NWT LTER VII

Long-term research on the dynamics of high-elevation ecosystems: a framework to understand ecological responsiveness to climate change

Year 3 Annual Report
2018-2019

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 interactions across levels of ecological organization as well as connectivity across landscape positions, outlining how responsiveness of one level of ecological organization (Q3) or spatial scale (Q4) 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.

We unify our investigations of ecological responsiveness by focusing on a specific aspect of climatic change in these high-elevation snow-governed ecosystems: the EXTENSION OF SUMMER (Fig. 1). Winter snow cover has been noted as one of the fastest changing climate features globally (Vaughan et al. 2013). Across Colorado, snowmelt timing has advanced approximately three weeks since the 1970s (Clow 2010), with a longer and hotter snow-free period. In year 3, a lot of effort was put into analyzing our long-term datasets in reference to extended summer and our 4 over-arching hypotheses.

![Figure 1. Climate at NWT is changing towards longer and warmer growing seasons, a trend we call "extended summer." (A) Climate conditions in multivariate space as summarized by principal component analysis using data from Nivot Ridge Saddle and Green Lake 4. Over 50% of year to year variation is described by climate characteristics (blue text) related to extended summers (PC1): high summer potential evapotranspiration and warmer mean summer temperature, advanced start to the growing season (days to a five-day running max temp of 5°C or 12°C) and lake ice-off in the Green Lake 4, a long growing season and high number of growing degree days. Variables related to the amount of summer precipitation and moisture deficit describe the second axis (PC2) and capture almost 20% of yearly variation. GDD is the growing degree days (base 5°C), GSL is defined as the growing season length, where the boundaries for the season are defined by 3 consecutive days where the minimum temperature is below -3°C. (B) Since the start of the NWT program, extended summer has significantly increased (β = 0.04, adj-R² = 0.49, p << 0.001) with much inter-annual variation. Years 2002, 2012, and 2018 were years that particularly characterized this phenomenon. Data sources: knb-lter-nwt.405; knb-lter-nwt.413; knb-lter-nwt.416; knb-lter-nwt.106]
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, lakes, and pikas. **Pikas.** Capitalizing on a single metric that describes the phenomena of early snow melt and longer and warmer growing season across years (e.g., after Fig. 1), we have been able to examine a broad range of ecological responses to extended summer conditions. While correlational, this step leverages patterns in our long-term data to confirm and guide expectations. It also highlights the varied responses across landscape position, organism, and level of organization.

**Alpine tundra.** In year 3, we have continued to follow tundra plant production and compositional change in established tundra (88-plot saddle grid) as well as added plant surveys alongside our newly-established sensor network in the Saddle Catchment. In the saddle grid, we find that production in the established tundra exhibits little response to extended summer climate conditions. Additional years of data since our proposal submission indicate that the decline in dry meadow production no longer holds, despite declines in soil moisture. We do find an increase in production in wet meadows (Fig. 2A), likely due to relaxed energy limitation and possibly relaxed temperature limitation. Lagged climate effects also do not appear to be strong determinants of aboveground net production.

In contrast to the stability in production, we find evidence of interannual shifts in species abundances that track climate conditions (Fig. 2B), an aspect of response that we did not strongly consider previously. A path analysis that incorporated species...
traits indicates the increased importance of functional diversity in maintaining aboveground production in extended summer years rather than shifts traits of the dominant species (Huxley et al, in review).

Analyzing vegetation responses in long-term experiments where we have manipulated resources and environmental conditions provide a starting point to test our expectation about how limitations shift in extended summer years. For instance, in a fully-factorial experiment we have manipulated snow (using snow fences), temperature (warming open-topped chambers) and nitrogen (N fertilizer additions in a moist meadow community since 2006. We find that years with extended summer correlate with lower biomass and plant cover, higher species richness, and shifts in species composition (Fig. 2 C,D) (Bueno de Mesquita, in prep). Experimentally adding snow (through snow fences) negates the effects of extended summer on vegetation cover, likely by moderating soil moisture limitation. In addition, it appears that the shift in cover is accompanied by shifts in species composition towards more opportunistic nitrophilic species in these years.

These results have changed our thinking about the importance of resource limitation across the tundra landscape in two ways. First, although we consistently find evidence of a climate signal on soil moisture limitation, we see less interactive effects of nutrient addition across climate conditions (e.g., Fig. 2D or our other N fertilization experiments, results not shown). Therefore, our expectation that these changing climate conditions would shift the relative importance of nutrient limitation may be unfounded. Second, based on modeling (Wentz et al. 2019) as well as revisiting studies from the 1960s and 1970s (e.g., Billings and Mooney 1968), we have also begun to consider more explicitly surface-level temperatures and temperature limitation across the tundra landscape. We detail more how high temperatures might be directly influencing plant response in part B, below.

We have found evidence for our expectation that release from energy limitation (a longer growing season) allows tundra to expand into unvegetated areas at higher elevations. Tundra vegetation has colonized these unvegetated areas over the last forty years (Bueno de Mesquita et al. 2017, Bueno de Mesquita et al. 2019). In long-term monitoring at the transition between vegetated and unvegetated talus areas, we also find a slight but significant increase in cover in extended summer years (results not shown), likely due to the benefit of a longer growing season.

**Tundra carbon flux.** Temporal analysis of the first seven years of alpine flux data also 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.

**Tundra plant populations.** In year 3, we have also initiated studies that track species survival and recruitment to better understand population-level responses as well as species turnover dynamics. We are currently establishing 40 0.25 x 0.25m observational plots (20 in dry meadow and 20 in moist meadow), where we will be tagging and mapping all individual plants within each plot. We will track recruitment and survival, of all individuals each year to begin to
examine how interannual climate variability influences tundra plant population dynamics beyond our community abundance measures.

**Pika.** We focus on the American pika (*Ochotona princeps*) as a model species for studying climate sensitivity in small, herbivorous mammals and (especially) sub-surface habitat specialists. We expected that loss of sub-surface ice, increasingly warm temperatures during the period of juvenile dispersal, and cold events in the absence of insulating snowpack would be aspects of extended summer conditions detrimental to pika populations. We find that extended summer conditions are associated with a strong decline in the number of juvenile captures relative to adult captures at the West Knoll on Niwot Ridge (Fig. 3A, Ray et al, in prep), indicative of decreasing reproductive success which could eventually cause declines in population growth. Sampling design for pika habitat occupancy monitoring (begun in 2016) in 72 plots grouped into 3 panels (differentiated here by color) and surveyed on a 3-year rotation (Fig. 3B).

**Chickadee.** We are in the initial stages of following the population dynamics of a small bird, the Mountain Chickadee (*Poecile gambeli*), in collaboration with Dr. Scott Taylor. We are now monitoring 100 nest boxes that have been installed along an elevational gradient at Niwot Ridge that will allow us to determine the relationship between breeding success of this boreal specialist and forest productivity. We will also be monitoring interactions between the Mountain Chickadee and a close relative, the Black-capped Chickadee (*P. atricapillus*), which sometimes hybridize where they co-occur. 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.

**Subalpine forest.** In our proposal, we predicted that extended summer climate trends would intensify soil moisture limitation in subalpine forest and reduce recruitment. Indeed, we find that extended summer reduces the number of seedlings recruited (Fig. 4) (Andrus et al. 2018b), and that most recruitment events occur during cool, wet summers. While we see detrimental effects
of warmer climate conditions on tree mortality and forest production, aboveground live tree biomass has actually increased since 1982 in NWT permanent plots, a trend we suspect is primarily driven by slow stand development following stand-initiating fires over a century ago.

We also predicted that forests will not track climate warming trends due to moisture limitation, with treeline expansion only occurring in wet topoclimates (e.g. north facing slopes). Consistent with this prediction, historical analysis of aerial photos have shown little change in treeline, and we do not see evidence of expansion in any specific topoclimates (Bueno de Mesquita et al. 2019).

**Alpine Lakes.** In our proposal we hypothesized responsiveness of lakes to extended summer conditions would vary with elevation. Our approach to addressing this hypothesis has been to combine analyses of long-term data from a high alpine lake (GL4) with comparative, among-lake data collected across an elevational gradient, with the assumption that differences across an elevation gradient might be similar to shifts in time with extended summer conditions (e.g., high-elevation lakes will exhibit lower-elevation characteristics). We also initiated long-term

![Figure 4. Permanent forest plots indicate extended summers significantly decrease tree seedling recruitment and increase tree mortality (not shown). Data sources: knb-lter-nwt.207](image)

*Figure 5. Seasonal-maximums of Chl-a in Green Lake 4 (log transformed) increase at all depths with extended summer conditions (A, yellow is 0m, blue is 3m, and dark blue is 9m sample depths). Zooplankton densities (also log transformed) show a weak decline with extended summer conditions (B, red) and remain low during the following winter (B, blue). Data sources: knb-lter-nwt.157; knb-lter-nwt.161.*
measurements on two lower-elevation lakes (GL1, Albion), which will enable us to observe trends within those lakes in the future.

At high-elevation, we do find that extended summer conditions increase seasonal maximum chlorophyll-a at all sampled depths in Green Lake 4 (Fig. 5), likely due to earlier ice melt and longer water residence times. Interestingly, adult zooplankton density in GL4 was lower in extended summer years (Fig. 5B), while average adult size of individuals from the two dominant groups (the large-bodied cladoceran, *Daphnia pulicaria*, and the calanoid copepod, *Hesperodiaptomus shoshone*), increased.

**15-Lake Survey.** In year 3, we worked on analysis of our spatial survey (Fig. 6) indicate that some spatial trends with elevation may be parallel to expectations for temporal trends with extended summer conditions, but others are not. For example, while maximum values of chlorophyll-a increased in years with extended summer conditions in GL4, we did not find a consistent trend with elevation. However, shifts in composition of both zooplankton and phytoplankton (e.g., greater densities of small-bodied cladocerans as well as high densities of phytoplankton groups (bacillariophytes, ciliates, chrysophytes, cyanophytes, and euglenophytes) suggest increased shifts towards increased grazing and top-down control, consistent with predictions.

**B. Modeling studies to explore limitation across space and time on Niwot Ridge.** Despite the many years of experimental studies of limitation on Niwot Ridge, our ability to understand, map, and predict how limitations will change across space, through time, and in response to changing climate has remained elusive. To address this gap, in year 3, we have implemented a new set of modeling studies that directly explore limitation across space and time on Niwot Ridge (Fan et al. 2016, Wieder et al. 2017, Dong et al. 2019, Wentz et al. 2019). We use a new heuristic
biogeochemistry model developed specifically for NWT (Niwot Biogeochemistry Model, NBM) to look at limitations over a growing season, a well-tested land-atmosphere model (the NCAR Community Land Model version 4.5, CLM) to further explore patterns across the landscape, and include plant traits to allow for shifts in functional responses at the species and community levels.

**Inclusion of plant traits.** To start investigating the role of plant traits, in year 3, we completed a new model-based analysis of the role of plant traits in overall plant responses to environmental change (Wentz et al. 2019). This modeling exercise makes some surprising predictions of how plants may respond to longer and hotter summers and highlights the important role that quantitative modeling plays in helping delineate future research questions on Niwot Ridge. Wentz et al (2019) used assemblages of traits representing acquisitive and conservative species on Niwot Ridge to show that photosynthetic rates are influenced by a number of factors including leaf N, leaf shape, and plant height. The trait-based modeling identified leaf temperature as a critical factor in C assimilation and specifically linked lower rates of C assimilation in conservative (dry) communities to high leaf temperatures during the peak growing season. These simulations also illustrate the sensitivity of productivity to the conditions likely in an extended summer scenario and have spurred us to revisit leaf-level temperatures in our current work (a focus of work several decades ago; eg., Billings and Mooney 1968). For instance, during the summer of 2019 we began measurement of surface temperatures across a landscape gradient to better describe how surface temperature varies across the alpine landscape.

To further use functional traits to describe resource use strategies across species and environments, we measured a suite of plant characteristics of 40+ species across the alpine tundra that are indicative of this spectrum of functional strategies, including leaf carbon isotope composition ($\delta^{13}C$; Fig. 7), specific leaf area, and leaf chlorophyll content. By combining existing information about species’ exposure to climate effects with a suite of plant traits related to carbon

![Figure 7. Tundra-wide variation in $\delta^{13}C$ among plant species, showing a weak phylogenetic signal (Pagel’s $\lambda = 0.29$), indicating closely related species are more similar to each other than expected by random chance. Despite a weak signal of genetic control at the whole phylogeny scale, we found a wide range of interspecific plasticity of species sampled in multiple habitat types suggesting that species may differ in their ability to track environmental variation. Data sources: knb-lter-nwt.500.](image-url)
and nitrogen metabolism, we are working to better understand differential responses to extended summer. These factors can be further developed to link with trait plasticity and evolutionary constraints (described more in H3).

**Changes and next steps.** In our original proposal, we planned to link the NBM with a distributed hydrology model to create a coupled spatially explicit modeling system for Niwot Ridge. Although there are benefits to this type of approach, it has become apparent we need to better empirically investigate the controls of production that have been highlighted by our current modeling efforts before undertaking additional modeling. We also decided to prioritize obtaining lake biophysical data prior to extending the modeling efforts to lake systems, due to the importance of understanding these physical controls. Accordingly, we have implemented a number of observational and experimental efforts that build from the modeling studies described above and which collectively will set the stage for future synthetic modeling and experimental work.

The sensor network is now generating data that will allow for the use of the NBM in the next 2-3 years with high resolution (in time and space) data. In our prior modeling work we had to rely on incomplete or infilled data to drive key aspects of the modeling (for example, soil moisture) and the emerging dataset will allow us to revisit these earlier assumptions and revise our modeling accordingly.

**C. New cross-cutting terrestrial and aquatic experiments.** We are in the process of establishing two large multi-investigator experiments – a terrestrial and an aquatic – to explicitly test our predictions of responses to extended summer climate conditions. Here, our focus is longer growing seasons and warming. These coordinated manipulations of extended summer across habitat types will allow integration of our long-term measures with focused manipulations of specific climate drivers and allow us to relate responses to natural climate variation with climate manipulations using standardized response metrics.

**Tundra manipulation of growing season length.** We are currently in the second year of our “black sand” experiment where we manipulate growing season length. By using a thin layer of black sand to reduce snow albedo and enhance melt rates without concurrently affecting snowpack depth, we can manipulate the length of the growing season (after Blankinship et al. 2014).

First-year results indicate that the treatment increases the albedo and speeds snowmelt (with the exception of the lowest elevation site, Soddie), with variable effects on soil moisture (not shown). We have established a series of subplots within each larger plot and have started measures of vegetation (cover, composition, production), tagged all woody individuals, and installed sensors to measure soil temperature and moisture. In addition, we have established a summer warming treatment using ITEX chambers (Fig. 8) within both the extended growing season and control plots, enabling us to look at the interactive effects of early snowmelt and warming. To our knowledge, this is the first experiment in the world aimed at teasing apart the effects of warming and extended growing season in a cold environment.
We expect to be able to start investigating experimental responses across the landscape gradient within the next year or two and look forward to comparing our findings with long-term observational patterns. Initial work on the phenology of five focal plants show species and site-specific response to warming and snowmelt timing treatments (Fig.8; Forrester et al, in prep), consistent with observational patterns (Winkler et al. 2018). We plan to continue these manipulations yearly in order to examine forecast persistent changes in growing season length; although the amount of sand added is small, we will monitor for cumulative effects. Summer 2019, we have also begun examining how early snowmelt may influence plant-pollinator interactions.

Lake manipulation of growing season length. In LTER VII, we proposed conducting an experiment parallel to the tundra manipulations in alpine lakes. While establishing this experiment has proved to be logistically challenging and we have had to change our proposed methodology, we are currently conducting a final set of pilot studies this year and hope to begin the entire experiment this fall.

Originally, we proposed to conduct factorial manipulations of water residence time and terrestrially derived DOM within 12 limnorrals deployed in Green Lake 4 (GL4) and 12 in Green Lake 1 (GL1). However, our partners at the City of Boulder Watershed (where the lakes are located) are reluctant to allow us to perform manipulations at this scale and the remote setting of the lakes make transporting supplies logistically challenging. Thus, we have been exploring the alternative of using large-volume mesocosms (2600 L) – which can be deployed inside watershed property and manipulated more directly with higher replication – as a tractable next step to test our hypotheses. Although mesocosms cannot capture the full complexity of biota and abiotic interactions unfolding within lake ecosystems, we use them here as one of several lines of
investigation (alongside long-term data, comparative sampling over an elevation gradient, and ecosystem modeling) to specifically address interactions in a simplified food web involving phytoplankton and zooplankton. This is further assisted by the large size of mesocosms employed in our study (~2600 L). We have carefully proceeded through a series of pilot studies and planning protocols, which collectively set the stage for a larger manipulation that began in Fall 2019.

A first pilot study performed at the Mountain Research Station confirmed that smaller-scale manipulations may offer a useful experimental context, particularly for the low-diversity aquatic communities found in alpine lakes (Preston et al, in review). In particular, we demonstrated the ability to manipulate water temperatures while maintaining natural variance regimes, helping to show the strong effects of temperature on dominant zooplankton responses.

Through another series of pilot studies, we have determined that we can successfully accelerate ice-off timing and water temperatures by varying the color of the mesocosms (black vs beige) allowed to naturally fill with winter precipitation at an experimental sub-alpine meadow site (which we call Soddie). Albedo alteration was effective in advancing ice-out while concurrently increasing average daily temperature.

Based on these preliminary results, we established 20 2,600-liter mesocosms at this site later this summer, with half light in color (control) and half black. A DOM addition treatment will be performed to half of these tanks (to test H2, below) in all factorial combinations (i.e., a 2 x 2 manipulation with five replicates per condition). We will seed the mesocosms prior to snow precipitation accumulation with sediment and leaf packs. Many planktonic taxa have resting egg phases, and so we expect that these communities will emerge when exposed to an aquatic environment in the experimental mesocosm tanks. Seeding of phytoplankton and zooplankton will also be performed the following summer after ice melts out. As with the black sand terrestrial experiment, we will measure response in parallel to our long-term measurements, including nutrients, DOC, chlorophyll-a and zooplankton. We hypothesize that decreases in mesocosm albedo will lead to tank warming, an earlier ice-off date, and a longer growing season, in parallel to the black sand manipulations of snowmelt and temperature. We anticipate the longer growing season and warmer water temperatures will facilitate increases in biological productivity, as indicated by greater chlorophyll-a concentrations (with an earlier seasonal peak) and more planktonic biomass. Effectively this will create characteristics in line with more intermittently mesotrophic lakes found below treeline rather than the ultraoligotrophic systems of the alpine. Zooplankton biomass may increase in response to increased phytoplankton resources, although previous experiments have also highlighted the potential for alpine-adapted species to decrease in abundance with warming (i.e., a compositional shift in the zooplankton).

2. BIOTIC INFLUENCE: How Do Biotic Effects Influence Climate Exposure And Ecological Responsiveness? At a spatial scale finer than landscape effects of complex terrain, our second hypothesis focuses on how biota can also influence climate exposure through effects on the physical environment. 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 correlational associations across space in conjunction with experimental manipulations that are linked with the climate exposure experiments that are described in H1. 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 in (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 of snow accumulation 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.

**Species associations.** With ten continuous years of species composition data in the saddle grid (prior to 2008 the measurements were sporadic), we are now at the point where we should be able to infer interaction strengths across plants using our long-term data. This fall, we plan to analyze population change (as annual cover changes) in our long-term vegetation dataset at the Saddle site. We will use Bayesian methods (JAGS in R) to fit a simple population model (Levine and HilleRisLambers 2009, Farrer et al. 2014) and estimate interaction coefficients quantifying the per capita effect of cushion plants (and perhaps other species) on each focal species. We will incorporate meltout date data into the models to allow interaction coefficients to depend on growing season length. We expect that community types (DM, FF) and years with longer growing seasons will be associated with more facilitative effects of cushion plants. We note that observational approaches do not definitively assess the relative importance of interactions but have value in being able to confirm patterns in species groups that we expect to have large biotic influences and assess patterns more broadly for a wide range of taxa that cover a range of habitat characteristics.

**Experimental manipulations.** In combination with the extended summer “black sand” manipulations (described above), we are manipulating biotic interactions to elucidate how physical protection from wind can facilitate plant performance. Originally, we proposed to plant foundational species as well as construct artificial wind barriers that simulate the presence of the individual. However, we had limited success transplanting live plants and instead have just pursued plans to implement artificial barriers that mimic the effects of a structure-forming shrub.

In the fall of 2018, within each of the large plots in the terrestrial growing season length experiment (5 control, 5 early melt out), we established artificial shrubs within each of three subplots, which are paired with control subplots. We adapted “con-mods” following Rachal et al (2015). Each con-mod consists of an X (30.5 cm tall with each of four winged panels 40 cm long, constructed using rebar and hardware cloth). Pilot studies have shown that these structures act as a small snowfence, accumulating snow at their leeward side (Brigham et al, in prep).

Starting this year, we will follow the composition and growth of vegetation with and without these artificial shrub structures. Our expectation is that the con-mods will modulate effects of the black sand manipulations on soil moisture and growing season length. These small areas of climate refugia will lead to plot-wide increases in environmental heterogeneity and overall diversity.
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.

**Experimental manipulations.** We will mimic the phenomenon of increased terrestrial input to lakes by adding DOM as an additional factorial treatment to the mesocosm experiment (discussed above). We will add DOM via leaf-packs composed of locally collected willow leaves enclosed within standardized nylon mesh bundles. We intend to increase dissolved organic carbon concentrations of manipulated mesocosms to be comparable to averaged open water DOC concentrations of previously surveyed subalpine lakes located north and south of the Green Lakes Valley (~1.49 mgL\(^{-1}\) (range: 0.590 to 2.78 mgL\(^{-1}\)) and about 0.637 mgL\(^{-1}\) lower than local alpine lakes (range: 0.486 to 1.743). Pilot studies in which we deployed leaf packs (constructed using the methods above) in a set of mesocosms illustrated the expected reduction in PAR (Fig. 21B), with measurements of DOC still pending.

We plan to assess the benefits of DOM additions mediating UVR stress in zooplankton assemblages through a combination of population- and trait-level responses, including (1) examining *Daphnia* for evidence of melanization (a common protective strategy in the presence of UV stress) and (2) assessing the prominence of taxonomic groups with high UV tolerance (e.g., calanoid copepods such as *Hesperodiaptomus shoshone* and *Holopedium gibberum*). Increases in DOM are also expected to amplify the degree of top-down regulation of phytoplankton and chl-a by zooplankton, for which we will quantify dynamic interactions based on the correlation between variation standing biomass in adjacent trophic levels (e.g., zooplankton and phytoplankton, and over multiple time lags). We further anticipate additive or interactive effects between growing season length and enhanced DOM treatments, such that planktonic biomass and community composition shifts will be most pronounced in the presence of both manipulations because plankton will have a longer growing period under less abiotically stressful conditions. Importantly, this experiment will help to decouple the relative influence of growing season length, UV-stress, and DOM availability, which typically co-vari with elevation.

C. Observational, Experimental and Model Integration. Because the type and mechanisms of biotic interactions can vary widely across taxa and systems, our approaches described here are just first steps. We are at the point with our tundra community long-term data where the time series should be long enough to model interaction coefficients and spatial associations. Experimentally, we are initiating tests of two general mechanisms by which biotic factors can influence response to shifting limitations: wind protection (and resource accumulation) in tundra and treeline environments, and terrestrial DOM subsidies in lake environments. We plan to link responses to these experimental manipulations to observational patterns in the future and are particularly interested to explore how these mechanisms may generate patterns of landscape diversity.

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. These are soil moisture and growing season length, which are important drivers of plant performance that are changing with extended summers. Our approach to testing these predictions is to use existing data and ongoing studies to characterize temporal variability and uncertainty in soil moisture and growing season length, test if and when these measures predict plant life history strategies, distribution patterns, and functional traits, and conduct new transplant experiments that explicitly quantify plant responses to environmental variability in target taxa. Ultimately, we aim to integrate the results of this work with ecosystem measures of hydrological connectivity, snow cover dynamics, and productivity to understand how organism and population-scale responses to temporal variability drive community and ecosystem processes.

A. Characterizing temporal variability and predictability. Although the sensor network infrastructure in the saddle catchment has only been fully operation since 2017, it has already provided exciting insights into patterns of spatial and temporal variation in growing season length and volumetric water content within a single catchment. Phenocams, installed in 2017, have captured clear shifts in community-level phenology that can be used to quantify growing season length at different landscape positions. For example, the timing of green-up (i.e., the onset of the growing season) was substantially earlier in 2018 than 2017, corresponding to earlier snow meltout and extended summer conditions in 2018 (Fig. 9). In fact, all aspects of community phenology (greenup, maturity, senescence, and dormancy) shifted earlier between 2017 and 2018, suggesting that many aspects of plant phenology are sensitive to interannual climate variation. We suspect that extended summer conditions might be affecting these phenological responses through the combination of alleviation of energy limitation in early spring and water limitation at the end of the growing season. The magnitude of year-to-year variation in growing season length differs among habitat types, with larger shifts in moist meadow communities and smaller temporal differences in dry and wet meadow communities. While these...
initial results indicate that the phenocams provide excellent measures of growing season dynamics at the community scale, more years of data are required to obtain robust estimates of intra- and inter-annual variation in those dynamics at each SNA node.

In year 3, we have used the 2018 soil moisture data from the sensor network to characterize plot-to-plot differences in within-season variability and predictability in volumetric water content. We are quantifying within-season variability at each node in the network as the number of times that the daily average volumetric water content decreased below 13%, a threshold that is correlated with reduced plant growth and productivity in the alpine (Billings and Bliss 1959, Winkler et al. 2016). We recognize that there is likely to be some interspecific variation in this threshold for different plant species (Winkler et al. 2016), and we plan to quantify species-specific thresholds for several focal taxa using controlled greenhouse experiments in the next several years.

The predictability of soil moisture content is the accuracy with which the conditions at one point in time can predict the conditions at a later point in time (Donaldson-Matasci et al. 2013, Nadeau et al. 2017), which is statistically evaluated using temporal autocorrelation analysis (Burgess and Marshall 2014). In this approach, predictability is quantified as the autocorrelation factor (ACF), which ranges from 0 (zero predictability) to 1 (perfect predictability). For a given time series, the ACF can be calculated across different time steps (lags) to evaluate how well conditions at time $t$ can predict the conditions at varying times into the future. Our analysis of the SNA data from the 2018 growing season has found that the highest variation among plots in ACF values occurs with a timestep of 10.64 days (1533 soil moisture measurement intervals), where ACF values ranged from ~0.25 to ~0.85 (Fig. 10). Because this time step best differentiates plots along an axis of soil moisture predictability and is a biologically relevant timespan over which plants can respond to changes in soil moisture, we are currently using these values to characterize the predictability

![Figure 10](image-url)
of VWC of each plot in the SNA (Fig. 10, y-axis). Beginning in 2019, we have marked individual plants adjacent to the sensor nodes to closely monitor plant growth and development over the growing season in the same plots where we are monitoring soil moisture. The data from these monitoring efforts will allow us to test if the ~10 day window is a biologically relevant time frame for detecting plant responsiveness to changes in soil moisture levels.

We plan to conduct the same analyses of soil moisture variability and predictability every season to ultimately develop a robust characterization of each plot that is based on data from multiple growing seasons. After data from the SNA have accumulated over several consecutive years, we will also characterize year-to-year variation and predictability in each plot using similar methods (threshold crossings and ACF values). We are optimistic that these data will soon provide a unique long-term record of both intra- and inter-annual variation in an environmental variable that is key for plant growth and sensitive to extended summers; for instance, 2018 was a year with strong extended summer climate characteristics and 2019 is turning to be the other extreme.

**B. Ecological responses to variability and predictability.** A key step toward addressing Q3 is to test if the variability and predictability of soil moisture is an important driver of life history strategies, functional trait variation, and distribution patterns of alpine plant species. In preliminary analyses, we have used plant community composition data (cover data collected in one 1 m x 1 m plot at each node) in the summer of 2018 to characterize the soil moisture conditions that are occupied by different plant species at Niwot Ridge – i.e., the “fluctuation niche” (Terradas et al. 2009) of different taxa with respect to within-season temporal variation in soil moisture (Fig. 11). Although we can detect some differences among taxa in the conditions that maximize their probability of occurrence, low sample sizes generate large confidence intervals around these estimates (Fig. 11): only 16 plots were surveyed for plant community composition in the SNA in 2018, and any single species only occupies a subset of those plots. To improve these estimates, we are doubling the number of sensor network plots where we collect plant community composition

![Figure 11. The distribution of different alpine plant species with respect to the variability and predictability of soil moisture. Circles represent the conditions where each species are most likely to occur, with the 20% and 70% confidence limits around those locations shown in dark and light gray, respectively. These figures were produced using plant community composition and soil moisture data collected during the 2018 growing season in the saddle catchment at Niwot Ridge. We view this as a proof of concept: confidence limits are low due to low sample size, something we will be addressing with more sampling this year. The top and bottom rows show patterns for three common graminoids and three common forbs, respectively. Data embargoed.](image-url)
data. In addition, we are tagging and monitoring individual plants of focal taxa so that we can include estimates of plant performance in these analyses in addition to the presence/absence information obtained from the annual community surveys.

Our preliminary analyses of plant functional trait variation at Niwot Ridge provides evidence of plant strategies for coping with variability in soil moisture differs substantially among species and habitat types (Fig. 12A). Specifically, some species exhibit plasticity (Fig. 12B; quantified as the relative distance plasticity index (RDPI) (Valladares et al. 2006) in water use efficiency ($\delta^{13}$C; hereafter WUE) while others have a fixed strategy (consistent with bet-hedging or specialization). Interestingly, plasticity does not seem to be correlated with intraspecific trait variation among habitats in all species. The species with the lowest observed plasticity, *Artemisia scopulorum*, shows significant differences in WUE among habitat types, while a species with relatively high plasticity, *Deschampsia cespitosa*, does not significantly vary among habitat types. However, 70% of the species that exhibit plasticity in WUE are showing trends of increasing in abundance over time in the tundra (based on data from Spasojevic et al. 2013), with only 8% decreasing over time and 22% remaining stable. Species that express less variation in WUE show a more ambiguous trend with 30% increasing, 30% decreasing, and 40% stable through time.

**Figure 12.** (A) Variability in $\delta^{13}$C among species and habitats. Intraspecific trait variation in $\delta^{13}$C within and among habitat types for six species that are the focus of pilot transplant experiments in the SNA (indicated by the 6 letter codes – see Table 1). (B) The plasticity of six focal taxa (see Table 1 for species codes) calculated from the trait data shown on the left (A-F). The Relative Distance Plasticity Index (RDPI; Valladares et al. 2006) was calculated for each species using the data shown on the left, with a value of 1 representing high plasticity and a value of 0 represents no plasticity. Large outlined points indicate target species used in pilot seed addition and transplant experiments. Data sources: knl-lter-nwt.500.
C. Field experiments and individual-level monitoring of plant strategies in temporally variable conditions. In year 3, we used the preliminary analyses of plant species abundances across soil moisture variability and predictability in the sensor network (Fig. 12), and estimates of plasticity in functional traits for WUE (Fig. 11), to identify a subset of alpine plant taxa to be the focus of experimental work moving forward (Table 1). This subset includes species that occupy different positions along our axes of variability and predictability in soil moisture (Fig. 11), and express different levels of phenotypic plasticity in water use efficiency (Fig. 12). It includes both graminoids and forbs, as well as three species in the Caryophyllaceae to provide comparisons among species of varying relatedness in phylogenetically structured analyses.

In the summer of 2019, we established eight 1 m x 1 m plots within the sensor network that span the range of variability and predictability measured in 2018 (nodes 6, 8, 9, 10, 11, 12, 20, and 21). Experimental plots were placed adjacent to the community, with one edge centered on the soil moisture sensor.

In each plot, we planted seeds of the target species (obtained from existing local collections) to pilot methods for seed addition experiments, transplanted adult plants of each target species, and marked naturally-occurring individuals of each species to document plant performance in each plot. We are monitoring seedling emergence, plant survival, plant growth, and reproductive output for all experimental plants over the growing season. We anticipate using the results of these pilot experiments to finalize protocols for expanding this experiment to more plots in the sensor network in subsequent years. In addition, we plan to use newly established plots to track recruitment, survival, and death of all individuals to examine how variability in climate influences tundra plant population dynamics.

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 provide a strong spatial and temporal context for much of our fine-scale foci of H1-H3. Flow paths, water sources, and residence times will dictate connectivity between high and low elevation ecosystems (e.g. alpine to montane) as well as between terrestrial and aquatic ecosystems (e.g. hillslopes to streams and lakes)(Webb et al. 2018), we expect that at the catchment scale, some areas may only meaningfully contribute in some years and not in others. Processes such as snowmelt, transpiration, nutrient uptake and microbial transformations will also interact with hydrology to affect catchment-wide nutrient retention and export.

| Table 1. Focal plant taxa, family, and primary habitat type for species that are being used in pilot field experiments (seed additions and transplants) in the Saddle Catchment SNA in 2019. |
|---|---|---|
| Species | Family | Habitat Type(s) |
| Artemisia scopulorum (ARTSCO) | Asteraceae | moist meadows |
| Arenaria fendleri (AREFEN) | Caryophyllaceae | fellfield |
| Silene acaulis (SILACA) | Caryophyllaceae | fellfield |
| Stellaria longipes (STELON) | Caryophyllaceae | moist meadows |
| Kobresia myosuroides (KOBMYO) | Cyperaceae | dry meadows |
| Geum rossii (GEOROS) | Rosaceae | moist meadows |
| Deschampsia cespitosa (DESCES) | Poaceae | moist meadows |
| Festuca brachyphylla (FESBRA) | Poaceae | moist meadows |
Since the relative importance of different parts of the catchment should vary with climate, we take several parallel catchment-scale approaches to integrate processes and temporal dynamics in response to climate conditions. We focus on two catchments that differ in their biophysical setting: the Saddle Catchment, which extends from established tundra through krummholz to subalpine forest; and the GL4 catchment, which extends from the Continental Divide through talus slopes to Green Lake 5 and 4. At a larger scale, we consider the watershed-wide region of the Green Lakes Valley, from the continental divide to subalpine forested Albion. Our overall goal is to integrate ecological responsiveness within a catchment (e.g., H1-H3) to responsiveness within and at the catchment-scale in terms of export of Carbon, nutrient and water export.

A. Integrative efforts at the Saddle Catchment. In LTER VII we are focusing on ways to integrate smaller-scale population, community, and ecosystem dynamics with catchment-scale dynamics. We chose the Saddle Catchment as this focal area because it links the Niwot Ridge Saddle with the Green Lakes Valley (Fig. 13). Accompanying our work establishing the SNA, we are using multispectral imagery to link fine-resolution spatial patterns to point measurements. In 2017, we began describing the spatial and temporal variation in the Saddle Catchment using high-resolution multispectral imagery (RGB, NIR, TIR) and thermal imagery collected from an unmanned aerial system. We flew drones bi-weekly for the 2016 growing season, which enabled us to identify areas within the landscape which were limited by water (wind-scoured) or growing season length (late melt out, energy-limited), as well as areas with increased production downslope from snow accumulation (Fig. 13). At the catchment scale, the primary limiting factor to NDVI was growing season length, tightly related to snow depth, and secondarily water limitation and wind exposure that combined to reduce observed NDVI by 15% (Wigmore et al, in prep). We are currently processing thermal imagery to better describe soil moisture as well as high temperatures, enabling us to link back to our smaller-scale work about temperature limitation.

To explore these patterns in the subsurface, in year 3, we are currently using geophysical methods (specifically, Electrical Resistivity Tomography) to image subsurface structures and
characterize fluid flow paths and their controls on water–rock interactions and ecosystem dynamics. Our particular goal was to evaluate seasonal subsurface connectivity of different ecological communities to the Saddle stream in the Saddle Catchment (Fig. 14) (Reys et al., in prep). We chose a study grid within the Saddle Catchment, bisected by the saddle stream with the dry meadow and krumholtz communities on the west side of the stream and a wet meadow community on the east side of the stream. The dry meadow and krumholtz communities on the west side of the stream appears generally disconnected from the Saddle stream catchment from September through April (i.e. current span of collected data). This may change during snowmelt (we do not have more recent dates processed yet). Geophysical anomalies corresponding to warmer and/or wetter conditions are present throughout the winter and correspond to areas of deeper snow, either due to complex terrain (H1) or structure-forming biota (H2). Use of geophysics is a new approach for our team that is adding critical resolution on subsurface structure to conduct planned research to understand hydrologic connectivity (and how it is changing) among patches across the catchment.

We have also initiated soil measurements at each node, to measure soil physical and hydrologic properties (e.g. hydraulic conductivity, soil texture, soil water retention). We are finding that hydraulic conductivity can be used as a proxy for subsurface soil structure and may be key in aggregating patch-scale-responsiveness to catchment scale processes (Hermes et al., in prep).

**Spatially-explicit hydrological modeling.** We are using the physics-based Distributed Hydrology Soil Vegetation Model (DHSVM; Wigmosta, et al. 1994) to evaluate and integrate hydrologic connectivity through time. This approach will allow us to identify key periods of connectivity across space within the catchment as well as changes in limitations of water, energy, and nutrient transport potential. In our initial proposal, we were planning on using a larger resolution (20 m x 20 m grid) and linking with the biogeochemical model (NBM). However, we have prioritized a finer-resolution model implementation to gain an understanding of important
hydrologic variability across the catchment before adding nutrient cycling processes. Thus, to lay the foundation for quantifying hydrologic connectivity, we focus on evaluating the variability in hydrologic states (soil moisture and snow water equivalent) and fluxes (streamflow and evapotranspiration) across the catchment and through time with with DHSVM at a 2 m x 2 m horizontal resolution over the Saddle Catchment. These simulations provide an estimate of key components of the water balance within the catchment, as well as time varying portrayals of streamflow variability (Fig. 15). They also indicate that the wind-scoured dry meadow and fellfield areas (a large proportion by area of the catchment) contribute less to catchment-wide water export and nutrient retention relative to other areas. In contrast, the treeline ecotone buffers streamflow from climate variability as the structural influence of treeline consistently traps snow in these areas. These findings are consistent with the preliminary results of our geophysical surveys, described above.

Our next steps are to expand our time-period (currently 2000-2010) to overlap with our SNA data collection (2017 and onwards) by extending our micrometeorological forcing and refining our spatial interpolation to cover all 2m x 2m grid cells. One important issue is how to realistically distribute precipitation at this fine-scale. Snow represents the majority of water input into the system and much of it is redistributed by wind. Therefore, we exploring using snowpack observations over space to capture the effects of blowing snow and to more realistically distribute precipitation (Fig. 15, inset). The sensor network array and our long-term data will allow us to further develop DHSVM by assimilating additional SNA observations, e.g. soil moisture and snow depth, and validating hydrologic portrayals with ancillary in situ observations.

**Integrating hydrological and biogeochemical modeling efforts with new field tracer studies.** In conjunction with the sensor array measures and hydrological modeling, we proposed to use targeted tracer additions to identify critical catchment locations that contribute greater runoff as well as those that generate less, i.e. quantify catchment connectivity under different conditions. We proposed coupled modeling-observation research, where DHSVM simulations will be used to identify locations of high and low connectivity and guide field deployment of the first set of tracer (i.e., $^{15}$N and LiBr) analysis. While this work is still in our plans, changes to our DHSVM
modeling has made us decide to wait to deploy the tracer study until the needed simulations are completed to guide locations of the tracer additions.

B. Integrative efforts at the GL4 catchment. We also continue our work in the higher-elevation Green Lake 4 catchment. This catchment includes the Arikaree Glacier, a rock glacier on its north-facing side, and a large proportion of talus unvegetated scree. This setting allows us to explore influences of changes in the Arikaree glacier and rock glacier, source water contributions to streamflow, as well as the influence of vegetation colonization of the unvegetated talus. It also allows us to directly tie terrestrial responses to aquatic lake ecological responses, something that is more difficult in the Saddle Catchment as it intersects Boulder Creek south of Lake Albion (our lowest elevation lake sampled).

Spatiotemporal variability in source water contributions to streamflow generation. Hydrologic mixing models parameterized with naturally occurring tracers help to identify various sources of water contributing to streamflow (Williams et al. 2015). We find at GL4 that snow is the predominate contributor to streamflow, contributing two-thirds of the water, with groundwater and talus water also contributing. In 2012, an extended summer year, we find that the contributions water from talus sources doubled, while snow and groundwater declined (Cowie et al. 2017, Zhang et al. 2018). However, talus water represents a limited hydrological reservoir and may not compensate similarly for decreased snowmelt in the future. At a larger scales, alpine areas contributed the majority of streamflow in the mixed alpine/subalpine Como Creek catchment, despite comprising just 31% of the catchment area; both alpine and subalpine areas over-generated discharge relative to a Budyko-type model due to the snow-dominated hydrological regime (Knowles et al., 2015c). following on this work, we are interested in further investigating the importance of the treeline ecotone to catchment hydrology as a result of persistent wind-driven snow redistribution from snow-scoured tundra (Knowles et al 2015b) in contrast to high sensitivity to climate variability in the absence these treeline effects.

Tundra plant colonization and downstream response. As plants colonize unvegetated C-deficient soils, they can change microbial communities and nutrient cycling. Efforts to map plant species richness and density, soil bacterial, fungal and eukaryotic species richness and phylogenetic diversity (using 16S, ITS, and 18S gene sequencing), and ecosystem function (levels of soil C and N, and rates of microbial enzyme activities) along the colonization gradient highlight the coupling between above- and belowground systems (Bueno de Mesquita et al. 2018, Porazinska et al. 2018). Microbial communities in these early successional systems are dependent on contemporary inputs from plants and therefore are strongly correlated with plant diversity and density.

We also have been able to link these changes in microbial communities and soils to downstream effects in high-elevation lakes. The microbial community shifts from talus soil to entering the lake (inlet) to within the lake body at GL4; the similarity of the communities within the talus soil and inlet indicate strong subsidies from the talus (Fig 16A). Once the communities enter the lake, they undergo strong environmental filters that cause many rare inlet taxa to increase in relative abundance while abundant inlet taxa become relatively rare (Fig. 16B).
C. Context within the LTER VII Framework. 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 H1 and H3 - 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.

5. CROSS-SITE SYNTHESIS.
A. Network-level Participation. Suding is active on the LTER Executive Committee. 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.

B. Synthesis Groups. Niwot investigators are PIs for two of the NCO-sponsored synthesis groups. Suding co-leads the “Synthesizing population and community synchrony to understand drivers of ecological stability across LTER sites” group. Building on many sources of long-term data, the LTER Synchrony working group aims to understand the drivers and timescales of synchrony and its effect on ecological stability. Many of the LTER vegetation datasets have reached a length (over a couple decades) that enables investigation of how ecological stability is influenced by whether populations rise and fall in tandem (synchrony) or are offset (asynchrony). Offset fluctuations between species can enhance ecosystem stability at one location and alternate fluctuations of the same species in different regions can support species stability across space.

Figure 16. (A) Microbial communities shift from those in the talus (soil, triangles), to entering the lake (inlet, circles), to that of Green Lake 4 (“Lake Body”, diamonds), with the inlet microbial communities showing intermediate similarity. (B) The abundance of taxa in the inlet do relate to the abundance of taxa in the lake, but also show strong selectional pressure, where many of the rare taxa in the inlet (green) are selected for in the lake and many of the abundant taxa in the inlet (red) are selected against in the lake (and become a C subsidy) (Gendron et al. 2019). These results were similar between the bacterial (16S) and eukaryotic (18S) communities. Metadata in prep.
Wieder co-leads the “Advancing soil organic matter research: Synthesizing multi-scale observations, manipulations & models” group, which aims to explore the Soil organic matter, a massive storehouse for carbon, as well as a key regulator of nutrient cycling and soil quality in terrestrial ecosystems. Their goal is to use LTER data to increase our understanding of the controls on stabilization and breakdown of soil organic matter. Two sets of competing theories underlie models that adequately predict site-specific dynamics but result in different sets of predictions about the response of soil organic matter to perturbations.

NWT researchers have been also active in recent syntheses related to a broad range of soil processes, including soil respiration (Bradford et al. 2019), hydrology in snow-dominated systems (Driscoll et al. 2018, Freppaz et al. 2018), terrestrial carbon cycling (Sulman et al. 2018, Vicca et al. 2018), and pika distributional changes (Smith et al. 2019). Of particular note, Niwot investigators worked on a global analysis of biome-wide relationships between temperature, moisture and seven key plant functional traits both across space and over three decades of warming at 117 tundra locations which showed the importance of temperature mediated soil moisture effects (Bjorkman et al. 2018). They also contributed the alpine assessment to the UN intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) Report.

6. EDUCATION AND OUTREACH LTER VII. As in our proposal for NWT VII, the outreach program has had a 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 are able to communicate the results of their research in an impactful way, prepares them for careers as engaged scholars, and makes NWT research accessible and relevant to public audiences of all ages. In addition to offering professional development around outreach for our graduate students, we have also been responsive to requests for tours and educational events, continued to grow the impact of our Schoolyard Book, and developed new partnerships for outreach and education in our community. We detail these efforts below.

A. K-12 Outreach and Education. In addition to giving graduate students opportunities to connect with public audiences and practice science communication, our other major outreach goal was to re-think how our Schoolyard Books (My Water Comes from the Rocky/San Juan Mountains) are being used in schools. With colleagues from the CU Museum of Natural History, we received a CU Boulder Outreach Award that has allowed us to design an entirely new curriculum kit for 4th grade classrooms called Adaptation and Variation in Colorado Mammals. The kits use the My Water books in the context of teaching early evolution literacy concepts. The kit and associated curricula were designed in partnership with Boulder Valley School District teachers through their Professional Pathways teacher professional development program.

We have also introduced well over 500 middle and high school students to NWT VII research through field trips to the Mountain Research Station and lab tours on campus. Our partnership with the Winter Wildlands Alliance and their Snow School program (https://winterwildlands.org/snowschool/) connected LTER scientists and CU undergraduates with ~200 children in 1st through 6th grade, and got them out on snowshoes, exploring snow science at the Mountain Research Station and sub alpine sites nearby. Additionally, NWT grad
students Cliff Bueno de Mesquita and Ashley Whipple helped design new activities about their NWT based graduate research for Snow School sites around the country.

In 2019, many of the NWT graduate students who took the outreach and communication seminar put their skills into practice via a new collaboration with Wild Bear Ecology Center (a non-profit, all-ages nature center located near NWT). NWT grads, staff and techs take children ages 10-15 into the field with them for four hours on each of 9 Wednesdays during the summer, demonstrating field techniques and teaching them about topics including pika biology, water chemistry, climate data, limnology, sub alpine forest ecology, phenology, and chickadee biology.

In addition, in all three years of NWT VII, NWT graduate students have participated as instructors in the Mountain Research Experience week-long residential field ecology course for high school students led by NWT Education and Outreach Coordinator Alex Rose. In all three years, 8 of the 14 high school students were recruited on scholarship through the Nature Kids Lafayette/Jóvenes de la Naturaleza program—an initiative to increase outdoor stewardship and environmental literacy in children from low-income and Latino families in Lafayette, Colorado.

**B. Undergraduate Students.** We are strongly committed to engaging and training undergraduate students as part of NWT LTER. LTER directly supports undergraduate workers as field assistants and many undergraduates obtain funding from their schools (CU and beyond) to do research at NWT; faculty and graduate students place high priority of mentoring these students. We also support a Snow Internship as well as REUs.

The Niwot LTER Snow Internship allows undergraduates to engage in the synthesis of field science, outdoor science education, backcountry winter travel and safety, and leadership skills for course credit. Snow Interns are trained to collect snow pack data through skiing to remote locations at two sites in the alpine and sub-alpine on Niwot Ridge. Here they dig weekly snow pits to record temperature, stratigraphy, density, and snow water equivalent (SWE). The data they collect contributes to a long-term data set of seasonal alpine snowpack, which is continuous from 1995 through the present, and unique to Niwot Ridge. Snow interns also present their findings at a scientific conference and conduct outreach with K-12 students.

In the summer of 2019, we partnered with the Research Experience for Community College Students (RECCS) program through the Cooperative Institute for Research in Environmental Sciences (CIRES) to host 3 REU students from regional community colleges. Two of these REUs are first-generation college students. Assuming this summer is successful, we will continue to support REU students from community college partners for the last three years of the LTER grant period.

**C. Graduate Students.** Each year of NWT VII we have given GRA and/or supplies funding to 13 grad students and 3 post-docs. 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. Twelve students affiliated with NWT have taken the course so far. In 2018-19, the course focused on the design and presentation of hands-on demonstrations, games, and info-graphics to explain NWT research. These demonstrations were presented to public audiences on campus, at a Meet a Scientist event at the Boulder Public Library, and they will be used in future outreach events and teaching.
D. Rotating Synthesis Postdoc. In addition to encouraging integration through our research planning process, we support a rotating 2-year postdoctoral fellow. We have found allocating a scientist with a proven track record of productivity to in-depth analysis and synthesis of NWT LTER projects exploits and amplifies a proven strength of the LTER program. In our first year, we tried a very open call, and found that it was very hard for someone outside the NWT program to be able to propose a project that also meets our project priorities. This spurred us to change the scoping process for each postdoc position, and collectively make position announcements tailored to the needs of the project. This has proven a very successful approach for us, allowing us to bring in talented individuals such as Oliver Wigmore (who tackled the UAV multispectral measurements for H4, and now is in an Assistant Professor position in New Zealand), John Crawford (who has been tackling data integration, particularly in our water chemistry long-term records, joining the project Jan 2019) and most recently Kyle Christianson (who fills a gap in limnology and biophysical aquatic work, joining the project May 2019). In addition, Courtney Collins joined the project as a postdoc on LTER-related funding September 2019 (who will be working with Sarah Elmendorf on biodiversity and trait synthesis across the alpine and arctic biomes).

E. Public and Stakeholder Audiences. We work hard to spread our work to the public and stakeholders. Faculty are regularly interviewed on print and other media; Ray and Molotch recently appeared in a film to be shown at Rocky Mountain Park, and Ray was recently on Science Friday public radio hour. Suding’s work was honored nationally in “Trailblazing Women in Conservation” symposium in Santa Barbara, California, and more locally at the Denver Zoo “Women in Conservation” symposium.

Work with Rocky Mountain National Park and the City of Boulder allow us to translate our results to important management questions. Niwot faculty and graduate students participate each year in a day long workshop with Rocky Mountain National Park scientists and volunteers to share research findings and strategies. In year 3, we also initiated a symposium specifically focused on the City of Boulder Watershed to share results related to Boulder’s water supply and downstream citizens. The success of this event has spurred us to plan these on an annual basis as well as to explore the possibility of releasing a “state of the watershed” report each year.

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. The Information Management System at Niwot Ridge has made substantial progress toward the goals in the NWT LTER VII proposal, and in particular to addressing weaknesses of our IM system that were identified in the panel review summary.

In Year 3, we have implemented a new unified system with the LTER/EDI repository as the primary repository for accessing all Niwot datasets. Required metadata elements are provided by researchers using a Microsoft Excel form downloaded on our website. This spreadsheet is then translated using R code in order to convert the user-provided information into a complete set of required elements for EML in tabular form,
which is stored in a GitHub repository. Both the raw data and tidied data are archived on the NWT server; the latter in a web-accessible portion where it can be harvested by PASTA.

A second set of R code is used to convert the tabular metadata into EML, which is uploaded onto the LTER/EDI repository. The aim is eventually to store the tabular metadata in a postgresDB; currently the tables are archived on GitHub. The data catalog on NWT’s website (https://nwt.lternet.edu/data-catalog) searches NWT data directly on the LTER/EDI repository and provides direct links to download and access data and metadata only from the LTER/EDI repository.

In addition, we have nearly completed the migration of all existing Niwot datasets that formerly were available only on Niwot’s website as well as updating versions of datasets on PASTA with the current Niwot version where checksums indicated previously submitted data on the LTER/EDI repository were out of date. To do so requires parsing text-based (ASCII) metadata files that were prepared by humans (not machines), and therefore often contained incomplete information or formatting issues. Together with the new datasets, we have added or updated ~100 NWT datasets on the LTER/EDI repository since 2017.

B. Website migration to Squarespace. With dataset search and discovery facilitated through the LTER/EDI repository, NWT no longer needs to host a complex CMS for its website presence. As a result, we revamped the website in Squarespace during Spring 2019. The new website is much easier to edit and maintain, while still aligning with the core requirements of LTER websites. Our website includes enhanced dynamic content such as the ability to “explore the ridge” via real-time weather graphs, current imagery, and our user-driven tundracam. At present, the public-facing publications list is hosted through Google Scholar; however, we did convert our publications record from the former (mysql) system to .bibtex for the LTER network bibliography, and are maintaining an updated Zotero library for future updates. This also provides flexibility to add more searchability to NWT’s website publications search query using a front-end to Zotero at a future date.

C. Next steps. Our vision for the next phase of NWT information management is to foster more team-based analysis and synthesis across disciplines within the NWT LTER. One model we are considering is a synthesis workshop retreat on an annual or semi-annual basis, where NWT researchers would come together and brainstorm about ideas for new analyses and publications that could be done with existing NWT data. The outcome of the workshop would be a focal topic for the semester; preliminary analyses completed; and a team of core participants self-identified who will carry the nascent ideas and analyses through to publication.

REFERENCES.


