–ecological disturbance. Ecosphere 13, e4019. 10.1002/ecs2.4019.

Heil, E., Warix, S., Singha, K., and Navarre-Sitchler, A. (2022). Decadal trends in solute concentrations, mass flux, and discharge reveal variable hydrologic and geochemical response to climate change in two alpine watersheds. Applied Geochemistry 144, 105402. 10.1016/j.apgeochem.2022.105402.

Heindel, R.C., Putman, A.L., Murphy, S.F., Repert, D.A. and Hinckley, E.L.S. (2020) Atmospheric dust deposition varies by season and elevation in the Colorado Front Range, USA. *Journal of Geophysical Research: Earth Surface*, *125*(5), p.e2019JF005436.

Hermes, A.L., Wainwright, H.M., Wigmore, O., Falco, N., Molotch, N.P., and Hinckley, E.L.S. (2020) From patch to catchment: A statistical framework to identify and map soil moisture

patterns across complex alpine terrain. *Frontiers in Water* (Special Issue: Water in the Critical Zone), 2, doi:10.3389/frwa.2020.578602.

Huber, M.E., 2021. Patterns of Sulfur and Carbon Biochemistry in Alpine Wetlands of Niwot Ridge, Colorado (Doctoral dissertation, University of Colorado at Boulder).

Kimoto, C., DeBano, S.J., Thorp, R.W., Rao, S., & Stephen, W.P. (2012) Investigating temporal patterns of a native bee community in a remnant North American bunchgrass prairie using blue

Knowles, J.F., Blanken, P.D., Lawrence, C.R. and Williams, M.W. (2019) Evidence for non-steady-state carbon emissions from snow-scoured alpine tundra. *Nature Communications*, 10(1): 1-9.

Lawrence, D. M., Fisher, R. A., Koven, C. D., Oleson, K. W., Swenson, S. C., Bonan, G., et al. (2019). The Community Land Model version 5: Description of new features, benchmarking, and impact of forcing uncertainty. *Journal of Advances in Modeling Earth Systems*, 11, 4245– 4287. https://doi.org/10.1029/2018MS001583

Litaor, M.I. (2022). Alpine ecosystem response to climate warming: Long-term monitoring data of stream chemistries revisited. Science of The Total Environment 839, 156292. 10.1016/j.scitotenv.2022.156292.

Loria, K. A., Christianson, K. R., & Johnson, P. T. J. (2020a). Phenology of apline zooplankton populations and the importance or lake ice-out. *Journal Of Plankton Research*, 1–15. https://doi.org/10.1093/plankt/fbaa050

Luecke, N.C., Bueno de Mesquita, C.P., Luong, M., Schmidt, S.K., Suding, K.N., and Crawford, K.M. (2022). Causes and consequences of differences in soil and seed microbiomes for two alpine plants. Oecologia. 10.1007/s00442-022-05271-z.

Monk, E.M., and Ray, C. (2022). Revisiting talus and free-air temperatures after 50 years of change at an American pika (Ochotona princeps) study site in the Southern Rockies. PLOS Climate 1, e0000049. 10.1371/journal.pclm.0000049.

Moore, M.A., and Brigham, L.M. (2022). Trends in alpine ecology: the role of microclimates in determining alpine plant response to climate change. Aquilegia 46, 20–21.

Janet S.Prevéy, Sarah ClaireElmendorf, AnneBjorkman, Juha M.Alatalo, IsabelAshton, Jakob J.Assmann, Robert G.Björk, Mats P.Björkman, NicolettaCannone, MicheleCarbognani, ChelseaChisholm, KarinClark, Courtney G.Collins, Elisabeth J.Cooper, BoElberling, Esther R.Frei, Gregory R.H.Henry, Robert D.Hollister, Toke ThomasHøye, Ingibjörg SvalaJónsdóttir, Jeffrey T.Kerby, KariKlanderud, ChristopherKopp, EstherLevesque, MargueriteMauritz, UlfMolau, Isla H.Myers-Smith, Susan M.Natali, Steven F.Oberbauer, ZoePanchen,

AlessandroPetraglia, EricPost, ChristianRixen, HeidiRodenhizer, Sabine B.Rumpf, Niels MartinSchmidt, TedSchuur, PhilippSemenchuk, Jane GriffinSmith, KatharineSuding, ØrjanTotland, TiffanyTroxler, HenrikWahren, Jeffrey M.Welker, SonjaWipf, and YueYang. The tundra phenology database: more than two decades of tundra phenology responses to climate change. Arctic Science. e-First https://doi.org/10.1139/as-2020-0041

Rixen, C., Høye, T.T., Macek, P., Aerts, R., Alatalo, J., Andeson, J., Arnold, P., Barrio, I.C., Bjerke, J., Björkman, M.P., et al. (2022). Winters are changing: snow effects on Arctic and alpine tundra ecosystems. Arctic Science. 10.1139/AS-2020-0058.

Seaver, M. (2022). Exploring the Effects of Shrubification on the Community-Level Flowering Phenology and Reproductive Success of Alpine Plants.

Shapiro, L.H., Tepedino, V.J., & Minckley, R.L. (2014) Bowling for bees: optimal sample number for "bee bowl" sampling transects. Journal of Insect Conservation, 18, 1105-1113.

Swenson, S.C., Clark, M., Fan, Y.y Lawrence, D.M., & Perket, J. (2019). Representing Intra-Hillslope Lateral Subsurface Flow in the Community Land Model. *Journal of Advances in Modeling Earth Systems, 11*. doi: 10.1029/2019ms001833

Webb, R.W., Williams, M.W. and Erickson, T.A. (2018) The spatial and temporal variability of meltwater flow paths: Insights from a grid of over 100 snow lysimeters. *Water Resources Research*, *54*(2), 1146-1160.

Wieder, W. R., J. F. Knowles, P. D. Blanken, S. C. Swenson, and K. N. Suding. (2017). Ecosystem function in complex mountain terrain: Combining models and long-term observations to advance process-based understanding. *Journal of Geophysical Research- Biogeosciences* 122:825-845.

Wieder, WR, D Pierson, S Earl, K Lajtha, GS Baer, F Ballantyne, AA Berhe, SA Billings, LM Brigham, SS Chacon, J Fraterrigo, SD Frey, K Georgiou, MA de Graaff, AS Grandy, MD Hartman, SE Hobbie, C Johnson, J Kaye, E Kyker-Snowman, ME Litvak, M Mack, A Malhotra, JAM Moore, K Nadelhoffer, C Rasmussen, WL Silver, BN Sulman, X Walker, & S Weintraub (2021). SoDaH: the SOils DAta Harmonization database, an open-source synthesis of soil data from research networks, version 1.0. Earth Syst. Sci. Data, 13(5), 1843-1854. doi:10.5194/essd-13-1843-2021

Wieder, W.R., Kennedy, D., Lehner, F., Musselman, K.N., Rodgers, K.B., Rosenbloom, N., Simpson, I.R., and Yamaguchi, R. (2022). Pervasive alterations to snow-dominated ecosystem functions under climate change. Proceedings of the National Academy of Sciences 119, e2202393119. 10.1073/pnas.2202393119.

Williams, K.E., McKay, C.P., Toon, O.B., and Jennings, K.S. (2022). Mass balance of two perennial snowfields: Niwot Ridge, Colorado, and the Ulaan Taiga, Mongolia. Arctic, Antarctic,

and Alpine Research 54, 41–61. 10.1080/15230430.2022.2027591.